A BAYESIAN BELIEF NETWORK APPROACH TO MAP SEASONAL CHANGES IN ECOSYSTEM SERVICES TRADE-OFFS AND SYNERGIES

AANCHAL SOOD
Enschede, The Netherlands, August 2020

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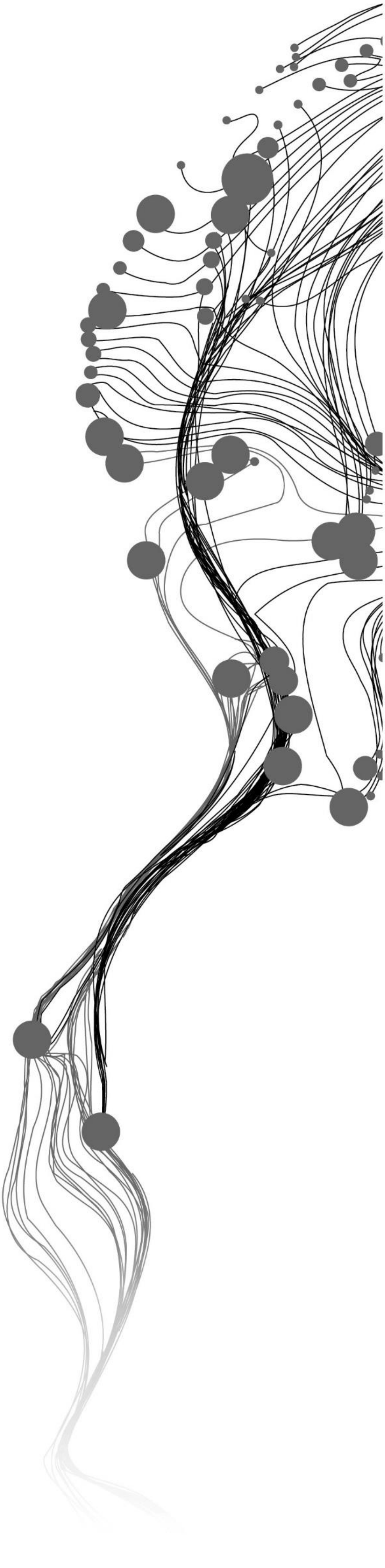

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Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialisation: Free Specialization

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ABSTRACT

To gain maximum benefits from nature, there is a need to identify the relationship among different interacting services and acknowledging that these relationships might not be constant over time. This information can help to make well-informed and efficient management decisions, that can minimise the trade-offs and maximise the benefits retrieved from nature. This explorative study used a spatial Bayesian Belief Network (BBN) to assess its ability to map seasonal variations in the trade-offs and synergies between different ecosystem services (ESS). The output maps from Bayesian Belief Network can help to identify and prioritise areas for adaptive management, keeping in mind the underlying parameter uncertainties.

Though several methods successfully have identified and quantified relationships among services, yet not many studies have explored the potential of the BBN to map ESS trade-offs and synergies. Therefore, this research presents a way to identify and map the interactions (trade-offs, synergies, and no-effects) among ESS using expert knowledge and then see how these interactions vary over seasons. In this regard, a case study area was selected as Mt. Oiti National Park in Central Greece. The creation of the network was based on data collected from twelve experts in the face - to - face semi-structured interviews. The interviews also included participatory mapping for collecting spatial data.

It can be seen from the results that Bayesian Belief Network can be used for generating ecosystem services interactions maps which may assist the decision-makers in making well-informed decisions. This can lead to effective and efficient utilisation of resources as it allows to identify areas of priority that need immediate attention during different seasons. It was found that there was a seasonal pattern in ESS pairs such that the services may have synergy or trade-off during one season and no-effect in the other. The outputs also help to visualise the change in the magnitude of interactions among four ecosystem services over the season. The interactions among provisioning service as timber extraction and cultural service as recreational canyoning, hiking and hunting services, show the ability of Bayesian Belief Network to combine qualitative and quantitative information captured for the four ecosystem services in a single model and capture relationships among them. Synergy was observed between recreational ecosystem services like hiking and canyoning and also provisional service timber extraction and cultural service as recreational canyoning service. Trade-offs are identified among cultural ESS like recreational hunting, and recreational hiking and also recreational canyoning. The most influential relationship is from provisional ecosystem services: timber extraction to all other services. It was found that this provisional service impacts all other services but is not influenced back by any other service. The Bayesian Belief Networks are suitable for applications like this study where there is a small dataset available with large uncertainty which impacts decision-making considerably. Altogether, the developed model was the first attempt in modelling the seasonal variations in interactions among the ecosystem services focusing on their flow component.
Keywords: Bayesian belief network; ecosystem services flow; ecosystem services interactions; trade-offs; synergies; no-effect; uncertainty; expert interviews; mapping.

ACKNOWLEDGEMENTS

First, I would like to thank my supervisors, Dr E. Drakou and Dr N. Schwarz, for the support and guidance provided throughout the research. It has been a great experience working under their supervision.

I would like to thank my parents, Vismita and Abu for all the motivation and support provided throughout the research and also for giving me the strength to move ahead in difficult times.

I am also very grateful to the faculty of ITC, University of Twente, for giving an opportunity to study with a scholarship and for honing my skills to be able to complete this challenging research. I am grateful that I could go to Greece for internship and data collection process.

I would like to give my deepest gratitude to Mrs. Jenny Kaliva, Avra Stamello and Eva Donta for all the support provided during the fieldwork. I would also like to recoganise the invaluable assistance that Ageliki and Terzi provided on the field.

I would like to express my gratitude to Ana for always finding time to reply to my queries and share her experience and knowledge on various related topics.

At last, I would like to thank my close friends Anirudh, Mohan, Harry, Athithya and all others for the endless support and encouragement.

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1. INTRODUCTION

1.1. Background

Human existence and quality of life depend on the direct and indirect services provided by the ecosystems. The Ecosystem Services (ESS) are the benefits the ecosystems generate through their structure and functions and provide to the people. If the functioning of the ecosystems is affected, the provision of services is also impacted, thereby influencing human well-being. Therefore, by examining the impacts of decisions made by decision-makers on the environment and human well-being due to the changes in ESS, they can make better-informed decisions by weighing alongside the ecological and socio-economic aspects of their decisions (Millennium Ecosystem Assessment, 2005).

Landscapes generally provide a multitude of ESS. ESS is dynamic in nature as they are generated from the ecological processes and functions, but also human activities which vary over time. It can be observed that with seasons, different ecological functions take place, which leads to a difference in either magnitude of ecosystem service produced, or different ESS provided by the same landscape altogether. There are various drivers of ecological systems like rainfall, human activity, temperature etc. which when recognized show presence of seasonality everywhere (White & Hastings, 2018). The seasonal changes introduce either changes in biophysical processes and/or management decisions and social practices which may lead to changes in relationship among the services. Seasonality can help understand different characteristics of ecological dynamics (White & Hastings, 2018). Moreover, the socio-cultural practices also change over seasons as people adapt to the changing season and plan activities accordingly. Therefore, seasonality occurs due to multiple reasons (temperature changes, timings of religious festivals, sunshine hours, vacations etc.) that have natural and anthropogenic causal factors, directly or indirectly influencing the supply or flow of ESS. The example from (Burkhard & Maes, 2017) has been provided below.

1. The cultivation of crops in floodplains is controlled by the seasonal floods. People move to higher lands during the floods and return during cultivation season to the valley. Thus, services consumed vary in space due to seasons.
2. We know that due to change in season, several biophysical changes occur in the tree. A tree is an ecosystem where both biotic and abiotic elements are interacting with each other. During Spring, the leaves on the tree provide a habitat to the birds. But during autumn, the leaves fall and instead provide new service by providing nutrients to the soil, helping it to fertilise (different regulating service in the same space in different seasons). Similarly, during Summers, people go and enjoy the shade under the tree (recreational service) but in autumn the form of recreational service changes where people admire the beauty of changing colours of leaves of trees and falling of the leaves (recreational services). Thus, the dynamics of ecosystem service supply and flow can be observed through time in this example.

With the seasonal change, the demand for specific ESS provided by the landscape can change. This can lead to modification of the ecosystems which can lead to changes in the type, magnitude and also a related mix of services produced by the landscape (Rodríguez et al., 2006). However, not all services can be enhanced simultaneously, and single-sector management can lead to reduction and losses of other services creating harmful unintended consequences (Rodríguez et al., 2006). This calls for trade-offs when the increase in the use of one ecosystem service leads to a decrease in the provision of other services. It is vital to manage the trade-offs as they can generate conflicts among various stakeholders, who have different priorities and are managing or benefitting from the same landscape. Also, proper management of landscapes might minimise trade-offs and promote synergies. Synergies occur when an increase in the use of one service leads to an increase in the provision of other service and vice-versa. Thus, by identifying the trade-offs and synergies, long term consequences of enhancing one service over others can be understood. Also, as the trade-offs and synergies arise due to choices made while managing ecosystems which can also depend on the seasonal changes, analysis of these interactions can help to identify areas of priority to minimise the risk of conflicts and can lead to maximising the benefits retrieved from nature, sustainably.

There are various methods available to identify and assess trade-offs and synergies among ESS, including but not limited to:

- The Spatio-temporal statistical analysis methods like pairwise correlation (Qiu et al., 2018)
- root mean square approach (Dai et al., 2017)
- factor analysis and clustering approaches (Vallet et al., 2018)
- multi-objective optimisation methods (Fox et al., 2019)
- regression-based methods (Liu et al., 2017)
- production possibility frontier (King et al., 2015)
- participatory approaches (Sun & Müller, 2013)

Pairwise correlation quantifies the interactions and is the most popular method among continuous quantitative indicators. Besides these, some simulation and optimisation models are also available like InVEST[1], ARIES[2], MIMES[3] etc. Different methods are used for visualising the trade-offs and synergies like star diagram, box plots, scatter plots, efficiency frontier, etc., but none of these graphic methods can quantify the strength of relationships.

Recently, network analysis methods like Bayesian belief network (BBN) are being used in the field of ESS modelling (Landuyt et al., 2013) to assess relationships between ESS. A BBN uses a directed acyclic graph to visualise the system as a chain of causal relationships (Burkhard & Maes, 2017) and follows the principle of Bayes theorem to quantify the causal relations between the different services using conditional probability. It is a flexible decision support tool that creates a space for an open dialogue. The stakeholders can be involved during the construction of BBN through participatory processes, which can help them to visualise the structure and interconnectedness among the systems and how the change in one system can lead to trade-offs in the other. This participatory approach can make the stakeholders aware of the environmental problems, who can then understand the consequences of their actions and discuss how to achieve viable and sustainable solutions (Farley & Voinov, 2016). Also, if there is a lack of data, involving experts can compensate for it, though it might increase the uncertainty involved.

The stakeholders have a local understanding of the functioning of ecosystems and their complex interactions with their components, management and ecosystem responses (Grêt-Regamey et al., 2013). Also, the experts, decision-makers and management bodies have local knowledge about the problems but might lack the spatial solutions and the certainty about suggesting an alternative management option.

[1] InVEST: Integrated Valuation of Ecosystem Services and Trade-offs: https://naturalcapitalproject.stanford.edu/software/invest
[2]ARIES: Artificial Intelligence for Ecosystem Services: http://aries.integratedmodelling.org/
[3]MIMES: The Multiscale Integrated Models of Ecosystem Services: https://toolkit.climate.gov/tool/

Maps are a symbolic representation of relationships between elements in space, region, or time; therefore, maps can provide certain benefits for addressing these issues. Maps can be used to visualise ESS in space to deduce the interactions (Tomscha & Gergel, 2016). ESS interactions can be linear and non-linear (Rodríguez et al., 2006; Deng et al., 2016), and these interactions can vary over space and time. Therefore, maps can be useful in identifying and investigating the Spatio-temporal patterns of ESS trade-offs and synergies, thus helping to understand complex systems and interrelationships of their components (Adhikari et al., 2018). The patterns identified can then help decision-makers in providing appropriate, well-informed, and efficient management solutions, which can be replicated to places facing similar issues and conditions.

The BBN's have been used in ESS modelling and mapping studies using spatially explicit expert knowledge and considering uncertainties. The BBN's have been used in assessing trade-offs and synergies, yet not many studies have explored to assess these interactions in a spatially explicit manner (Landuyt et al., 2016).

To understand and assess trade-offs and synergies among ESS, several studies were conducted during the last decade. Yet, most of these studies assumed that the relationship observed among services in space remains stable across time. This space-for-time concept is commonly used in ecological studies (Tomscha & Gergel, 2016) but can lead to ineffective management due to wrong assumptions for underlying mechanisms. Also, without including time in ESS assessment, the static assessments' will not give a complete picture (Lautenbach et al., 2019; Qiu et al., 2018). The existing knowledge about ESS is mostly looking at them in short periods but not considering variation over time (Birkhofer et al., 2015). Also, there are not many studies available that investigate the seasonal aspect of ESS trade-offs and synergies (Crouzat et al., 2016; Lautenbach et al., 2019). There are only a few studies available on ESS interactions at different temporal scales (Mouchet et al., 2014; Tomscha & Gergel, 2016; Hou et al., 2017) most of which focus on only a few services in isolation or consider limited interactions leading to over-simplification (Bennett et al., 2009; Renard et al., 2015). It has also been observed that there is limited use of models that consider interactions between services, especially looking into the flow component of ESS. Although there has been an increase in ecosystem service modelling cases, it has also been suggested that more sophisticated methods are needed for in-depth analysis of trade-offs and synergies to determine the driving forces of interactions (Landuyt et al., 2016)

Though BBN can holistically assess and quantify trade-offs and synergies arising due to interactions between ESS, yet the application of BBN has not yet been fully explored for mapping trade-offs and for integrated modelling of multiple services to understand their spatial dependencies and interactions (Landuyt et al., 2016). Reasons for its limited use can be due to needing for a detailed introduction to the topic and methodology to minimize the biases and any mistrust arising due to ignorance about its use (Uusitalo, 2007; Landuyt et al., 2013; O'Hagan, 2019).

Considering the limitations listed above, this study aims to use the Bayesian belief network approach to map seasonal changes in ESS trade-offs and synergies. A BBN can handle uncertainty, works with qualitative and quantitative data, integrates data from different sources (including results of modelling), incorporates inputs from stakeholders and can also work with missing data. The BBN's graphical representation of the interconnectedness of the system helps to represent complex socio-ecological systems in an understandable manner, facilitating stakeholder communication. In general, these models can be used to improve system understanding, communicate with stakeholders, identify trade-offs and synergies or understand the uncertainties involved in the process (Höfer et al., 2020). Therefore, it provides a solution to the shortcoming of other methods listed below:

- Assume linear relationship among the services which is not always true
- Work with only two or three ESS to see how they interact, which does not give a complete picture and can lead to the generation of more trade-offs due to over-simplification of the model.
- Cannot integrate different data types together
- Cannot include information from multiple sources especially the stakeholder's perceptions
- Are not simple enough to be understood by non-experts
- Unable to work with missing data
- Cannot account for uncertainty

Thus, this study aims to fill the gap to understand how, where and when the changes among ESS interactions occur, by taking advantage of a Spatial Bayesian Belief Network to assess the seasonal changes in ESS trade-offs and synergies looking into the flow component of ESS. A Spatial BBN is a BBN with integrated GIS capabilities such that it can define relevant spatial relationships. The GIS capabilities can be used to quantify spatial nodes and also visualise the results from a BBN as spatially explicit maps (Johnson et al., 2012).

1.2. Research objectives and research questions

The main aim of this research is to assess seasonal changes in trade-offs and synergies among ESS, in a selected case study, using a Bayesian Belief Network approach. The main aim will be achieved by addressing the following objectives with the associated research questions:

1. To identify the relationship between the selected ecosystem services of priority with the chosen stakeholders, in the focal study sites.
    a. Which sites will be chosen for the study from all the sites under the case study, and what will be the selection criteria?
    b. Who are the relevant stakeholders? What are the key criteria for prioritising the ESS for stakeholders and for the objectives of this research?
    c. Which are the ESS of priority? Which indicators will be used to quantify the selected ESS based on available data and site relevance?
    d. What types of relationships (synergistic or trade-off) between the ESS are identified?

2. To assess the ESS relationships through a BBN structure.
    a. What modelling platform is most suitable to construct the BBN for the objectives of this study?
    b. Which variables will be chosen to build the network? How will the different data types be integrated?

3. To develop and implement a BBN mapping approach to assess the changes in ESS trade-offs and synergies, across space and time.
    a. How will the identified relationship between the ESS be quantified by the experts?
    b. How will the BBN be used to visualize and quantify the changes in these identified relationships across space over the different seasons?
    c. How will the results of the developed model be validated?

2. THEORETICAL BACKGROUND

2.1. Ecosystem services concepts and definitions

Several definitions are available for ESS and its concepts. However, for this study, the following definitions and concepts have been considered.

- **Ecosystem Services:** are the benefits people obtain from the ecosystems (Millennium Ecosystem Assessment, 2005).
- **Ecosystem Services Components:** The ESS act like an interface between the social and ecological systems and therefore can be described by three attributes:
- **Supply:** The provision of ecosystem service by a particular ecosystem irrespective of its use or according to Villamagna et al. (2013), "An ecosystem's potential to deliver services based on biophysical and social properties and functions".
- **Flow:** Amount of ecosystem service mobilised in space and time. According to Villamagna et al. (2013), "the benefits actually delivered to the people".
- **Demand:** According to, Villamagna et al. (2013), "the amount of a service required or desired by the society".
- **Interactions among ESS:** When multiple services respond to the same driver of change or when changes in one service leads directly to change in the other, then ESS have interactions. These interactions can be trade-offs, synergies or bundles (Raudsepp-Hearne et al., 2010).
- **Trade-offs:** According to Raudsepp-Hearne et al. (2010), trade-offs are situations that occur when "the provision of one service is enhanced at the cost of reducing the provision of another service". The trade-off can arise due to conflicting land-uses, rivalry between ESS or negative correlation between spatial occurrences of ESS i.e. are causally linked.
- **Synergies:** According to Raudsepp-Hearne et al. (2010), "synergies occur when multiple services are enhanced simultaneously". Interactions among ESS in this case are multiplicative or exponential in nature.
- **Drivers:** An ecosystem can be modified directly or indirectly through natural causes or human-generated factors. These natural causes or human induced factors that cause changes in nature, anthropogenic assets, ESS or human well-being are called drivers of change. A **direct driver** can be one ecosystem service influencing the other directly i.e. there is a clear influence on ESS component or Ecosystem processes, whereas an **indirect driver** can bring changes to one component of ecosystem service which might then affect the other components of the same service or different components of other ESS. Therefore, the indirect drivers influence one or more direct drivers to bring a change in ecosystem processes (Ruskule et al., 2018). Examples of drivers can include ESS use, ecological changes, management policy etc

2.2. Bayesian Belief Network

2.2.1. Introduction

BBN's were first introduced by J. Pearl in 1986 to solve human reasoning problems and deal with uncertainties (Landuyt et al., 2013) and are now being used for modelling uncertain and complex systems such as ecosystems and environmental management (Uusitalo, 2007). Due to the several advantages, it has been suggested that BBN may be considered as one of the key methods to integrate transdisciplinary knowledge especially while managing the environment (Duespohl et al., 2012; Uusitalo, 2007).

A BBN is a useful tool that helps to visualise the relationship between and see the interconnectedness within a complex system (Uusitalo, 2007). It is a model that represents a complex real-life system's components and relations in a probabilistic causal network (Duespohl et al., 2012). These causal relationships between variables are displayed through the links between different system components displayed as nodes in graphical structure (Directed acyclic graph- DAG). This makes it easy for stakeholders to understand the system encouraging them to participate and understand points of views and requirements of different stakeholders. Therefore, they can also be able to understand the trade-offs involved while taking any decision.

As explained earlier, there can be some missing data or lack of information about some processes in nature which is true for ESS studies as ecosystems have heterogeneous and dynamic processes whose quantitative data is often missing (Van Der Biest et al., 2014). This generates uncertainty and models that depend on data alone cannot account for the uncertainty. By being able to recognise uncertainty explicitly, trade-offs related to different management strategies can be identified. BBN's can remove data limitations by the integration of several data sources and data types like models, observations, scientific information, remote sensing data or by involving stakeholders in a participatory approach etc. Also, as BBN are probabilistic models, they deal with uncertainties using Bayes theorem. The uncertainties are propagated through the network. Therefore, the BBN's are useful tools for addressing the uncertainty (Uusitalo, 2007) in ESS research. Thus, the advantages of the BBN overcome the drawbacks of the other methods mentioned in section 2.3.1 for assessing trade-offs and synergies.

Advantages of BBN include:

1. A graphical representation of integrated knowledge from different domains, which makes it easy to acknowledge various perspectives and their relative importance.
2. Integrate qualitative and quantitative information which are represented as different variables. These variables are the nodes of a BBN linked to each other via causal links.
3. Account for uncertainty while specifically including stakeholder knowledge and perspectives.
4. Support communication and enhance understanding among people from different spheres; leading to a deeper understanding of the system, human-environment relationships and setting up priorities to choose appropriate combinations of interventions.
5. Involve stakeholders to deal with the ambiguities related to changes in the interactions among multiple ESS, through space and time. Therefore, BBN's are good for visualising and quantifying relationships.
6. Work with missing data, i.e. the inputs derived from multiple sources, including stakeholders' perceptions.

Thus, BBN fulfils the basic characteristics needed by any simple model to support transdisciplinary research (Duespohl et al., 2012).

2.2.2. Bayesian Belief Network concepts

- **Directed Acyclic Graph (DAG):** Graphical representation of BBN containing nodes and arrows that make a network.
- **Node**: Graphical representation of variable that represents the factor relevant to an environmental system.
- **State**: All possible values a variable can acquire. The state must be finite in number, mutually exclusive and discrete.
- **Arrow/Links**: Linear graphical representation of causal relations in BBN.

Probability Distribution: When the state of an event is unsure or uncertain, we talk about the likelihood of the event to occur. This likelihood is the probability distribution $P(A)$ of the event, which deals with this uncertainty by quantifying different states the variable can be in. Thus, probability distribution provides a list of possible values a random variable can take, along with its corresponding probability values.

Marginal Probability Distribution: Probability distribution of occurrence of a single event A is $P(A)$ and is represented as bar plots in the BBN model's nodes. Marginal probability is also called Unconditional Probability. For two random variables A and B, when the joint distribution is known, the probability distribution of A when the values of B are not considered is marginal probability. It is calculated by adding joint probability distribution over all values of B.

$$pA(a_i) = \sum_j p\,(a_i, b_i), \quad and \quad pB(b_i) = \sum_i p(a_i, b_i) \qquad \text{……. (1)}$$

Joint Probability Distribution: It is the probability distribution of two or more events occurring together and being states simultaneously. If the two events are A and B, their probability of occurring together is given by $P(A\ and\ B)$ represented as

$$P(A\Pi B)\ or\ P\left(A_{\,,}\,B\right) \qquad \text{……. (2)}$$

If $A\ and\ B$ are **independent** of each other, which means the two events do not affect each other, then:

$$P(A\Pi B) = P\left(A_{\,,}\,B\right) = P(A) * P(B) \qquad \text{……. (3)}$$

If $A\ and\ B$ are **mutually exclusive/disjoint,** which means the two events cannot happen at the same time then

$$P(A\Pi B) = 0 \qquad \text{……. (4)}$$

as these two events cannot happen together, so there will be no joint probability.

Conditional Probability: Joint Probability cannot be used to calculate how much influence does the occurrence of one event have on the other. So, the probability that an event B will occur when event A has already occurred, or event B will affect or is affected by event A is given by conditional probability which quantifies the causal relations represented by arrows in BBN. These conditional probability distributions that quantify the causal relations are stored in a table called CPT (Conditional Probability Table).

$$P(B|A) = \frac{P(A \Pi B)}{P(A)} \quad \text{.......} \mathbf{(5)}$$

Where the probability distribution of variable B depends on the state of variable A.

If A and B are independent events, then:
$\boldsymbol{P(B|A) = P(B)}$ which tells us that when one event has occurred, it does not change the probability of the other event.

Bayes Theorem: The conditional probability can be calculated based on Bayes Theorem as below:

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)} \quad \text{.......} \mathbf{(6)}$$

Where,
$P(A|B)$ is the posterior probability(inference) - The conditional probability of occurrence of event A (called proposition) after all evidence, event B (called evidence), has been considered. $P(A)$ is the prior probability of the proposition: actual probability distribution of A.
$P(B)$ is the prior probability of evidence.
$P(B|A)$ is the likelihood ratio, measures the probability of occurrence of B given event A.

Mutual Information: Mutual information is a criterion that indicates the sensitivity of one variable to other variables. If the value of one variable in a system is known, then mutual information measures the corresponding reduction in uncertainty for predicting the value of the other variable. It is calculated for two discrete random variables A and B based on the formula:

$$I = H(A) - H(A|B) = \sum_a \sum_b \frac{P(a,b) log_2[P(a,b)]}{P(a)P(b)} \quad \text{.......} \mathbf{(7)}$$

With,
$I =$ Entropy reduction (Mutual Information)
$A =$ Output variable with the state a
$B =$ Input variable with state b
$H(A)$ = Entropy of A before finding at B
$H(A|B) =$ Entropy of A after findings at B

Shannon's Index: It is a standardised measure of entropy that expresses uncertainty. It's valued between lie between 0, which depicts complete certainty of an event to occur and 1, which shows maximum uncertainty and depicts a uniform distribution between all possible values an event can take.
Shannon's evenness index of the posterior probability distribution for discrete target nodes is given by:

$$J = H'/H_{max.}$$

Where, **……. (8)**

$H' = -sum_{i=1}^{N}(p_i * log_2 p_i)$
$H_{max} = log_2(N), p_i$

Where,
p_i is the probability of state i
N is the number of states

2.3. Assessment of ESS relations

2.3.1. Overview of methods used for analysing ESS trade-offs and synergies

Research on trade-offs and synergies gained importance after they were considered in a study for optimised decision-making in the 1990s (Deng et al., 2016). Several studies for analysing and mapping trade-offs were produced in the last decade. A few studies introduced frameworks explaining concepts of interactions and drivers. Bennett et al. (2009) proposed a framework that helped to differentiate the direct relations in ESS from indirect relations caused by an external factor. They stated that trade-offs and synergies are circumstances which may arise due to response to a common driver or from direct interactions between ESS, where a driver is a natural or human-generated factor which modifies an ecosystem, therefore, changing the type, magnitude and interactions among the services. Rives et al. (2012), who looked into the interactions among ESS based on the provision by ecosystems and also affected by social management actions in Niger, suggest that looking at ESS from the social-ecological perspective is essential for understanding changes in complex systems. Mouchet et al. (2014) proposed an interdisciplinary methodological approach that shows how different quantitative methods can be used to assess and quantify ESS synergies and trade-offs, both on supply and demand sides. Crouzat et al. (2016) came up with a more detailed framework to describe relationships among the components of ESS with social and ecological variables. They created networks of influence relationships in-order to understand different facets of ESS and investigated these different perspectives to highlight trade-offs and synergies.

Even though assessment of trade-offs and synergies is successfully achieved using a diversity of methods yet their applications in decision making are limited (Deng et al., 2016; Daily et al., 2009; Vallet et al., 2018). Methods used for trade-off/ synergy analysis should be able to report the type, direction and the strength of the relationship in a comparable way. Visual map comparison outlines the spatial relationship and is the simplest method to visualise positive and negative associations (Anderson et al., 2009). They help to understand and visualise potential trade-offs among ESS by providing detailed information on ESS indicators. But their limitation is that they do not quantify the strength or type (synergy or trade-off) of interactions (Baiqiu et al., 2019). Although correlation is a popular quantitative method, which helps to study the relationship directly, it cannot give underlying causes (Baiqiu et al., 2019). Also, it works best to study the relationship between two or three ESS but fails to represent real and complex interactions among multiple ESS and assumes linearity between interactions. Besides, they show only general trends in paired ESS, thus assuming that the pairs always have the same relationship, which is not always true (Gong et al., 2019). Similarly, a chi-square test on the two-way contingency table works with two categorical variables but cannot work with multiple variables. Maes et al. (2012) used correlation biplot method-based on Principal component analysis(PCA) to identify trade-offs between multiple ESS. Qiao et al. (2019) used Principal Component Analysis method on multi-period land-use/landcover data to estimate Spatio-temporal variations of trade-offs and synergies produced by multiple ESS. PCA works with multiple quantitative variables, but it assumes the relationship between the variables to be linear, which is not always the case (Birkhofer et al., 2015). For qualitative data, multiple correspondence analysis (MCA) is used. Factor analysis works with mixed data combines PCA and MCA functionality to work with both quantitative and qualitative data. Qiu & Turner (2013) used factor analysis to identify synergies and trade-offs across the landscape. Dai et al. (2017) used the root mean square deviation method to evaluate the synergies and trade-offs between supplies of ESS under different land-use schemes. They used data from models and remote sensing to identify interactions, but also to quantify all trade-offs and synergies. The root means square method requires a large amount of data, quantifies the trade-offs but cannot tell whether they are directly or indirectly related. The multi-criteria analysis method analyses several conflicting criteria in decision making and involves stakeholders, but the process needs to improve fairness in decision making. So just like the other methods mentioned above, it is not able to handle uncertainty. Nguyen et al. (2015) proposed to analyse targets affected by spatial distribution factors by combining the Geographical Information System (GIS) with multi-criteria analysis. The other studies assess ESS relationships to identify trade-offs and synergies by using methods like production frontier and participatory methods (King et al., 2015), simulation and optimisation models (Mouchet et al., 2014; Deng et al., 2016; Lee & Lautenbach, 2016; Cord et al., 2017). A multivariate method, including multidimensional production frontiers, was used in the study by (Ruijs et al., 2013). Lautenbach et al. (2010) recognised the need for better tools to analyse ESS trade-offs. In their study they compared the capability of different approaches to analysing trade-offs among different ESS, suggesting building a classification system based on common parameters that would describe interactions between ESS such that each ESS can be expressed as a function of these parameters.

Although spatial and temporal components need to be taken into account when trade-offs and synergies between ESS are to be identified, yet very few studies have looked into studying changes in ESS relationships over time. Tomscha & Gergel (2016) calculated static spatial correlations for different dates to detect the changes and called the approach "change-over-time approach". They correlated the mapped changes in ESS by incorporating historical data, and thus showed temporal relationships along with spatial relationships. They talk about the importance of using baseline information in the assessment of ESS interactions across heterogeneous landscapes affected by multiple drivers, which can help avoid trade-offs and track synergies. Lautenbach et al. (2010); Crouzat et al. (2016) also mention The ecosystem processes and functions are also affected by seasons; therefore, changes in ESS are also observed. This shall also provide an understanding of their Spatio-temporal variability. Yet the consequences of seasonality have mostly been underestimated and have not been explicitly included in empirical studies.

Furthermore, most of the methods do not account for uncertainty, and they might not be transparent and flexible to use. Their underlying processes might not be understood by the user as the tools are a black box and thus cannot be verified or controlled by the user. This may build mistrust and lead to misapplication of model results (Herman, 2019). There can be many causes of uncertainty, such as uncertain input data or relations among the biophysical structure of ecosystems or biased human inputs and preferences. By accounting for uncertainty, we can assess the risks and confidence in the result. Therefore, it becomes essential to deal with uncertainty which most of the methods are unable to handle. Therefore, it is necessary to include social aspects in decision making and management, which means involving stakeholder is important.

Considering stakeholder and expert views are useful to help focus on the most important aspects and in evaluating and comparing the models created to well-known theoretical properties (Höfer et al., 2020). Even advantage of using expert knowledge to fill in missing data or other information needed may become a problem due to increased bias to the system (Aguilera et al., 2011; O'Hagan, 2019). The expert's inputs can provide great insights and assist in filling missing data, but this also includes high uncertainty and bias. This may not be acceptable to decision-makers.

The plethora of methods available makes it difficult to compare the results of the studies to analyse trade-offs and synergies among services as different methods work with different data types and have different assumptions. The input data can be a result of models, empirical data, remote sensing data, expert knowledge, scientific publications, and technological reports. The methods thus, should be flexible to work with different data types that can then be integrated into a single method. The more recent network analysis tools like BBN are not only good for visualising and quantifying the relationships but can also work with qualitative and quantitative data, manage uncertainties and work with missing data by including the inputs derived from multiple sources including stakeholders' perceptions.

2.3.2. BBN for ecosystem service modelling and trade-off analysis

Aguilera et al. (2011) reviewed several papers and suggested that BBN's potential has not been fully explored in environmental modelling. With qualitative and quantitative methods for ESS being used, complex process-based models were introduced (Landuyt et al., 2013). Haines-Young (2011) reviewed a collection of studies on environmental management using BBN by including stakeholder participation along with mapping ESS and developing scenarios. Smith & Dick (2012) used BBN to model ESS valuation. They discuss all stages from the functioning of the ecological ecosystems to valuation based on the service delivery through flow and human demand. Grêt-Regamey et al. (2013) used expert knowledge along with GIS-based BBN for valuing forest ESS studied under climate change and land-use scenarios. They demonstrate the advantages of including expert knowledge while assessing ESS for reducing uncertainties. The spatially explicit ESS quantification and valuation processes were intermediary nodes in BBN which received input from spatially explicit input nodes. The trade-off analysis was based on the results of the BBN and was compared using spider diagrams. Landuyt et al. (2013) carried out SWOT-analysis to know the strength weakness opportunity, and threat while applying BBN to ESS modelling. Landuyt et al. (2014) also developed a plugin to integrate the GIS capabilities to BBN. Schmitt & Brugere (2013) used a probabilistic impact matrix to assess trade-offs arising from the development of shrimp agriculture in Thailand. Frank et al. (2014) used BBN's and Bayesian Decision Network (BDN) to understand perspectives of experts from forestry science and urban vegetation management in regard to the potential of urban and peri-urban plants to mitigate dust weather and to provide shade. They utilised the advantages of the BBN's that can work with uncertainty, handle non-linear relationships and work with qualitative and quantitative data.

Gonzalez-Redin et al. (2016) applied a BBN with GIS to preserve biodiversity in forested habitats by looking at the trade-offs between forest production and conservation. The BBN was developed through a participatory approach along with expert knowledge about biodiversity conservation and timber production. The BBN diagram is integrated with GIS layers, thus assigning spatial probability values to each pixel, which then help to generate maps of interest. Höfer et al. (2020) take advantage of that fact that BBN's can be fed qualitative and quantitative information from different sources, including uncertainties and visualise trade-offs between the services linked to human perceptions and services linked to physical processes. They visualised the trade-offs between different types of ESS by plotting each state of each output node for the four scenarios with their computed posterior probabilities. The expert elicitation[4] is done using BCI- which measures the certainty assigned to an elicited prior probability. They also suggest BBNs have huge potential and should, therefore, be further improved in structure and application for a more consolidated methodology. Their identification of trade-offs was based on analysing the prior and posterior probability values, and they suggest that method used by (Landuyt et al., 2016) needs to be explored more for identification of trade-offs and synergies. They also suggest model validation should be carried out before a BBN in applied to real-life decision-making. May et al. (2019) used a BBN to assess ESS trade-offs between hunting, nature-based tourism, biodiversity and human welfare in the Greater Serengeti-Mara Ecosystem of protected areas. They provide a web interface of a spatially explicit BBN. Their work helps to understand the likely consequences of different human-induced and management-based scenarios on the provision of ESS. Landuyt et al. (2016) talk about studies that use different methods to quantify trade-offs and their disadvantages. He mentions about different methods like ANOVA, MANOVA etc. that are suitable to find the relationship among different services which also provide details of the strength of the relationship. But these methods are data intensive. As most studies confirm that data available for such kind of studies are scarce and involves uncertainty, thereby justifying the use of BBN. In their study, they use BBN, which works on Bayes theorem and joint probability distribution, to quantify trade-offs and synergies along with identifying the causal driving forces. The results of the BBN later were linked to correlation coefficients.

The BBN has transparent working and can combine multiple sub-models, making it a multidisciplinary modelling approach (Landuyt et al., 2013). It has been used to model problems from different domains including modelling complex socio-ecological systems that require to integrate data of various types ranging from process-based models to participatory approaches, earth observation and socio-economic data. BBN itself is not spatially explicit but can be integrated with GIS using different platforms, techniques and methods. Stritih et al. (2020), created an online toolbox that links spatial data to BBN. The tool is able to address one of the limitations of the BBN, i.e. working with feedback loops by allowing the BBN to run with spatial data over multiple time steps, where the output of one-time step can act as an input to the next. Also, Netica (Norsys Software Corp. - Bayes Net Software, 2016), a software that helps to work with Bayesian network, has an extension called Geonetica. This extension allows to use BBN prepared in Netica, providing its spatial capabilities.

Given these advanced capabilities of being able to work with multiple data types including spatial data, dealing with uncertainty explicitly and being able to combine stakeholder inputs, makes BBN standout over the rest of the methods above. Yet, its applications to map trade-offs and synergies have been limited.

[4] Expert elicitation: For uncertain quantitites when the expert knowledge is expressed in terms of probability distributions, the process is expert elicitation (O'Hagan, 2019).

2.4. Conceptual framework

The conceptual framework described below has been developed for the MSc thesis to provide a better understanding of the concept of ESS interactions, i.e. trade-offs, synergies or no-effect relationships. This framework helps to visualise the ESS interactions which take place at the interface of socio-ecological systems. The ESS has three dimensions, i.e. supply, demand and flow. These dimensions of ESS can have an impact on each other due to interactions among them or due to response to a common driver which is seasons in this study. In order to develop a better understanding of interactions among ESS along with factors that cause them, it is crucial to look at interactions at the level of these dimensions (Crouzat et al., 2016). This shows that the assessment and management of trade-offs/synergies are not straight-forward but involve identification of common supporting functions, a common response to pressures and understanding interactions among the services. However, assessing those extends beyond the scope of this study (Figure 1). This study focuses on observing interactions among ESS that are formed by use and management of ESS through the complex interactions among multiple stakeholders and then observing how seasons play a role in bringing changes in interactions among those ESS. Seasons are the main drivers in the study, which bring socio-ecological changes to the system under study and directly or indirectly influence the supply or flow of ESS.

Ecosystems, as we know, are mostly multifunctional, i.e. they provide several ESS depicted as (ESS-n) in the framework below. As multiple ESS are generated by an ecosystem, unidirectional or bi-directional interactions among these services exist due to common underlying ecological functions (Cord et al., 2017). These services may interact with each other and lead to trade-offs and synergies (Turkelboom et al., 2016). In Figure 1, below, the various kinds of interactions among ESS are shown. ESS-1 can have a trade-off with ESS-2 such that one of them will increase in magnitude, and the other will decrease. Similarly, the ESS-2 with ESS-4, for example, can have synergy such that both ESS either increase or decrease in magnitude together. There can be multiple ESS interacting in different ways due to different reasons. Interactions among ESS can arise due to seasonal changes and may vary with type, magnitude and mix of services provided by ecosystems. The ESS interactions depend on the supply and demand components of ESS, based on which the flow of ESS exist. If there is supply but no demand, there is no flow. If there is demand but no supply, the flow cannot exist. However, the flow of ESS measures the actual amount of ESS being mobilised in space or actual benefit received by the stakeholders.

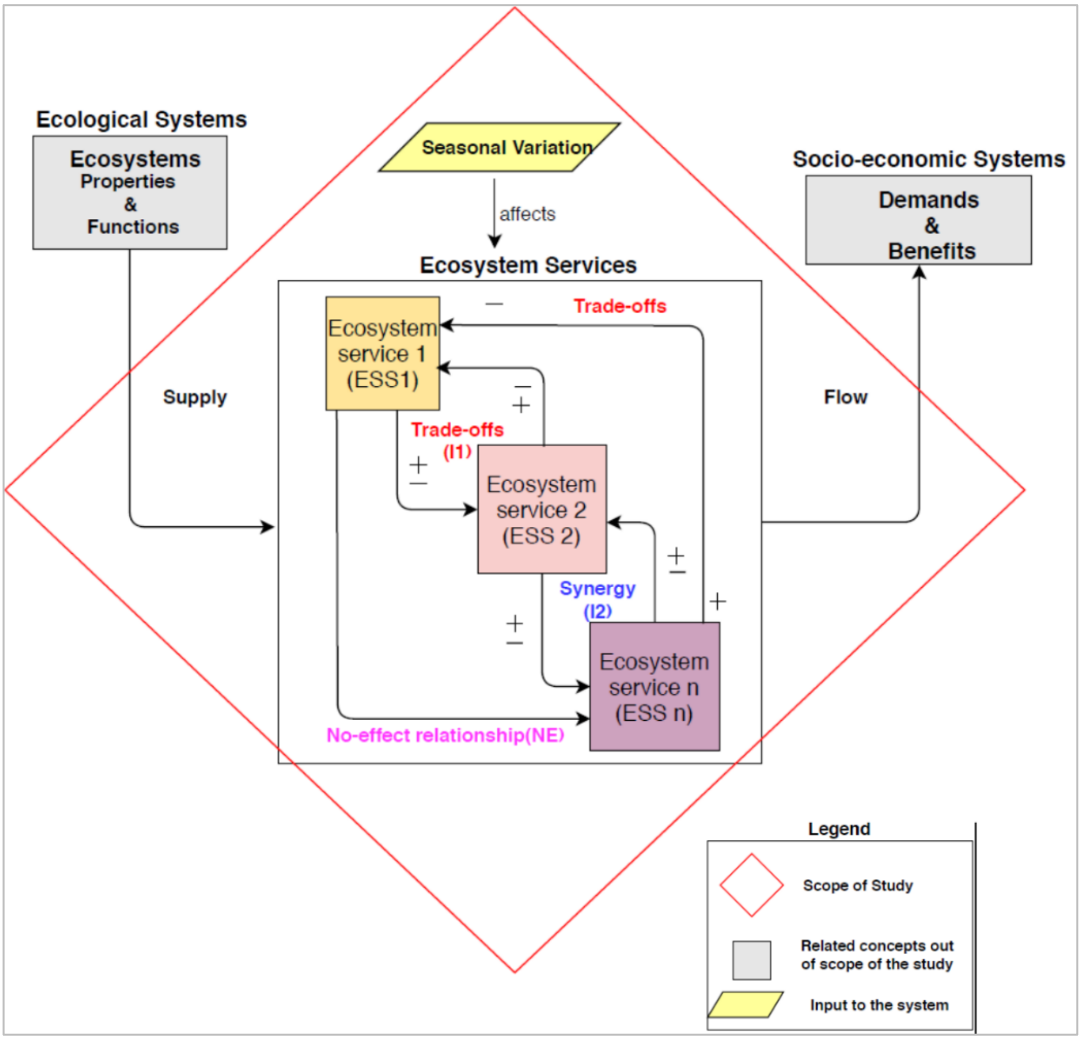


Figure 1: The conceptual framework

The ESS generated (is supplied) by ecological systems and (flows towards) used by social system. Several ESS are generated by same landscape in time and these services interact with each other to generate trade-offs, synergies or have no-effect. The seasons can act as a driver of change which can lead to changes in magnitude and type of ESS provided in the area. These processes will be modelled in the BBN to understand the relationship among the interacting ESS and observe the changes occurring due to seasonal variations.

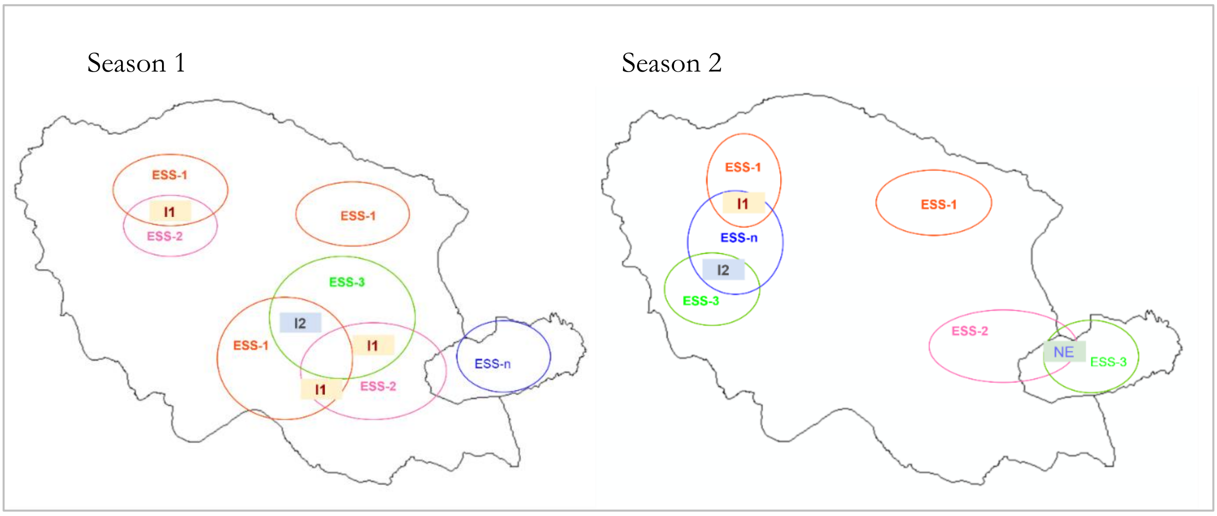


Figure 2: A hypothetical representation of multiple ESS interacting in space over the same landscape in 2 different seasons.

Figure 2 shows that the same landscape produces n number of ESS. The left side represents interactions among ESS during season 1, and the right side shows that in season 2, ESS change over space, in magnitude and their interactions also change.

In season 1, a location may be generating one type of ecosystem service (ESS-1) of a certain magnitude, which will be interacting with another ecosystem service (ESS-2) of some magnitude. But as the season changes, it might be that the same landscape doesn't produce ESS-1 at all or may produce it of different magnitude as shown by (ESS-4) in Figure 2. The same place might as well produce a different ecosystem service which would change the underlying interactions with the other ESS. This can be understood well with the example of a tree, which has already been described under the seasonality section in the introduction.

3. THEORETICAL BACKGROUND

The methodology chapter is divided into two sub-chapters:

- Methodological framework (Section 3.1):
    - Aims to describe the basic methodology for BBN development to map ESS trade-offs and synergies based on expert knowledge.
- Case study Application (Section 3.2):
    - Aims to put the methodological framework described in (3.1) in the context of the case study selected for this research. The Mt. Oiti National Park in Central Greece has been selected as a study case where the results produced by the BBN i.e. the maps showing seasonal variations in identified interactions in space can be useful for targeted management in the area. Following the steps in the methodological framework, a descriptive BBN is constructed such that it provides information about the current situation in the study site, helping to visualise trade-offs and synergies among different services, which change over seasons in magnitude.

3.1. Methodological framework for BBN development

This sub-chapter describes the methods used to collect and prepare data as well as the approach followed to develop and populate a BBN which will be used to identify relationships among chosen ESS. It involves interviewing the experts to develop an understanding of the system, collect and process the qualitative and quantitative data, identify relevant influencing factors, and then integrate the data with expert knowledge into a BBN model. This research follows the generic steps described in the scientific literature (Bromley, 2005; Marcot et al., 2006; Chen & Pollino, 2012), for constructing a successful BBN. The generic methodology can be divided into four stages (see flowchart in Figure 3) based on Höfer et al. (2020): knowledge acquisition stage (3.1.1), design stage(3.1.2), BBN operationalization stage (3.1.3) and spatial BBN application and validation stage (3.1.4).

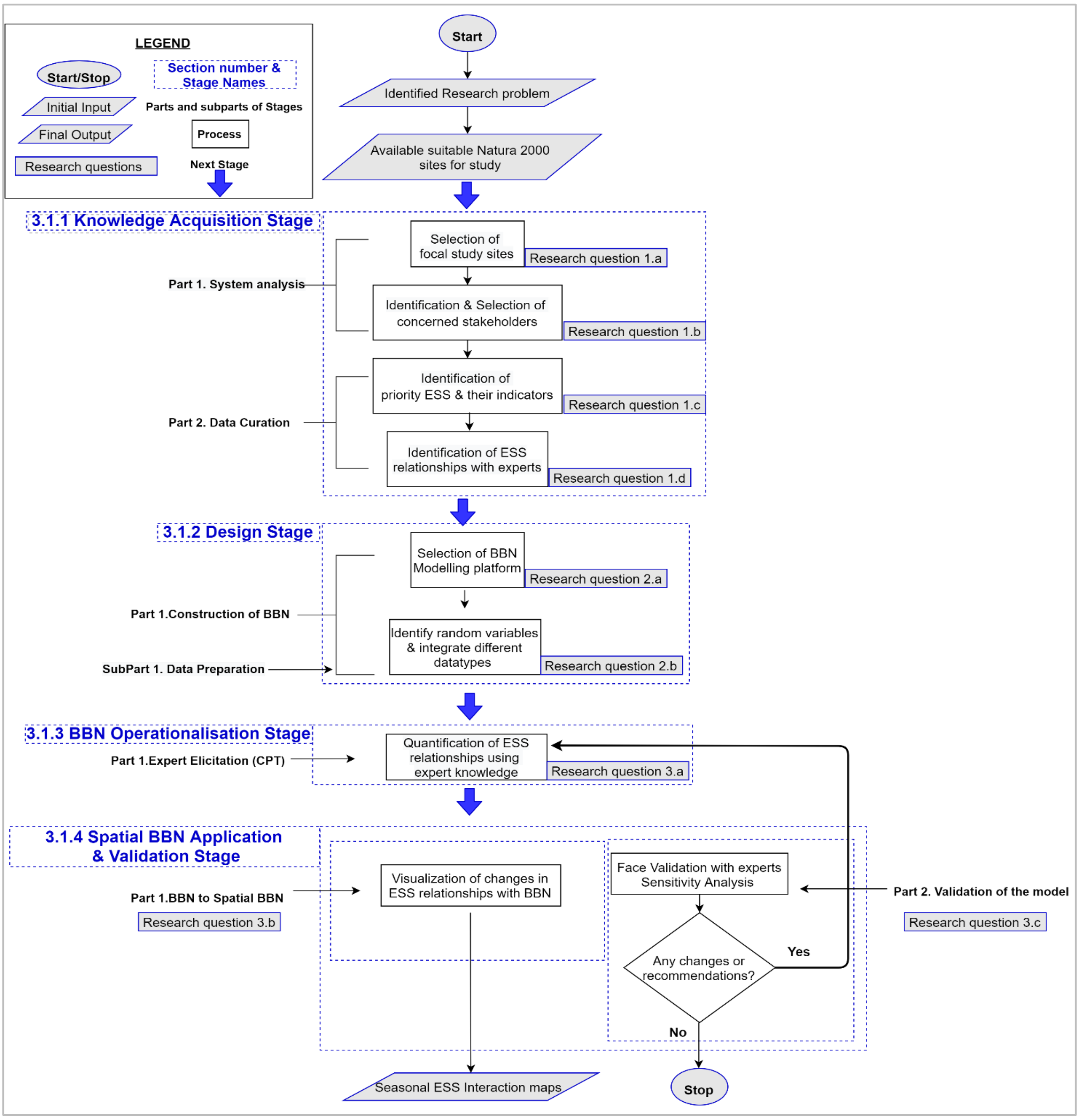


Figure 3: Steps followed in four stages of methodology to answer specific research questions

3.1.1. Stage 1: Knowledge acquisition

Part 1: System analysis

The flowchart (Figure 4) provides a summary of the system analysis part of Stage 1, which results in answering research questions a and b of sub-objective 1. This part involves:

- Review of related literature and expert consultation to choose focal sites to work on given that the focal area is extensive.
- Identification of an initial set of ESS, their indicators and relevant stakeholders
- Checking for availability of data to calculate the identified indicators. Collect relevant spatial and attribute data which can be of different types depending on the type of indicator (e.g. Biophysical data, socio-economic data). Also, collect information about the kind of relationship the identified stakeholders think (based on their experience) the ESS have with each other.

Thus, the outputs of this system analysis part of Stage 1 are choice of selected sites, list of relevant stakeholders and list of the initial set of ESS of priority along with the creation of a database to store collected data.

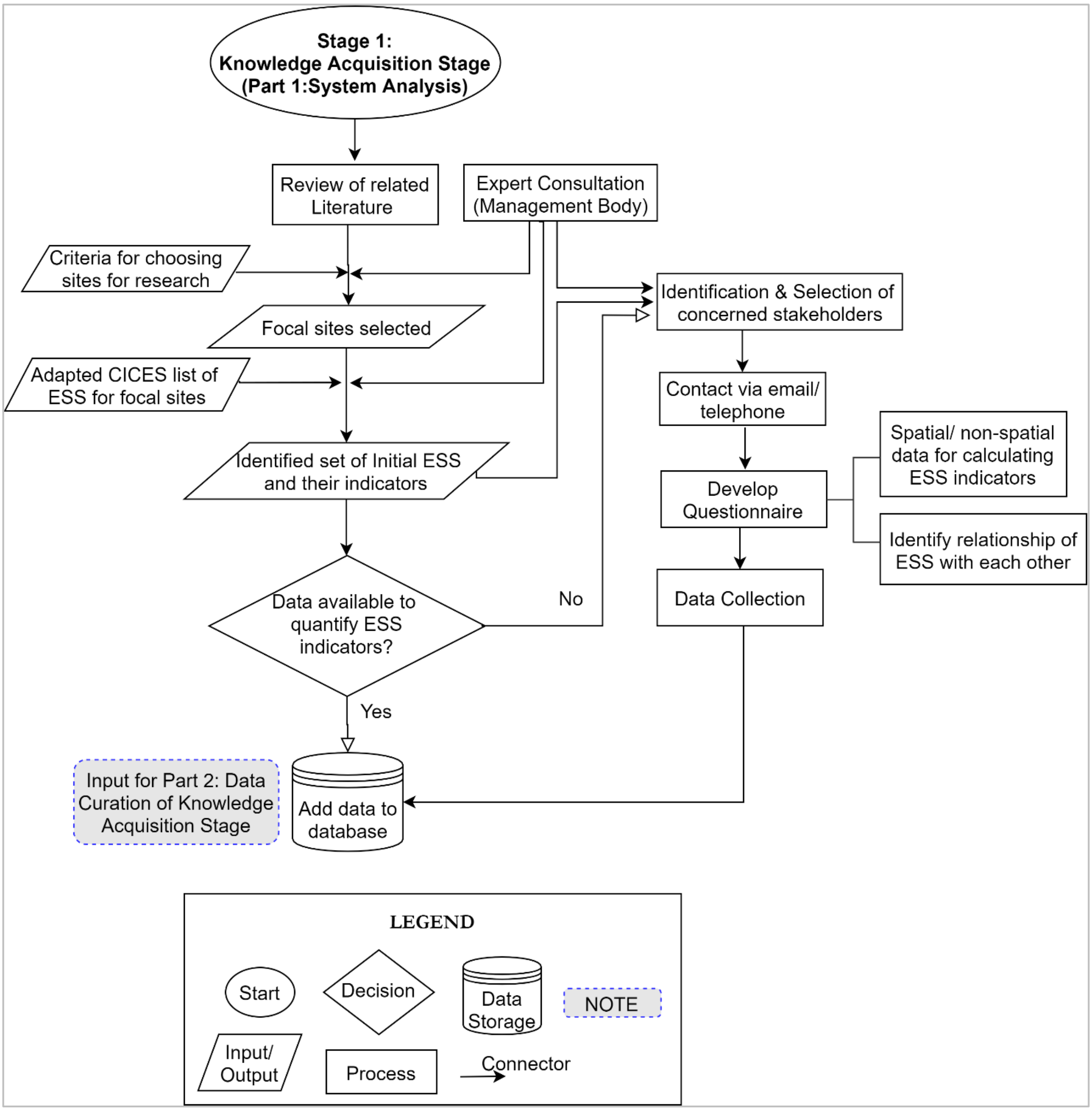


Figure 4: The flowchart shows the steps followed in the Part 1: System analysis of Knowledge acquisition stage

Part 2: Data Curation and preparation

Once the data is collected in the database, it needs to be cleaned, prepared and processed. The attribute data is organised in Microsoft Excel to manage it better, remove inconsistent data, remove errors, transform units and formats, map and align columns with preparing data in a tabular format so that it can be linked to related spatial data. The spatial data, on the other hand, is projected, georeferenced, checked for inconsistent geometry and clipped to the study area. Once data is in the required format and compiled together, it helps to create meaningful information from data. By applying the criteria to choose ESS of priority on the organised data, one output of this part of the knowledge acquisition stage is obtained, i.e. identification of the final set of ESS of priority along with their indicators. Also, once the final ESS has been selected, the identified relationship between those ESS can then be visualised using influence diagrams. These diagrams are the second output of the stage. The generic steps followed in this part of Stage 1 are shown in Figure 5.

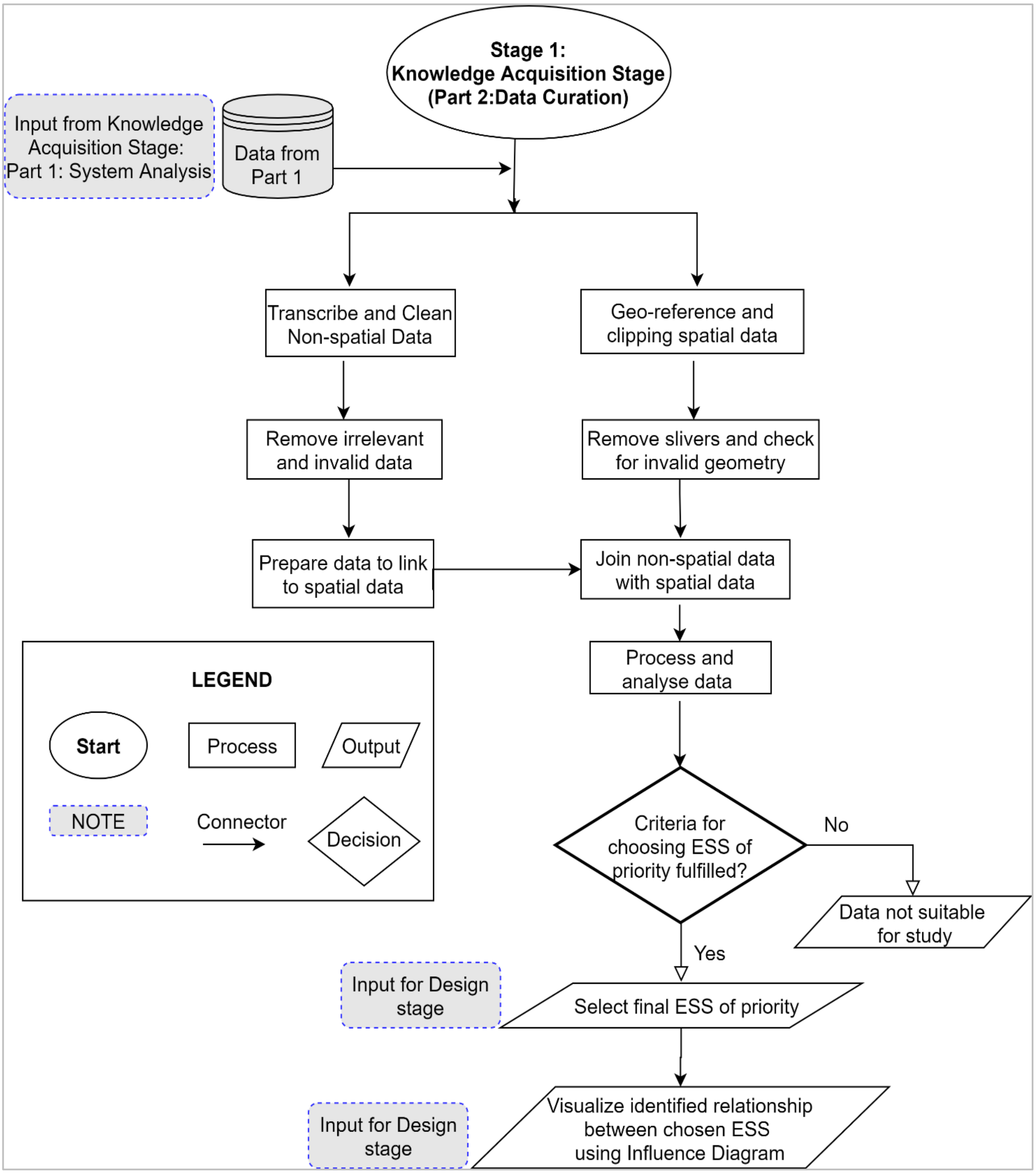


Figure 5: The flowchart shows the steps followed in the Part 2: Data Curation of Knowledge acquisition stage

3.1.2. Stage 2: Design stage

The qualitative and quantitative methods of data collection provide a holistic understanding of ESS in the study area in Stage 1, Knowledge acquisition stage. Once the knowledge about the system is acquired, stakeholders identified, data collection and system understanding developed, the next phase involves converting it into a directed acyclic graph (DAG). For constructing a BBN, a modelling platform needs to be chosen. A BBN can be built in different ways as it depends on several factors like objectives of the study, the stakeholders involved, socio-cultural environment, time availability etc. Bromley, (2005). However, there are some important facts to consider before starting the construction of the BBN (as discussed below in this section (Considerations while building a BBN). The data can then be prepared into a format which is acceptable as input by the nodes of the BBN. The output of the design stage is a directed acyclic graph which is the structure of the BBN constructed from the nodes, links and states defined in this stage and it answers the research questions a, b and c of sub-objective two. The steps followed are shown in Figure 6

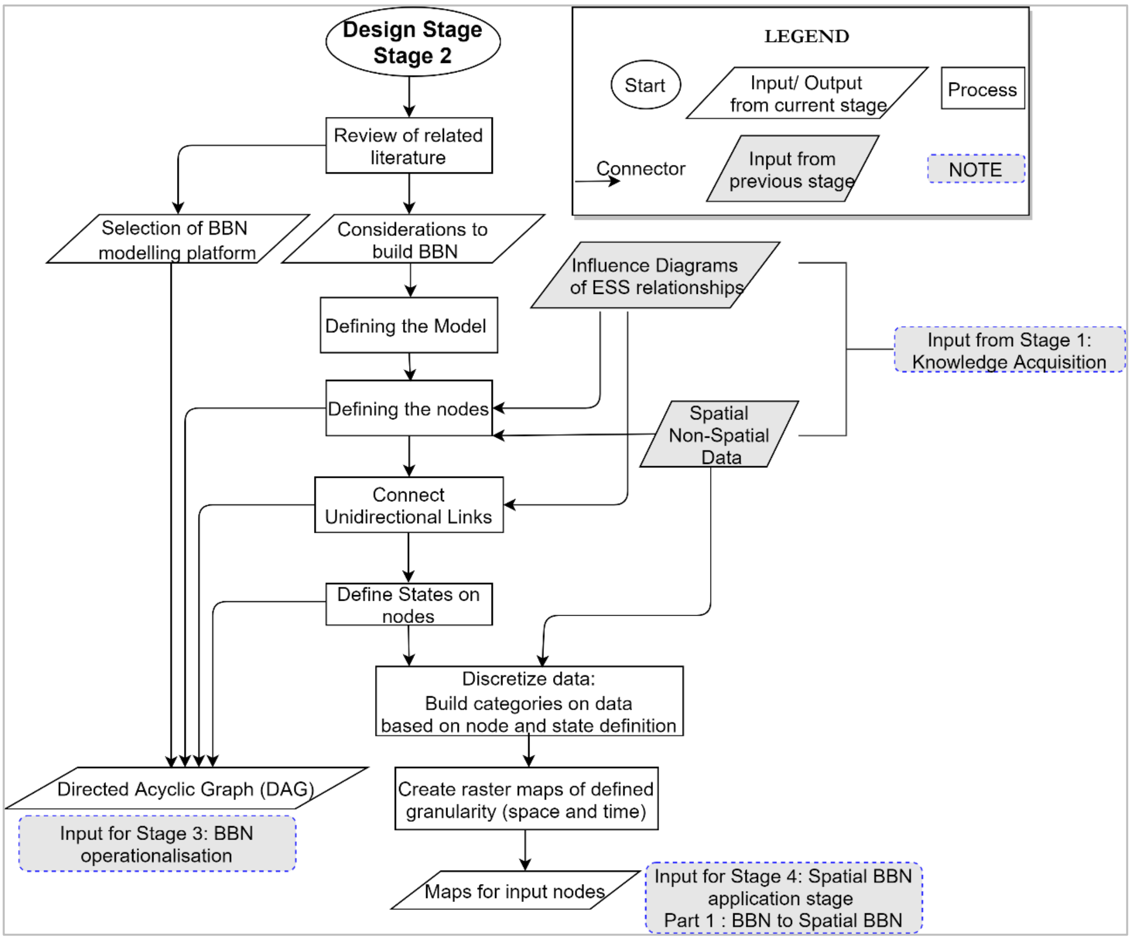


Figure 6: The flowchart shows steps followed in Stage 2: Design stage

Part1: Construction of BBN

A BBN has three basic elements (Figure 7): a set of nodes which represent the system being modelled, links between those nodes and conditional probability tables (CPT) for each node. The system variables or nodes are represented by boxes, which have a causal relationship between them represented by directed arcs with a set of conditional probabilities, that define the strength of causal relationship for every node (Duespohl et al., 2012). The nodes should be representative of the system under study. The links should show relationships between different system components displayed as nodes in a graphical structure.

These links are created based on knowledge of the system and information collected through experts. They are defined in a way to facilitate the construction of CPT. The various types of data can be integrated due to the structure of links which are quantified by CPT for each node, defining the relationship between those nodes. Once the structure is created with nodes and links, then the state of the nodes is defined (Bromley, 2005). The states represent different values a node can take under different conditions.

Table 1: Marginal probability table

Forest Cover suitable (A) (Marginal Probability Table)	
True (State 1)	50
False (State 2)	50

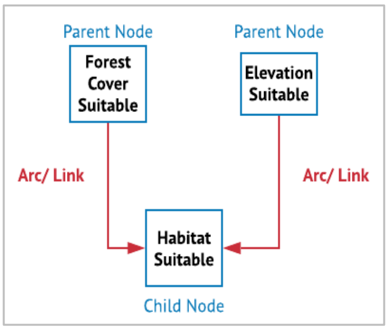


Table 2: Marginal probability table

Elevation suitable (B) (Marginal Probability Table)	
True (State 1)	50
False (State 2)	50

Table 3: Conditional Probability Table for child node C

Habitat suitable (C) (Conditional Probability Table)	
True (State 1)	50
False (State 2)	50

Figure 7: A hypothetical example presented shows that the suitability of a habitat for a species is dependent on two factors: the parent nodes (blue): forest cover suitable (A) and elevation suitable (B) linked by (red) arcs to child node, habitat suitable (C).

The example describes whether the habitat is suitable when information about forest cover and elevation being suitable for a species is known. The nodes are linked in a causal way which means that depending on the state; the parent nodes are, affects the state the child node can take. Each node has binary states (either true or false) which means that a node, for example, elevation suitable can either be suitable = "True" or it cannot be suitable =" False". There is no other value that this node can take.

The parent nodes that do not have parents are called root notes (in this example A and B) can be described probabilistically by a marginal probability distribution as its occurrence is not conditioned on any other node. If these values are not specified, then the chance that the node can be in one of the states at a time is equally likely, i.e. 50% each. However, unlike parent nodes, the probabilities of states of child node are conditional on how the state of its parents combine (Pollino & Henderson, 2010). Here the conditional probability values for C have not been specified in the CPT, therefore, CPT shows 50% probability distribution for each state of the child node.

i. Choice of the modelling platform

There are various software packages available to build a BBN (Pérez-Miñana, 2016; Mahjoub et al., 2011) which have different learning efficiency and accuracy, like Hugin Expert[5], Netica[6] , BayesBuilder[7] , Smile/Genie[8], R-package (CRAN)[9], BayesiaLab[10] etc. Looking at the pros and cons of the software by reviewing the literature, based on the objectives of the model along with the time and resources available to conduct the study, a choice can be made for selecting the platform which best fits for one's purpose. The software can either provide a graphical user interface or can be flexible to allow construction of BBN from scratch using some programming skills using open source libraries and packages. The choice of the platform can be made based on case study requirement, time and resources available.

According to Pérez-Miñana (2016), Netica is most commonly used BBN software in the ecosystem service modelling community. Netica implements both influence diagrams and Bayesian networks using expert inputs who define the model structure (it is suitable for participatory modelling purposes). It is user-friendly and transparent software to use. The advantages of using Netica are that it offers easy to use graphical interface for BBN development with many functionalities like the integration of discrete and continuous nodes, learning from data, generation of the confusion matrix and test the performance of the network using sensitivity analysis (Marcot et al , 2001). Netica is commercial software, and its license provides additional functionality, allowing the integration with GIS by using an extension called GeoNetica. This is a significant advantage over most of the other software.

ii. Considerations while building a BBN (Bromley, 2005; Marcot et al., 2006)

There are a few things to keep in mind before constructing a BBN.

- The nodes must be connected by unidirectional links, i.e. between two nodes the arcs must work in a single direction, not both ways.
- There should not be any feedback loops, i.e. the network must be 'acyclic'.
- The system variables can be continuous or discrete nodes. These nodes should be measurable, observable, and predictable.
- All model users should be able to understand what each node represents.
- The state of a variable should represent all possible outcomes for that node (exhaustive). The state should be finite in number, discrete and mutually exclusive. However, the number should be kept as small and representative as possible, as the underlying probabilities are distributed through the states, and CPT will grow exponentially with each additional state of the parent node.
- It is suggested to restrict the parent nodes to three to make CPTs manageable. This is because for each parent's state, a probability value for each state of the child node needs to be provided by the expert and with a huge table, the task becomes cumbersome and confusing. If there are too many parent nodes of a child node, parents can be "divorced" by the introduction of an intermediate node.
- The number of parameters should be minimum so that probability elicitation or belief updating is easy. This means limiting the number of intermediate nodes to avoid complexity. The nodes to be included must directly or indirectly impact or be impacted by the output variable.

[5]www.hugin.com
[6]www.norsys.com
[7]www.snn.ru.nl
[8]https://www.bayesfusion.com/smile/
[9]https://cran.r-project.org/web/packages/BayesianNetwork/vignettes/BayesianNetwork.html
[10]https://www.bayesialab.com/

The DAG prepared by linking the selected nodes together should logically represent the system under consideration.

iii. Defining the Model

The model definition is based on the knowledge acquired during discussions with the experts during system analysis part of Stage 1 and highlights some important aspects to consider in order to build comprehensive and robust BBN. This part of knowledge acquisition stage involves:

- Defining the purpose and objectives of the model
- Defining physical and social boundaries of the modelled system
- Identifying the spatial and temporal scales in which chosen ESS will be investigated

iv. Defining the nodes and their states

The relevant nodes could be defined through literature or consulting experts. There are many factors which can be relevant nodes, and a choice needs to be made into which factors will be more relevant. These can be physical, social, economic, or ecological factors which influence the system. The factors can be seasons, temperature, slope, management or policy interventions, land-use, roads etc.

The discrete nodes have a set of defined states (Bromley, 2005). The states can be descriptive or numerical based on the type of node and what the node wants to represent. A series of separate states describe the discrete nodes, while the states in continuous nodes are described in terms of means and variance as a Normal distribution function. The states that a node can take can be in the form of labels, boolean, numbers or intervals. The nodes with no parents can represent the present condition of the ecosystem, driving factors or management interventions while nodes with no children can represent ESS of interest (Bromley, 2005). This helps to answer the research question 2.c by helping to understand how to choose the nodes. The nodes can be of the following types table 4:

Table 4: Node types of a BBN with their description (Bromley, 2005)

Node type	Description
Target/Objective nodes	Output nodes of the network. These nodes give values that we want to observe.
Controlling Node	The external influencing factors that affect other nodes. These factors (which define the node) influence the system in some way but cannot be controlled, e.g. Climatic conditions
Intermediate nodes	Link objective (Target node) with intervention node. These can be ecosystem properties (structures and processes) or management intervention, socio-ecological factors etc.
Intervention nodes	Represent factors we wish to implement in order to achieve our objectives. They can also be thought of as management options.
Implementation nodes	Represent factors that directly affect whether an intervention might be successful such as available funding for the action, or availability of resources.

Based on the knowledge collected from experts, the nodes are linked together. The links show causal direction, originating from a parent node to the destination node called a child node. Those nodes which have no incoming links are root nodes, and those who do not have outgoing links are leaf nodes. Once the nodes are chosen, states defined and the links between the nodes set up, the construction of BBN is complete.

SubPart1: Data Preparation

Once the structure is ready, the data now needs to be prepared to populate the network. Some data will already be collected in Knowledge Acquisition Stage, and main sources of data will be identified. There might be a need to collect more data for intermediary nodes which can be collected from various sources previously identified. If there is little or no data available, expert opinion can again be sought. Once the data is collected, it can be manipulated and prepared in the same way the data was treated in Stage 1. Depending on the data type, the nodes can be decided to be discrete or continuous. The data can then be prepared in a raster format (though some software can work with vectors too) to input to the nodes in the BBN.

Once all the data is collected and organised to prepare a BBN, the actual construction by building the model can start in the selected software. The outputs of this stage are spatial input maps generated by using data prepared in a suitable format to input to the spatial nodes, data prepared for non-spatial nodes and the structure of BBN.

3.1.3. Stage 3: BBN Operationalization

The flowchart (Figure 8) provides a summary of steps followed for operationalizing the model. This stage involves taking the structure of the BBN (DAG) prepared in the last section as input and then providing conditional probability values to each of the child nodes. The output is a completed BBN which can then be compiled to start making inferences. When evidence is set on a node, i.e. a state is set on one of the nodes, this new information flows through the network depending on the structure of the network and the way the different nodes are connected. The intermediate nodes can either make other nodes conditionally dependent or independent. The nodes which are directly connected indicate direct causal relationships. Based on network structure, an overall probability of the outcome of interest can be observed along with its sensitivity to changes in other parameters of the network and also find factors that have the most influence on the output probability (Uusitalo, 2007).

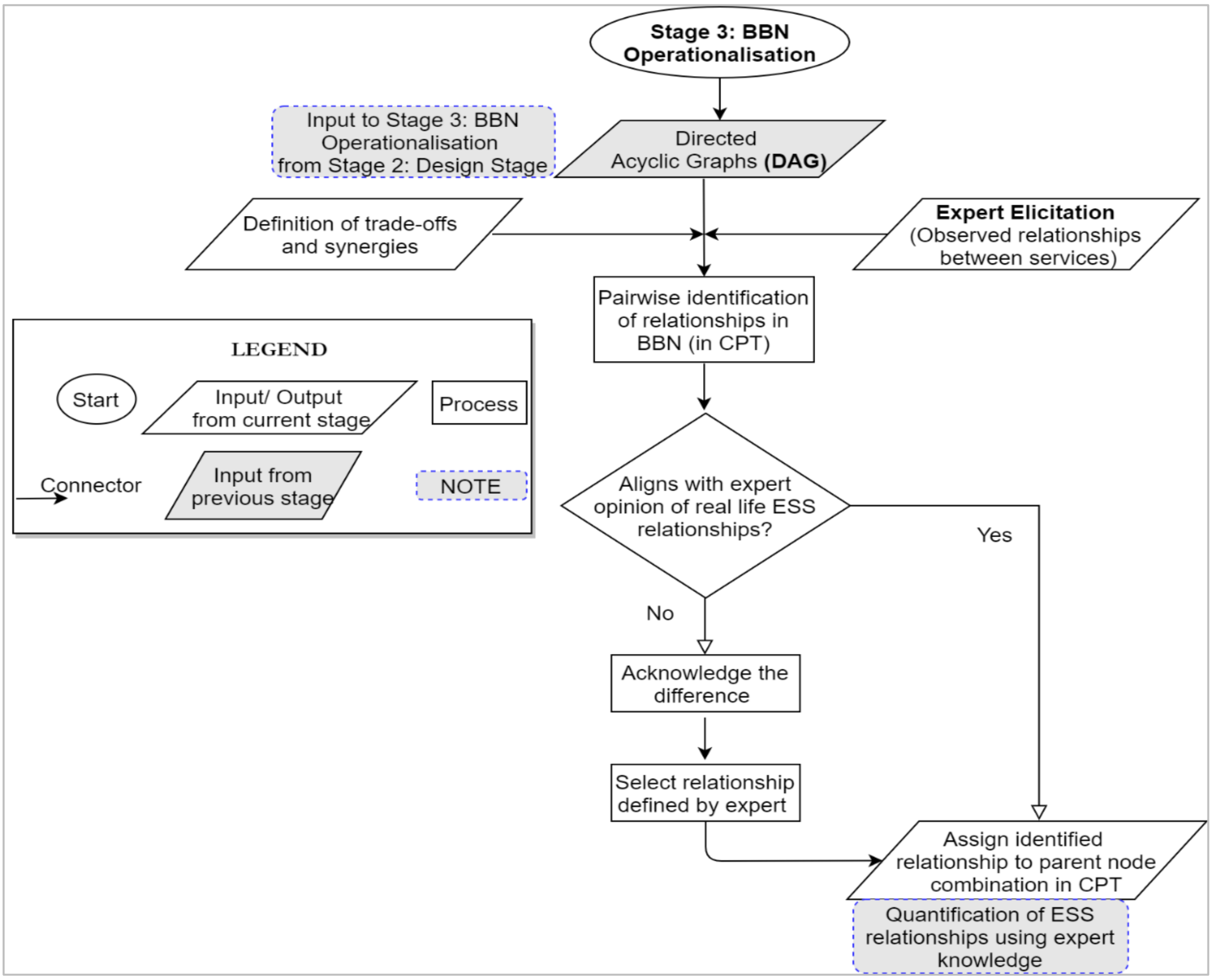


Figure 8: The flowchart shows the steps taken to make the constructed BBN fully functional

The hypothetical example of habitat suitability is presented to explain further how to fill the CPT (Figure 9).

Table 5:prior probability table for parent node A

Forest Cover suitable (A) (Marginal Probability Table)	
True (State 1)	54
False (State 2)	46

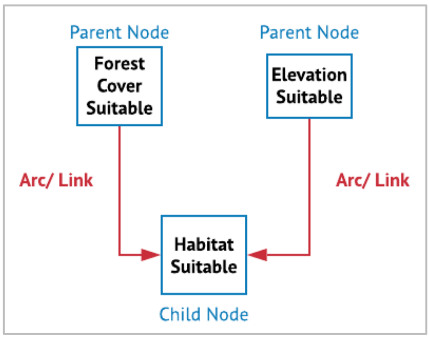


Table 6: Prior probability table for parent node B

Elevation suitable (B) (Marginal Probability Table)	
True (State 1)	41.5
False (State 2)	58.5

Table 7: CPT for child node C

Habitat Suitable Probability Distribution (C) (Conditional Probability Table)		True (State 1)	False (State 2)
Forest Cover suitable	Elevation Suitable		
True	True	1	0
True	False	0.75	0.25
False	True	0.30	0.70
False	False	0.05	0.95

Figure 9: The probability distribution for the parent nodes have been specified and represent the marginal probabilities provided randomly. The CPT (for node C) is populated in form of scenarios taking each combination of parent nodes states and stating the probability of occurrence of those two combinations together. The CPT can be elicited from the expert or can be self-elicited based on knowledge acquired from the experts.

An example of filling the CPT:
Given that A is in true state and B is also in a true state, then what is the probability that C will also be in the true state? So, when forest cover is suitable, and elevation is suitable then the probability that the habitat is suitable for a species can be 100% true, shown in Table 7 as 1. The values provided to the CPT have been randomly provided. Similarly, given that A is true, and B is false, then what is the probability that C is true? When forest cover is suitable but the elevation is not suitable then the habitat is suitable for a species has a 75% chance to be true and 25% chance that habitat is not suitable for the species as shown in Figure 9 (CPT table of habitat suitability node). Similarly, the rest of the combinations get probability values based on expert knowledge or data collected from the field.

Expert Elicitation

The network structure and CPT can be learned directly from data, or if relevant data is hard to find, then expert knowledge is virtually the only source of useful information for calculating some unknown quantities (Bromley, 2005). Once the structure is ready, the links are quantified using expert knowledge by populating CPT. The CPTs hold the information about the relationship between the parents and the child based on the nature of dependency of the child on the parents. Each node in the network has a probability table associated with it (Figure 9). The parent nodes take the prior probability values or unconditional probability values while the child node takes conditional probability values which are based on the probability of the child node to exist in a particular state given the states of its parents' nodes. Thus, the relationship between the nodes is calculated and expressed using CPT (Pollino & Henderson, 2010), which represents the distribution of each variable in the network. Once compiled, it shows prior probabilities for the nodes (Figure 11a). The evidence can then be added to the nodes and probability values propagating through the node can be observed (Figure 11b). This updates the joint probability distribution of the nodes in the network (Bromley, 2005). The inference can then be carried out by applying the Bayes' Theorem.

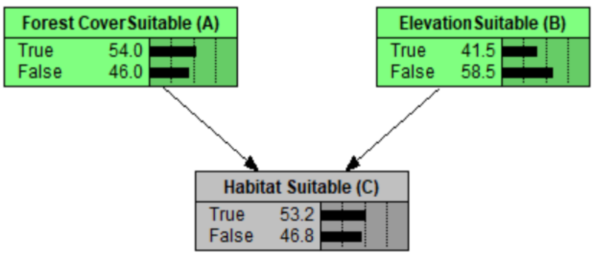


Figure 11a: Compiled BBN with prior probabilities using Netica

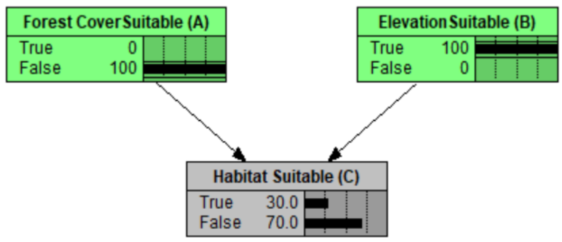


Figure 11b: BBN with Evidence updated in Node A: False=100% and node B True = 100% using Netica

The Bayes theorem can help to calculate the posterior probability to determine relationship from cause to consequence and vice versa. Therefore, once evidence is entered into a node, all the nodes linked to that node will be updated based on the underlying CPT (Figure 11b).

$$P(A|B) = \frac{P(B|A)*P(A)}{P(B)} \qquad \text{.......} \ \textbf{(9)}$$

When the evidence is added to the root node, i.e. it is set to 100%, the probabilities at each connected child node is updated using the formula of a joint probability distribution

$$P(A\Pi B) = P\left(A_{,} B\right) = P(A) * P(B) \qquad \text{.......} \ \textbf{(10)}$$

Where the formula is used by BBN software to recalculate the probability distribution of the child nodes. Then the software sets the probabilities for each state of the child node using marginalization

$$pX(x_i) = \textstyle\sum_j p\,(x_i, y_i), \quad and \quad pY(y_i) = \sum_i p(x_i, y_i) \qquad \text{.......} \ \textbf{(11)}$$

For the upward propagation where the evidence is added to child node, i.e. example target node = 100% then using Bayes Theorem, the probability distribution for parent nodes is updated (Frank et al., 2014).

The result is in the form of probability distribution along with the states of a node which explicitly represents uncertainty attached to the prediction. Therefore, wider probability distribution means a higher degree of uncertainty which can decrease when more information and true values of the variables are available (Uusitalo, 2007).

3.1.4. Stage 4: Spatial BBN Application and Validation Stage

Part 1: BBN to Spatial BBN

Once the BBN is fully functional, the model is uploaded to an online platform (like gBay) or used with a spatial extension (like GeoNetica) that can help the non-spatial BBN generate spatial output in the form of probabilistic maps. gBay, takes as an input spatially explicit datasets for spatial BBN root nodes. A raster map for the selected target nodes is generated (most of the platforms/extensions work with raster images and gBay can work with vectors as well), which links the spatial information of each pixel with corresponding posterior probability distribution generated by the BBN. The output raster represents each state of the target node as a band with the values giving probability distribution of a particular state which amounts to using a BBN for spatial prediction of trade-offs synergies and no-effect. Thus, the expected outcome probability is the interaction between pairs of ESS (trade-off, synergy or no-effect), which is determined for each pixel of the raster. In some toolbox like gBay, care needs to be taken that all input raster maps have the same extent, cell size and coordinate reference (Stritih et al., 2020).

gBay also provides a raster map for each target node which has one band with Shannon's evenness index of the posterior probability distribution, which quantifies uncertainty.

$$J = H'/H_{max.} \qquad \text{……. (12)}$$

It is a standardized measure of entropy whose values lie between 0 and 1, where 0 shows complete certainty of a node to be in a particular state while 1 shows maximum uncertainty which is depicted as the uniform distribution between all possible states (Stritih et al., 2020).

Part 2: Model Validation

i. Face Validation

To evaluate the structural uncertainty, expert assessment can be useful, especially when there is not enough data available for comparing model results and real (data) observation. Therefore expert-based qualitative approaches like face validation can be used for expert elicited BBNs (Pitchforth & Mengersen, 2013). Besides a qualitative validation, to help gain confidence for the working of the model, a validation through sensitivity analysis can be done.

ii. Sensitivity Analysis

A model is a representation of reality but cannot replicate reality as a whole. Therefore, it is important to judge how close a model's result can represent reality. The validation develops confidence in the findings of the model and leads to its acceptance by the end-user (Pitchforth & Mengersen, 2013). If the data is scarce, the experts play a crucial role all through different phases of BBN, from data collection to BBN construction, provision of CPT and also for validation. In order to validate the accuracy of logic used for filling the CPT and also the performance of the model, sensitivity analysis can be used to identify the nodes which have a significant impact on the target nodes. Mutual information can measure the sensitivity by analysing how the target node's output values behave when some other fixed variable's values are changed within its assigned probability distributions (Uusitalo et al., 2015). It informs about how much a finding at one node will likely change the beliefs at another and also about the direct and indirect information flow rate (Zou & Yue, 2017). If the variables are independent, then that means the mutual information will be 0 as there cannot be any entropy reduction. This is because the information available for one variable will not contribute to any information for the other. However, if the variables are strongly dependent, then the degree of mutual information is high (can be 1), and the joint probability distribution of these variables will give more information. Thus, joint probability distribution quantifies the amount of information that can be obtained from one process for the other. If the variability in output value is small, then it is likely that there is little uncertainty about the value. On the other hand, if the value of the output variable shows larger changes, this can indicate that there is larger uncertainty in the variable's value. Maximum uncertainty is found when probability distribution is uniform. The formula used for the calculation of mutual information is:

$$I = H(A) - H(A|B) = \sum_a \sum_b \frac{P(a,b) log_2[P(a,b)]}{P(a)P(b)} \qquad \text{……} \; \textbf{(13)}$$

Those variables which have a greater contribution to probability values of target node events can thus be determined, which can later help the end-user to take adequate measures to reduce/enhance the probabilities of the target node events as desired (Zou & Yue, 2017).

3.2. Case Study Application – Mt. Oiti National Park, Central Greece

The sub-chapter implements the steps highlighted in the generic methodology (3.1) in the case study area and follows the flowchart (Figure 3) sequentially.

3.2.1. Stage 1: Knowledge Acquisition stage

Part 1: System analysis

The sub-section below follows the steps mentioned in the flowchart (Figure 4)

i. Selection of focal study sites: -

Natura 2000 mountainous sites in Central Greece - The selected case study for this thesis was Mount (Mt.) Oiti National Park, Sperchios Valley and Malaikos Gulf in Central Greece. It is a set of Natura 2000 areas, protected under the EU Habitats Directive (92/43/EEC) for their unique habitat type, flora and fauna. The area is managed by a Management Body which aims to manage and protect the Mt. Oiti area. A seven-member Administrative Board of the Management Body with seven deputy members and nine personnel with different job expertise comprise the Management Body. Recently (in 2018), six more Natura 2000 sites were added under its jurisdiction (Figure 12) therefore managing a total of eight Natura 2000 sites. The duties of the Management Body are to protect the mountain ecosystems and raise awareness among the locals and visitors, regarding the need for protection of the mountain ecosystem. These areas provide several ecosystem services and have various stakeholders involved who have different sets of priorities. As there are a limited number of personnel in the Management Body who have to manage large areas, they face challenges to provide opinion on decisions made for activities happening within all these diverse sites. Therefore, this research focuses on exploring the working of BBN to map the seasonal changes in ecosystem services trade-offs and synergies such that the resultant maps can be used to identify the areas that need more management efforts during different seasons and can lead to a more targeted management approach. Such maps can be useful to the Management Body who can then focus on areas that need immediate attention to minimise trade-offs. This will help in efficient resource utilisation rather than using all resources to manage the entire area in a similar way, which might lead to generation of more trade-offs thereby degrading the area.

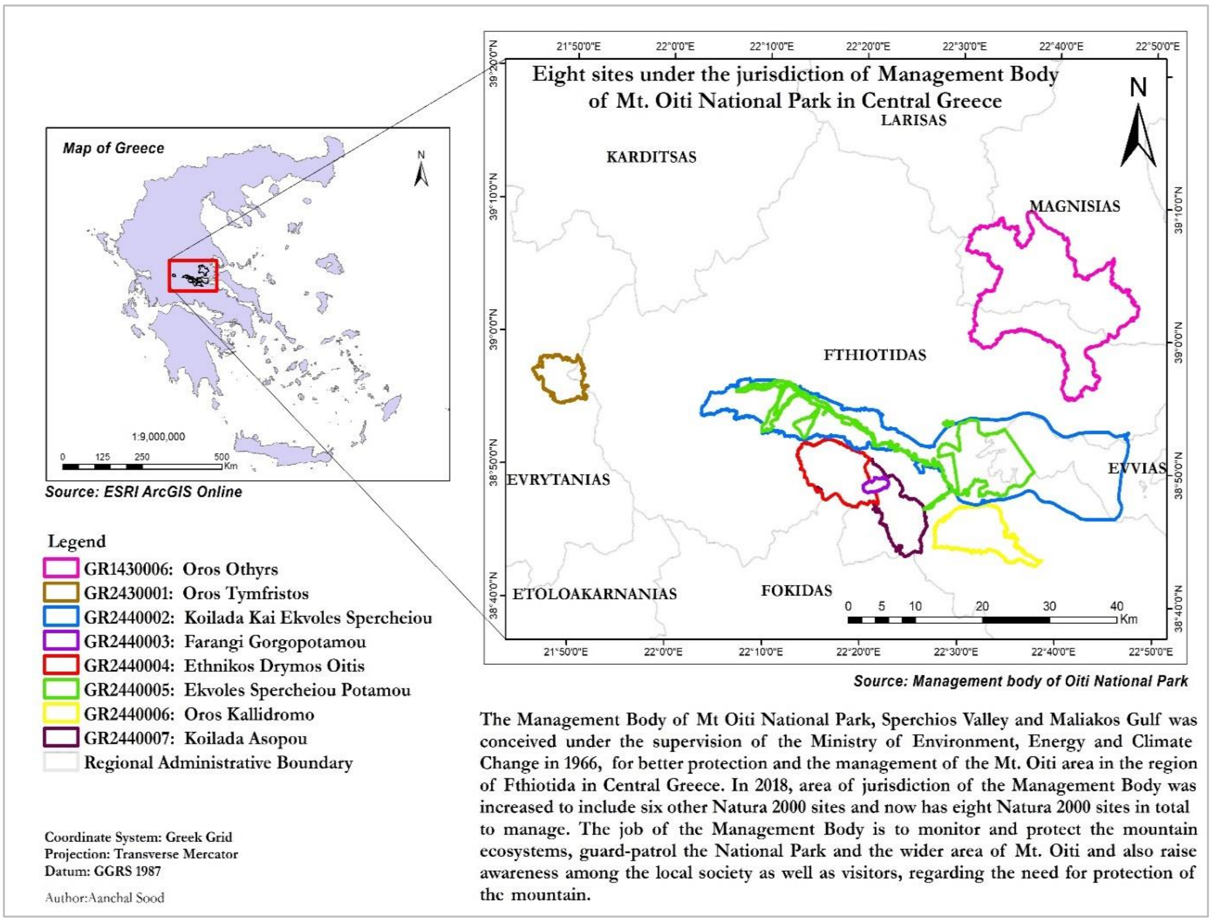


Figure 12: The eight sites under the jurisdiction of Management Body of Mt.Oiti National Park in the region of Fthiotida, Central Greece

Criteria for selecting focal study sites - As the Management Body has a vast area under its jurisdiction, a choice had to be made to select a case study area, given time and available resources. A brief discussion with personnel of the Management Body took place which was based on the knowledge acquired for the area from literature related to that region (Mertzanis et al., 2016; Vlami et al., 2017; Kokkoris et al., 2018) and also the Natura 2000 database ("Natura 2000 data - the European network of protected sites", 2020) to identify the significant activities and associated threats mentioned in the standard data forms for the area under the jurisdiction of the Management Body. The mentioned activities include off-road vehicle recreation, intensive grazing, hunting, poaching, loss of specific habitat features and antagonism with domestic animals. Also, according to Kokkoris et al. (2018), Greek landscape provides multiple ESS and especially the study area has been mentioned by Mertzanis et al. (2016) of having great potential for providing several cultural, recreational ESS like (outdoor sports activities in nature: hunting, hiking, canyoning, rock-climbing, education and research) besides providing regulatory services like maintenance and conservation of habitats of importance. Still, limited research has been conducted for assessing cultural services provided by protected areas. Vlami et al. (2017) mentioned the importance of assessing these services in order to stop the degradation of cultural landscapes, spread awareness and promote cultural services in Greece's protected areas. The criteria for choosing focal sites are as follows:

- The familiarity of personnel of the Management Body with the sites and priority areas for management.

- Availability of experts /relevant stakeholders for interviews for data collection.
- The feasibility of conducting the study based on the availability of data, time and resources.

These criteria and initial discussion with personnel of Management Body helped to finalise the focal sites for study (see results Section 4.1.Part1.i). The selected protected areas provide a wealth of ESS such as surface and groundwater for drinking and non-drinking purpose, recreation in the form of hunting, hiking, canyoning, micro and regional climate regulation etc. For the initial identification of ESS provided by the area, data about threats arising from human activities that are allowed inside and outside these study sites were derived from Natura 2000 database. It helped to understand which activities happen within the protected area and who are the stakeholders[11] of the ESS generated in the area. After gaining a general understanding of the area along with the dependency of the people on nature in different ways, an unstructured interview was conducted with two members of the Management Body. An adapted list, based on the CICES classification system (Appendix Table A 1) of ESS available in the study area, was presented to the Management Body and this qualitative assessment led to the identification of the initial set of ESS along with the relevant stakeholders. It also led to formulating the criteria to choose the final set of ESS, which are of priority to stakeholders and fulfil the research objectives.
<u>The criteria for selection of the final set of ESS along with their indicators are as follows:</u>

- ESS that shows seasonal variations in their supply and flow.
- The ESS which have a spatial overlap help to know where these services have interactions and whether they can impact each other in space.
- ESS of priority for the Management Body identified as those services whose relationship with other services need to be understood better or those that have more trade-offs and need better management.
- The potential of the interaction of an ESS with other services, based on discussions with the personnel of the Management Body.
- The availability of meaningful secondary data which help to quantify the indicator for chosen ESS and experts who have knowledge about these services and their interactions.

<u>ii. Identification & selection of concerned stakeholders</u>

Two members from the Management Body were the initial point of contact, and the first experts consulted for the study. They have been contacted time and again for clarification about the study area and also for any other details required throughout the research. Once the list of initial identified ESS is created, (Section 4.1.Part1.Table 8), along with consultation with experts from Management Body, the people who are directly or indirectly dependent on those services are identified.
Among the different stakeholders identified according to the ESS being looked at, purposive sampling and the snowballing sampling techniques were followed to select the stakeholders to interview, based on their expertise, availability, knowledge and the contribution they could make to the study by sharing that knowledge.
Purposive sampling technique was suitable for this study as it is the most effective method when domain knowledge is needed, and when only a few people are available for primary data collection (Tongco, 2007). It allows choosing a representative sample cost-effectively. The experts were chosen in

[11] Stakeholders were identified as any group or individuals who can either impact the provision of services or be impacted directly or indirectly by any decisions that change the provision or flow of ESS (adapted based on (Modvar and Manuel-Navarrete, 2015)).

consultation with the personnel from the Management Body, according to their knowledge of the area or/and knowledge of ecosystem service and also their experience in managing these areas. They were the domain experts belonging to other Government departments like the Forest Department, Education Department and Water Department, whose decisions directly control the availability and use of the services in the study area.

Snowball sampling technique was also used to interview stakeholders who were directly or indirectly benefit from those services. They are considered experts based on the knowledge gained by performing the activities in nature through which they experience the benefits from the services nature is providing and not necessarily through education. They have a lot of knowledge about the study area as they spend their time performing activities in nature like canyoning, hiking and hunting. This included key-informants for services like cultural services (in the form of recreational hunting, canyoning and hiking). These key-informants (called experts further on) were recommended either by the people who had already been interviewed or the Management Body personnel, to be interviewed based on their goodwill of being knowledgeable on the topic of interest. This technique helped to reach and interview relevant stakeholders through referrals (Tongco, 2007) who would otherwise be difficult to be contacted.

The selected stakeholders were approached through emails or contacted through telephone calls for making appointments for face-to-face interviews. They were briefly informed what the case study objective was, its importance and the kind of data needed for the study. They were also informed about how this study could be useful in future for the study area as well as for them. The doubts about the study were clarified, and then the experts were asked to provide data (spatial distribution of ESS and intensity of use) available with them. In case some data were available, the data was requested to be shared. After checking the data (if available), if more information was needed, then an appointment was requested from the experts for face to face interview via telephone or email. The date, time and place of the interview was fixed based on the availability and suitability of the experts.

iii. Data Collection

Expert Interviews - The primary data was collected through face-to-face semi-structured expert interviews in January 2020. The aim of these interviews was to collect data about the spatial and seasonal occurrence of the services, get an understanding of the system and the kind of relationships the services have with each other. This information was later put together in the form of influence diagrams which were the basis for constructing the BBN. A pilot questionnaire was conducted with the Management Body experts, and it was realised that it was necessary to come up with some common definitions to maintain consistency in the way the interview questions were understood and answered. Therefore, along with the Management Body experts, I formulated some common terminology to keep the ideas consistent and comparable among different stakeholders. The adapted terms have been included within the questionnaires in Appendix 1.3.1.

Before scheduling the interviews, an initial discussion about data availability was done with experts on the phone to understand what data was already available and prepare the questionnaires accordingly. In most cases, both spatial and non-spatial data had to be collected through interviews. Therefore, the questionnaires (Appendix 1.3) were designed, keeping in mind the criteria for selecting the ESS of priority. When spatial information was not available directly, participatory mapping with the experts was carried out to understand where the service was being delivered or where the beneficiaries received the actual service benefits and, in some cases, how much. The mapping involved using free high-resolution imagery in Google Earth Pro. Some details like the boundary of the study area, core and wildlife refuge, the hiking routes with names, rivers and roads; were added to the base map or the satellite imagery. Most of the experts felt comfortable using the on-screen digitising technique (heads-up digitising) to mark the areas/ points of interest and referred to the hardcopy- a printed bilingual (English and Greek) topographic map provided by the Oiti Management Body, in case of doubts. The interviews were nearly two hours long, which helped to understand experts' view of the protected area and the relationship between different services in the area. Appendix Figure A 1 & Figure A 2 show the participatory mapping exercise being carried out with experts. This approach was also used for mapping hunting areas with three hunters, marking in-out points for canyoning and marking points/polygons of interest that the people observe while hiking. A local student had volunteered to help with conducting the interviews outside Management Body premises. For some ESS like provision of timber: timber extraction and provision of groundwater, the spatial and non-spatial data was directly available from the Government offices of the Forest Department of Lamia and the Water Department of Lamia. In these cases, the interviews were conducted to understand the relationships of each service with one another.

For consistency, the ESS will be referred to in the following way from this point:

- Recreation/Entertainment outdoor sports: Canyoning as: Recreational ESS: Canyoning
- Recreation/Entertainment outdoor sports: Hiking as: Recreational ESS: Hiking
- Recreation: Hunting (Game) Outdoor activities – hunting for sports and leisure as: Recreational ESS: Hunting
- Fibre and fuel products: Wood used for fuel production by logging wood as: Provisioning ESS: Timber extraction

Note 1: The way ESS are referred to from this point ahead throughout the study

Part 2: Data Curation

The main aim of this step was to clean, organise and transform the data by following the steps mentioned in the flowchart (Figure 5) in a way to make it suitable for future use. Once the data was collected, it was organised and added to the database. Since the data were gathered from multiple sources and in different formats, they needed to be transformed into a set of variables with suitable formats. During the interview, the experts answered the questions and provided explanations for their choices. These explanations then had to be coded to compare and consolidate the data to derive meaningful output. The output of this part was a final set ESS along with their indicators (section 4.1.Part2 Table 10) and influence relationship diagrams (section 4.1.Part2.ii).

3.2.2. Stage 2: Design stage

Once the data was organised in data curation part of knowledge acquisition stage, it led to the identification of ESS of priority among which the trade-offs and synergies were needed to be identified. Also, through interviews, a system understanding of how different components are interconnected within the system was gained. This led to the creation of influence relationship diagrams which showed how different selected ESS and their flow components were related to each other. The relationships were either direct, where the flow of one service impacts the flow of another service directly; or indirect, where there were other linking factors which influence the relationships or responses to the common drivers. It led to the identification of different factors that can seasonally influence the interactions among different ESS. Also, the knowledge about perception and opinions of experts on the relationship among different ESS was gained. This led to the creation of a generic perception of the causal relationships among considered ESS. It was assumed that the views of the experts remained close to the perception of people benefitting from the chosen ESS. Since every interviewee had their own understanding of the same concepts which meant different to different experts, therefore, the definitions (Appendix A.1.3.1) were referred to. These relationships were visualised through influence diagrams for easy visual interpretation. This translation of acquired knowledge led to the construction of the structure of BBN. The steps mentioned in the flowchart (Figure 6) in the methodology section have been followed.

Part 1: Construction of BBN

i. Selection of software/platform to build BBN

The main goal of this study was to be able to feed spatial input to the otherwise non-spatial BBN and be able to derive spatial outputs after computations of posterior probability values in target nodes. There are not many tools openly available to run BBNs with spatial data over time (Pérez-Miñana, 2016; Stritih et al., 2020). So, one of the criteria to choose a platform was the availability of simple-to-use software that provides the spatial capability to fulfil modelling objectives. The selected software has been mentioned in results (4.2 Part1.i).

ii. Defining the model

Based on the considerations mentioned in (3.1.2. Part 1), the construction of the BBN started by defining the scope and purpose of the model.

- **Define problem and objectives**

The objective of the model was to identify and quantify interactions among ESS using a descriptive BBN model and then observe how these identified interactions changed based on seasonal changes. These identified interactions then led to highlighting the areas of high priority where immediate attention might be needed for conservation.

- **Define physical and social boundaries**

This BBN only considers those processes or influences taking place within the boundary of the study area even though the services can be influenced by the same or different variables occurring outside the boundary of the area under study. The only external variables being considered are preferences for hiking routes, accessibility of the hiking routes, accessibility of hunting areas and legal restrictions for hunting that have a significant impact on the flow of ESS in the area and also have seasonal variations.

- **Identify time scale for network**

The period set was four seasons of the year 2015 for all ESS. The experts informed that the data for all cultural services remained similar for all the years. As the timber was extracted in two different quantities in three different locations, therefore, to observe the change in the relationship of timber extraction with other services in space, an exception was made for timber extraction ESS for which data was modelled for two years (2015, 2019).

- **The model usage**

The model can be used to improve system understanding, communicate with stakeholders, identify trade-offs and synergies, and understand the uncertainties involved in the process. Once the trade-offs and synergies are identified, the Management Body can use the maps generated, to focus on those prioritised areas during different seasons and apply problem-specific solutions to decrease trade-offs among ESS. It can allow for better management and resource utilisation by targeting the areas for management.

iii. Defining the nodes, states and connecting the links

The influence diagrams acted as the starting point for designing the DAG. These diagrams helped to understand how the different ESS was related to each other, whether they had direct influence or were they indirectly linked through intermediate factors (indirect relationship). This information helped to understand the complexity of the relationship between the different ESS and helped to identify the main nodes to model the relationships between services. The rationale behind the chosen nodes was their ability to represent trade-offs and synergies, nodes being impacted by seasons and thereby affecting the target nodes. To avoid the cyclic relationships and to keep the model simple, only those nodes which were necessary to show the interactions among the ESS were included and the other identified factors had to be ignored. The spatial and non-spatial data collected helped to define the nodes, which for this study are discrete in nature. The construction of the BBN started by building the target nodes that represent the interactions between each pair of ESS. Next, the intermediate ESS flow nodes among which the interactions need to be observed were created, the season's node was set as the main controlling node whose changes are propagated through the entire network to observe how seasonality affects the ESS interactions. The other input nodes connected were the spatial nodes which are connected to the ESS flow nodes. This led to connecting all nodes chosen for the study to be connected by directed links (point from cause to effect). Once the structure was created with nodes and links, the states of the variables (nodes) were defined. Based on the node definition which also depends on the type of data collected (qualitative or quantitative), states are defined in a way such that with changing seasons, the states are able to represent the change in the value of the associated node. The states were also formulated based on expert definitions and categories mentioned while interviewing. Also, based on the information gained from the spatial and non-spatial data, the data was discretised into states. In most cases, there are no actual threshold values but standard definitions and accepted subjective values proposed by the experts.

SubPart1: Data Preparation

Discretize data and create raster maps

Once the structure was ready, and states were defined, then data was processed to be entered into the network. The data was manipulated and transformed into a required suitable format following the steps in the flowchart (Figure 6). The GIS data was prepared with common pixel alignment and resolution. By using a raster of 100m resolution, the entire area which has a site-specific boundary was divided by a common land division unit which made a comparison between different services easy, i.e. by looking at the pixel level interactions. The vector datasets were converted into a raster of 100m resolution to be used as input for the BBN. The raster map was created for each spatial input node of the developed BBN in the form of ".tif" files such that the output of the BBN was mapped to each cell of the raster and a probability value was associated with that pixel from the BBN.

iv. The DAG

This representation of data in the form of nodes, arcs and states led to the integration of different types of data which is one of the advantages of BBN. It led to the creation of a complete DAG structure (Section 4.2.SubPart1. Figure 20).

3.2.3. Stage 3: BBN operationalisation stage

In-order to make the BBN a fully functional model, once the structure was ready, the conditional probability tables were populated. The parent nodes (season and spatial inputs) do not need a CPT but have a marginal probability associated with them. The child nodes in the model have CPT defining their prior probabilities. These conditional probabilities are the parameters to be estimated, and this can be done by providing probability values between zero and one for each combination of parent nodes expressing the chance of that situation happening as explained in methodology (section 3.1.3 Part 1.Figure 11a and 11b).

3.2.4. Stage 4: Spatial BBN application and validation stage

Part 1: BBN to Spatial BBN

The spatial implementation of the BBN that identifies and quantifies the changes seasonally in ESS interactions can be beneficial for managers to identify priority areas for management. The maps produced help to visualise the changes in ESS relationships using a BBN and sensitivity analysis is carried out by changing evidence in BBN. The BBN can guide the Management Body to make decisions based on the changes produced to the output node when new information is added to the network. This information causes a ripple effect of changes across different nodes as nodes are interconnected directly or indirectly with each other. Thus, Management Body can also understand how their decisions can, directly and indirectly, affect many interactions and will those decisions be beneficial or increase trade-offs.

Part 2: Model Validation

In order to check the working of the BBN, I self-evaluated the model by adding a number of evidence on different nodes and checking whether the model generated expected outcomes. The unexpected results led to critical analysis of the working of the BBN and led to the restructuring of the BBN and updating of CPT values. This was an iterative process, and once satisfactory results were generated, then the model was sent for validation from experts.

i. Face Validation

Once the pilot BBN was constructed, i.e. all nodes connected through links, states defined, and probability values assigned, a skype meeting was scheduled with the experts from Management Body. These were the same experts who had been contacted for initial discussions. The experts were chosen due to their site knowledge and relevant thematic knowledge. Also, as the output of the model can be useful for the Management Body; therefore, the experts from Management Body were chosen for validating the output of the model. The plan was to contact different experts from the Management Body than the one interviewed before along with experts from a different department, including other hunters and hikers, to validate the model. Out of the two experts from Management Body, only one was available for reviewing the BBN and its outputs. This expert is a biologist and provides an opinion about the effects of any decisions that other Government departments take that bring changes in the Mt. Oiti National Park. The validation was performed by using face validation technique with an expert to validate the model's structure, the parameter values and maps of the interactions among ESS. Four major questions were asked from the expert:

1. Was the model structure self-explanatory and did it visually convey information about relationships among ESS the way she had expected?
2. Did the logic used for populating the CPT represent the way she understood the relationship among the pair of services?
3. Did the output map look representative of the priority areas which need immediate attention during different seasons?
4. Did she find the BBN and its results useful for the Management Body?

A brief presentation describing the basic concepts of BBN along with the definition of nodes, their states, the structure of the BBN and an output map were sent through email so that the expert gets familiarised with the concepts before the presentation was scheduled. During the presentation, through DAG, the modelled system was presented to the expert. Then she was asked to provide critical feedback on the proposed structure, causal links, and the conditional probabilities in the tables. The details are provided in Section 4.4 Part 2.i)

ii. Sensitivity Analysis

A measure of uncertainty reduction (also called mutual information) was used for carrying out the sensitivity analysis using "Sensitivity to findings"[12] in Netica[13]). To determine which nodes had the highest influence on the six target nodes: pairwise interactions between ESS, a sensitivity analysis was carried out for each target node. The mutual information helped to identify the variable that provides maximum information about the selected target node. In this thesis, seasons node and individually, the target nodes were selected to see if the ESS, BBN and the CPT functioned correctly. Sensitivity analysis of the target nodes revealed the key nodes that affected the interactions between two services the most. From the BBN structure, an idea was framed about influencing nodes; however, the mutual information criterion in sensitivity analysis showed the dependency of the node on some hidden influencing variables as well. The outcome was validation of the logic used for filling in the CPT, and it also helped to determine the top-most influencing factors for each target node. This led to investigating the robustness of output probabilities in the network.

[12] https://www.norsys.com/WebHelp/NETICA/X_Sensitivity_to_Findings.htm
[13] Netica software uses the equation mentioned in 2.2.2. x for calculating entropy reduction

4. RESULTS & FINDINGS

This chapter has been organised into four sections in-line with the steps mentioned in methodology. It sequentially provides answers to the research questions beginning with results from the Knowledge acquisition stage (Section 3.2.1), Design stage (Section 3.2.2), BBN operationalisation stage (Section 3.2.3) and Spatial BBN application & validation stage (Section 3.2.4).

4.1. Stage 1: Knowledge Acquisition Stage

This section presents and discusses the results of steps carried out in two parts: system analysis and data curation based on literature review and knowledge gained from the experts during the process.

Part 1: System analysis

i. Selection of focal sites for study

The two sites: Farangi Gorgopotamou (as Gorgopotamos Gorge) (GR2440003) and Ethnikos Drymos Oitis (as Oiti National Park) (GR2440004) fulfilled all the three criteria mentioned in section 3.2.1 Part 1.i and were selected as the focal sites for the case study. Out of the eight sites, the Management Body has been working on and is highly familiar with these two sites. Also, taking time and resources available into consideration, along with the mentioned criteria and choice of priority sites to work on as suggested by the Management Body, these two sites have been chosen for the case study (Figure 13). This answered the research question 1.a (Which sites will be chosen for study and what will the criteria for selection be?)

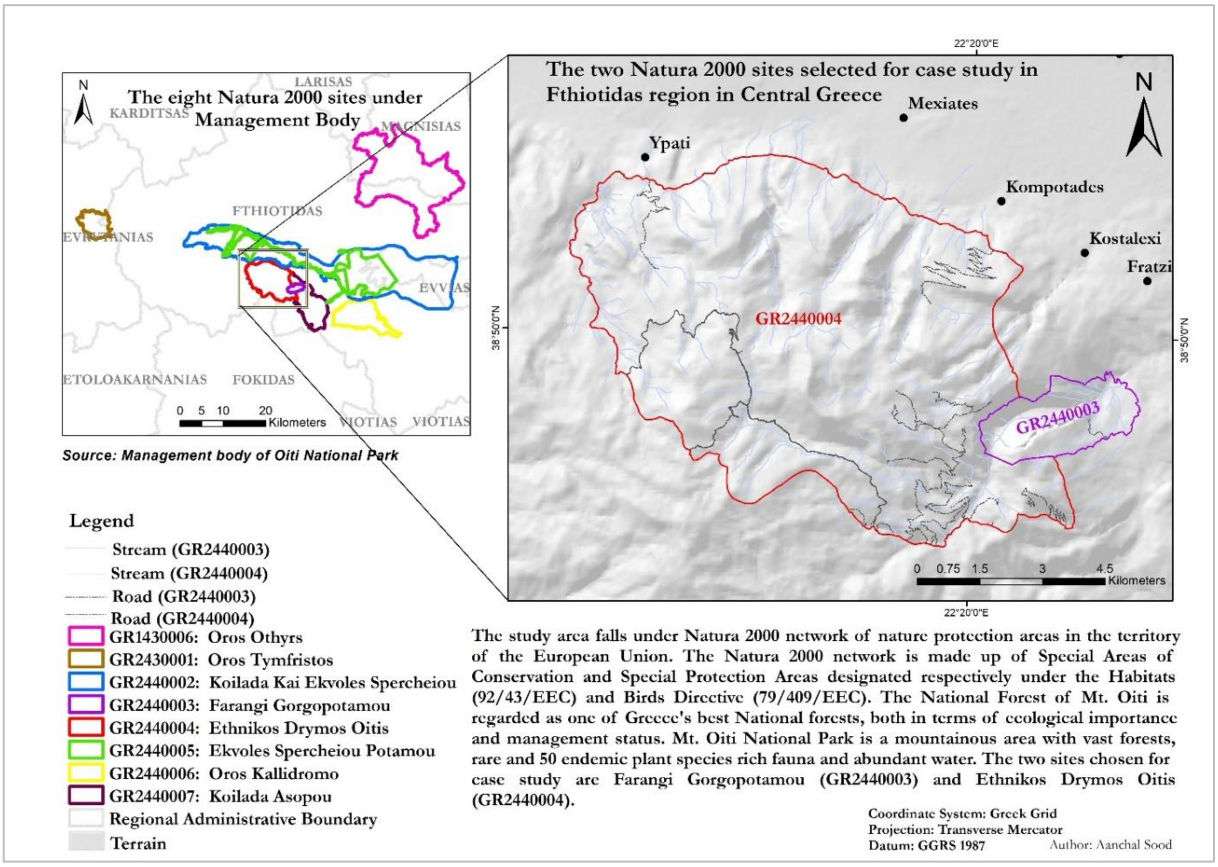


Figure 13: The two sites GR2440004 and GR2440003 selected for case study in Mt. Oiti National park, Central Greece

Characteristics of study sites: Mt. Oiti National Park and Gorgopotamos Gorge

The Mt. Oiti National Park specifically covers an area of 70 km^2 out of which 33.70 km^2 of the area form its core zone, and the remaining 36.30 km^2 of the area forms the peripheral zone. The core zone of Mt. Oiti National Park is in a full protection status, in order to keep flora and fauna of the area intact. Therefore, activities like excavations, placement of advertisement tablets, industrial activities, construction of buildings, agricultural and silvicultural activities, pasturing, hunting as well as the operation of mines and quarries are forbidden.

Fourteen habitat types listed in the EU Habitats Directive (92/43/EEC) can be found in National Park of Mt Oiti. The site is of importance due to the presence of a variety of habitats in a small area with a lot of endemic taxa. Mt. Oiti is dominated by Greek fir forests but also has oaks and evergreen trees; has plenty of water throughout the year and is also known as the mountain of flowers. Mt. Oiti is one of the easily accessible mountains of Central Greece. There are many small villages nearby, and the mountain can be accessed using hiking trails. The area also has cultural and mythological importance.

The site of Gorgopotamos gorge contains a very deep, two km long gorge with very steep slopes, making it practically inaccessible. The total area covered by the site is 5.3 km^2. Due to its geomorphological structure and inaccessibility, it provides a natural refuge to the vultures, especially for the golden eagle and chamois. The area is dominated by discontinuous, widely spaced bushes like macchia and phrygana found in the limestone soil of the area. The low evergreen shrubs like *Ruscus aculeatus* are also present. The area is well known to canyoners, as Gorgopotamos gorge is Greek's most challenging canyon. It also is famous for its historical and mythological heritage.

ii. Selected ESS and their indicators

Based on the discussion with the experts from Management Body, available literature and Natura 2000 database, the initial set of ESS were considered for the case study. Table 8 lists a set of relevant stakeholders identified for each initial chosen ESS.

Table 8: Initial list of relevant ESS along with their identified relevant stakeholders

Ecosystem Service	Stakeholders
Provisioning Service: Reared animals and their products, Animals by amount	1. Farmers 2. Consumers of products 3. Associated Government agencies
Provisioning Service: Ground water for drinking	1. People consuming ground water 2.Government agency collecting and distributing water
Cultural service: Recreation/Entertainment outdoor sports: Canyoning	1.Canyoning enthusiasts 2. Tourists 3.Associated Government & private agencies/ tour guides
Cultural service:	1. Hiking enthusiasts

Recreation/Entertainment outdoor sports: Hiking	2. Tourists 3. Associated Government & private agencies/ tour guides
Provisioning Service: Fibre and fuel products: Wood used for fuel production/heat by logging wood	1. Loggers/labourers: jobs 2. Villagers: consume directly- fuel or use of wood 3. Associated Government & private agencies
Cultural service: Recreation: Hunting (Game) Outdoor activities - hunting as form of sports and leisure	1.Hunters as they recreate 2. Forest Department and Hunting Organisations 3. Management Body 4. Associated Government Departments
Cultural service: Environmental education based on ecosystems, habitats and landscapes along with importance of conservation of important plant and animal species, for students	1. Students/ teachers/ professors/scientists attending the educational tours 2. Management Body spreading awareness and earning money 3. Associated Government & private organisations
Regulating Service: Maintenance: Protected areas: Natura 2000 sites for conservation	1. Management body: fulfil objective of conservation 2. Tourist for knowledge and enjoy presence of such species

Out of the identified relevant stakeholders mentioned in Table 8, 12 stakeholders were selected for conducting semi-structured face-to-face interviews. Table 9 below shows the stakeholders selected based on their expertise, availability and willingness to participate in the interviews with their field of expertise and affiliation. They have been chosen using techniques explained in the methodology section like purposive sampling and snowball sampling techniques (Section 3.2.1 Part1.ii). This answered the research question 1.b, (who are the relevant stakeholders?)
The ESS will be addressed from this point in the way described in the note below.

Table 9: The experts selected through purposive sampling and snowball sampling techniques

Job titles/Role of experts (or key-informants)	No. of Participants	Interviewed for
Forester, Management Body of Mt. Oiti National Park	1	All ESS especially more information about timber extraction
Biologist, Management Body of Mt. Oiti National Park	1	All ESS especially more information about conservation of species
Member of Administrative Board, Management Body of Mt. Oiti National Park	1	Hiking; Relationship of hiking recreational service with other services
Hunters	3	Hunting; Relationship of hunting recreational service with other services
Hikers	2	Hiking; Relationship of hiking recreational service with other services
Canyoners	1	Canyoning; Relationship of canyoning recreational service with other services
Personnel of Water Department of Lamia (DEYAL)	2	Groundwater for drinking
Forest Department of Lamia	1	Timber extraction
Total	12	

Part2: Data Curation

i. Selected ESS and their flow indicators

After organising, cleaning and transforming the data in section 3.2.1 Part 2, it was noticed that some ESS did not have any influence on or did not affect the other services based on interpretation derived from expert interviews. Also, after linking this data to prepared spatial data, it was found that some services did not spatially overlap. As these services did not fulfil the criteria for choosing ESS of priority, these services had to be dropped. Also, for some services, the experts were not available for interview or data was completely missing; hence these services had to be dropped as well (Appendix, A.1.5). Thus, based on the criteria mentioned in section 3.2.1 Part 1.i, a final list of ESS is presented in Table 10 below. Also, the indicators were chosen depending on the availability of data to be able to quantify the flow component of ESS considered in this study. This answered the research question 1.c (Which are ESS of priority and which indicators will be used to quantify selected ESS?)

Table 10: Final four selected ecosystem services with their indicators

Type of service	Ecosystem Service	ESS Indicator
Cultural service	Recreation/Entertainment outdoor sports: Canyoning	**Flow**: Number of visitors visiting the route per ha per season
Cultural service	Recreation/Entertainment outdoor sports: Hiking	**Flow:** Number of visitors visiting the route per ha per season
Provisioning Service	Fibre and fuel products: Wood used for fuel production/heat by logging wood	**Flow:** Volume of timber extracted in tons per ha per season
Cultural service	Recreation: Hunting (Game) Outdoor activities - hunting as a form of sports and leisure	**Flow:** Number of game species killed per hectare per season

Description of the data collected for populating indicators

1. Number of visitors visiting the route per ha per season: Recreation service (Canyoning)
The indicator assessed for the flow of recreational ESS: canyoning, was the number of visitors visiting the route per hectare per season. The data was collected through expert interviews. Through participatory mapping, the expert mapped the canyoning routes. A book (Andreou, 2007) with a lot of information about canyoning in Central Greece was also used as a source of information to understand the factors that can affect the flow of recreational ESS: canyoning during different seasons. The canyoning routes found outside the study area were removed. The collected and processed data can be seen in the appendix (B.1.1).

2. Number of visitors visiting the route per ha per season: Recreation service (Hiking)
The indicator assessed for the flow of recreational ESS: hiking, was a number of visitors visiting the route per hectare per season. The data was collected from different sources. The websites, ("Management Body of Mt. Oiti National Park, Sperchios Valley and Maliakos Gulf", n.d.) and ("pezoporia.gr - The site for hiking trails in Greece", n.d.) provided some description of the routes which helped to identify the factors that can affect the number of people visiting a route (for example, length of route, signs and markings, the difficulty of the route, condition of the route etc.). The spatial data was already available with the Management Body, but interviews were conducted to collect data about the number of visitors. When data was being collected through interviews from the experts, it was found that though some routes had spatial data which proved their existence but were not well maintained and therefore were inaccessible. These routes were removed from the study. The collected and processed data can be seen in the appendix (B.1.2).

3. Number of game species killed per ha per season: Recreation service (Hunting)
The indicator assessed for the flow of recreational ESS: hunting, was the number of game species killed per hectare per season. Spatial data were collected from three hunters in a participatory mapping exercise using Google Earth Pro. They were asked to mark on the map, hotspots, i.e. areas where maximum kills take place during a particular season. They drew polygons on the map that showed places where they expected maximum kills of a particular type of species in a particular season. The collected and processed data can be seen in the appendix (B.1.3).

4.Volume of timber extracted in tons per ha per season: Provisioning service

The indicator assessed for the flow of provisioning ESS: Timber harvest was the volume of timber extracted in tons per hectare per season. The spatial data was digitised from topographic maps which showed the areas where the extraction was allowed. During 2015, the extraction took place in Plakoto-Fratzi (in GR2440003) and Pavliani-Dyo Vouna (in GR2440004) and in 2019, it took place in Kastania in the forest of Vistriza. The volume of timber extracted in tons was shared by the personnel from the Forest Department of Lamia. The collected and processed data can be seen in the appendix (B.1.4).

ii. Identification of relationships among ESS through expert consultation

One of the outputs of the knowledge acquisition stage (Section 3.2.1 Part 2) is the identification of relationships among ESS through expert consultation which answers the research question 1.d (What types of relationships (synergistic or trade-off) between the ESS are identified?

These relationships are visualised through influence diagrams for easy visual interpretation. In this thesis, I explored how seasonal variations bring changes in the actual flow of ESS. Once the flow is altered, it can lead to changes in ESS interactions showing how the actual use of one service changes the access to, the supply of or demand for other services (Turkelboom et al., 2016). As the flow component of ESS is being looked at in this case study, and it is known that ESS is not independent of each other, they interact to have trade-offs and synergies, so, some of the interactions can also depend on interactions among various stakeholders who can influence the use and management of ESS (Felipe-Lucia et al., 2015). Based on the definitions of ESS trade-offs and synergies explained to the experts during interviews, the experts described the observed relationship among different ESS, though only in terms of direct trade-offs between beneficiaries of those services and not from the level of trade-offs between system-level objectives (Daw et al., 2015). The information collected contributed to identifying other factors that are influenced by seasons and also influence the flow of ESS, contributing to BBN structuring through the identification of variables for nodes. These diagrams also helped to identify which services have a stronger influence in interactions which later during BBN operationalisation stage helped in eliciting probability values. The identified relationships among services are explained below and shown with the help of diagrams. The legend is in Appendix B figure 1.5.

1. Cultural, recreational services: Hiking and Canyoning (Figure 14**)**

Recreational service provided by canyoning has positive unidirectional[14] interaction with recreational service provided by hiking. The direction shows flow of recreational canyoning influences flow of recreational hiking. People going for canyoning, hike through the hiking routes, thereby adding more visitors on the hiking routes. Hikers cannot go for canyoning without preparation and therefore there is no effect on flow of canyoning ESS. The presence of canyoners on the hiking routes increases the flow of recreational hiking ESS as more visitors gain benefits from the two recreational services in the same hiking area. Therefore, this relationship represents synergy as there is an overall increase in benefits gained in the hiking routes common to both recreational services.

[14] Based on Bennett et al. (2009), the interaction between the services is unidirectional means that the level of flow of one ESS affects the level of flow of the other ESS but not vice-versa Figure: Interactions (canyoning & hiking).

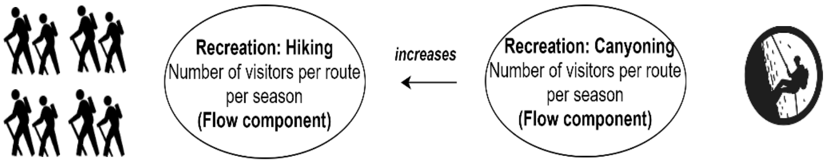


Figure 14: The visitors going for canyoning, hike through the hiking routes increasing the number of people who benefit from hiking recreational service. The difference in number of icons depicts the increase in number of visitors on hiking routes, showing synergy.

2. Cultural, recreational services: Hiking and Hunting (Figure 15**)**

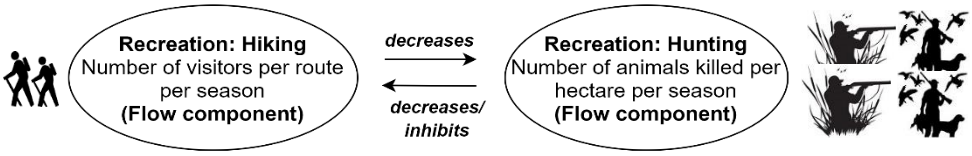


Figure 15: There is an inverse relationship between recreational hunting and recreational hiking ESS. More the ESS flow for hunting (increase in number of kills) greater the decrease in flow of hiking recreational service and can also completely be inhibited. The difference in number of icons depicts the decrease in number of visitors on hiking routes with increase in number of kills in the same area, thereby showing trade-off.

Hiking and hunting activities cannot co-occur in same space at the same time and are marked as "conflict" by the stakeholders, resulting in a trade-off as when there is increase in benefits gained from hunting recreational services and it decreases the benefits received by recreational hiking and vice-versa. These services have a bi-directional[15] relationship figure 15. As the ESS flow of recreational hunting and hiking look into the actual quantity of service received, therefore if there is interference or competition for the same resources, the flow of both the ESS is impacted. This is also mentioned by Reis & Higham (2009) who mention that the conflicts can arise due to human relationships and their demands for same resources at the same time in the same area which remains valid for recreation and outdoor sports activities. From the knowledge gained through interviews, it was found that recreational hunting has a higher influence on recreational hiking as the hikers have to leave the area for safety, so the flow of the service decreases and thus low/no benefits are received from the recreational service (hiking).

[15] Bidirectional means that the level of flow of one affects the other's flow and vice versa, Figure: Interactions (hunting & hiking).

3. Cultural recreational services: Canyoning and Hunting (Figure 16**)**

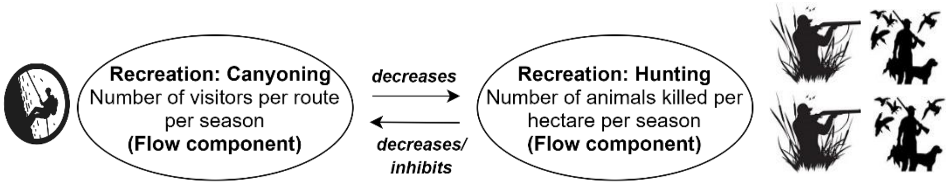


Figure 16: There is an inverse relationship between recreational hunting and recreational canyoning ESS. More the ESS flow for hunting (increase in number of kills) greater the decrease in flow of canyoning recreational service and can also completely be inhibited. The difference in number of icons depicts the decrease in number of visitors on hiking routes with increase in number of kills in the same area, thereby showing trade-off relationship.

Similar to the conflict between hikers and hunters, the recreational canyoning has an inverse relationship with recreational hunting. Whenever there are canyoners hiking towards canyons and hunters are hunting in the same area, then a trade-off situation arises for both the recreational services. These events cannot co-occur in the same place at the same time. Therefore, they are marked as a conflict by the stakeholders and result in a trade-off. Recreational hunting has a higher influence on recreational canyoning, similar to hiking where the canyoners in the area have to leave it for safety, so the flow of the service decreases and thus low/no benefits are received from the recreational service (canyoning). Also, it is clear from the figure 16 that there is a bidirectional relationship between the services. The presence of canyoners affects hunting but they do not stop hunting from happening completely.

4. Provisioning ESS: Timber Extraction and Cultural Recreational service: Hiking (Figure 17**)**

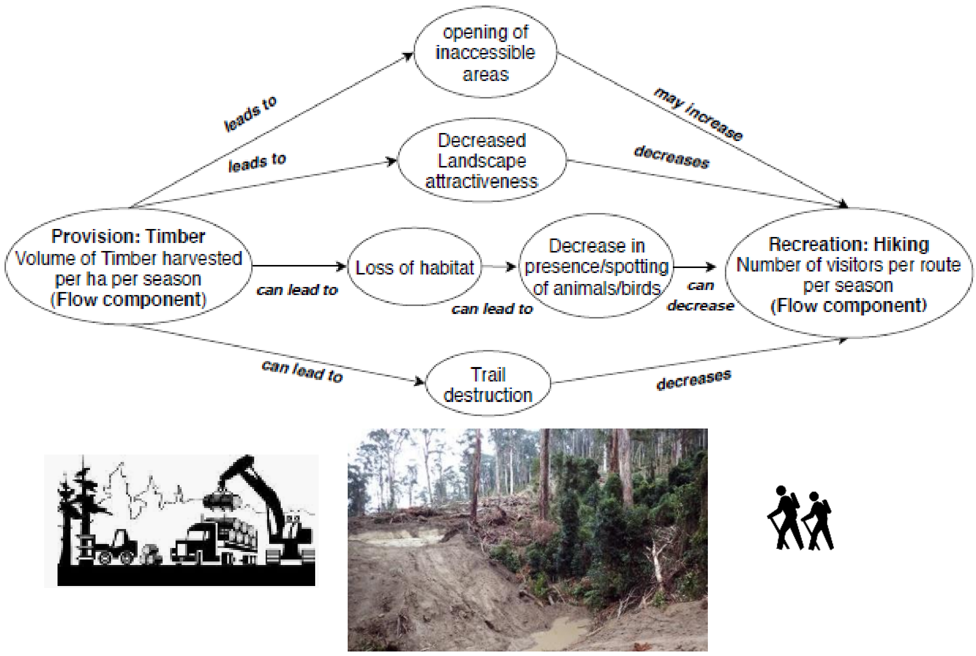


Figure 17: The visitors hiking in an area where timber has been extracted have multiple factors that affect the relationship. The choice of factor being considered affects the relationship between services. The factor considered here is trail destruction so higher flow of timber extraction has inverse relationship with flow of recreational hiking service. The influence is from provisional timber extraction ESS to recreational hiking ESS therefore it is unidirectional. The difference in number of icons depicts the decrease in number of visitors on hiking routes when timber extraction takes place in the same area thereby showing trade-off relationship between these services.

The landscape in the protected area is highly valued by visitors visiting the area for nature-based recreational activities. The volume of timber extracted from an area brings physical changes to the landscape. This influences the flow of recreational ESS: hiking. It can be seen from the figure(17), that there is no direct influence of volume of timber extracted on visitor numbers on hiking route, but there are intermediate factors which result in either increase or decrease in the benefits gained from hiking recreational service in the same area. Out of all these factors, the experts mentioned that when timber extraction takes place, most often the hikers are impacted due to the destruction of the hiking trails. Therefore, this factor was taken into consideration for defining the relationship between two services when populating the CPT in the BBN. Also, it is clear from the figure 17 that there is a unidirectional relationship between services, such that timber extraction influences the number of visitors visiting the hiking routes when it co-occurs in space, and there is no influence of hikers on the volume of timber extracted. The effects of timber extraction on the landscape continue over time, but in the BBN, it is assumed that the two services only interact when they co-occur in space as well as time. This relationship represents trade-off as there is an increase in benefits gained from provisional service timber extraction and a decrease in the flow of recreational hiking service.

5. Provisional ESS: Timber Extraction and Cultural Recreational ESS: Canyoning (Figure 18)

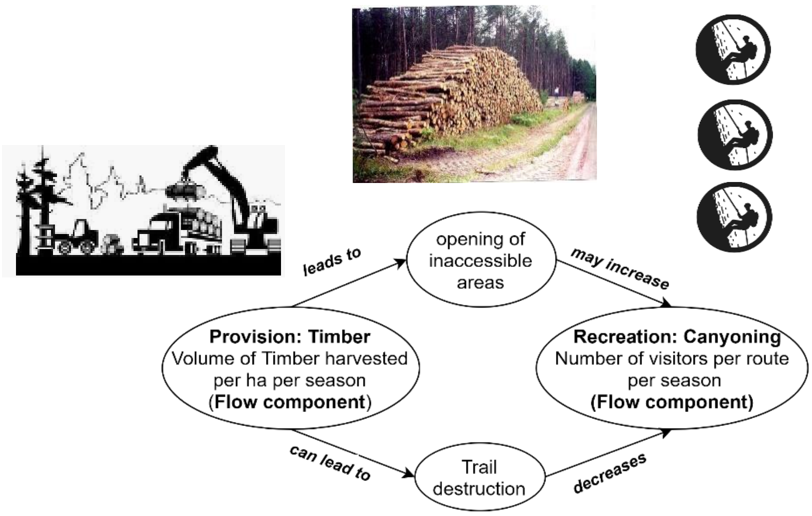


Figure 18: The visitors going for canyoning in an area where timber has been extracted have multiple factors that affect the relationship. These services have indirect relationships. The factor considered here is opening of inaccessible areas so higher flow of provisional timber extraction service more the flow of recreational canyoning service. The influence is stronger from provisional timber extraction ESS to recreational canyoning ESS. The increased number of icons depict that there increase in number of visitors on canyoning routes when timber extraction takes place, showing synergy relationship between these services.

The timber extracted from an area brings physical changes to the landscape, which influences the flow of recreational ESS: canyoning. From figure 18, the benefits gained from the actual flow of provisional service may either increase or decrease the benefits that can be received from the recreational canyoning service in the same area. Different recreational activities have different requirements and goals. While for the hikers the landscape beauty, pristine environment and wilderness are more important factors, for canyoners, accessibility to the canyons is of higher importance than other factors. Therefore, for the BBN, the relationship between timber extraction and recreational canyoning is considered to be a positive one as an increase in the volume of timber extracted in an area, increases the accessibility of inaccessible areas, which may lead to increase the inflow of recreational canyoning. It has a unidirectional relationship; such that timber extraction influences the number of people visiting the canyoning routes when it co-occurs in space, but a number of canyoners have no influence on timber extraction. This relationship represents synergy as there is an increase in benefit gained from provisional service timber extraction and an increase in the flow of recreational canyoning service.

6. Provisional ESS: Timber Extraction and Cultural Recreational ESS: Hunting (Figure 19)

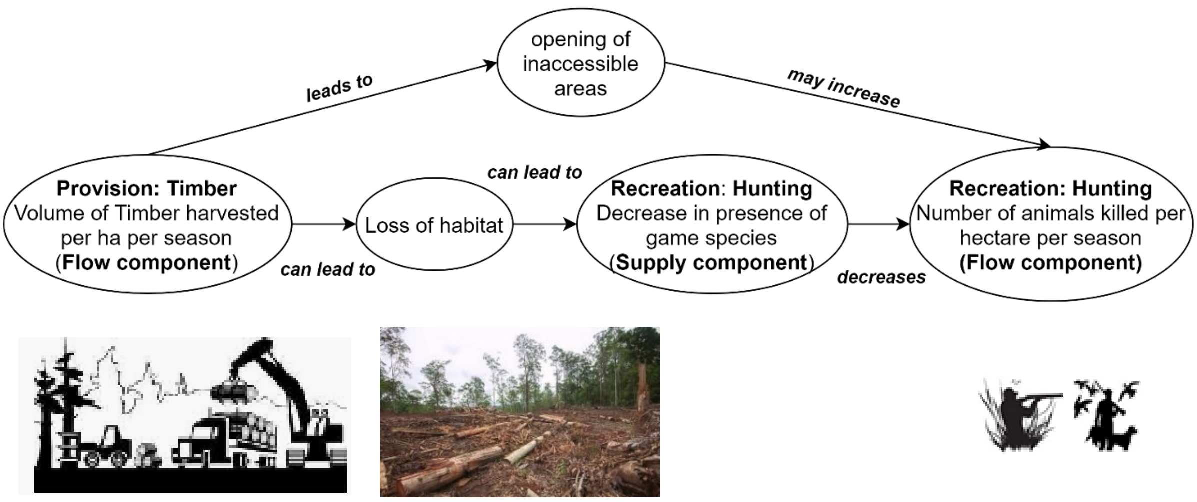


Figure 19: The hunters going for hunting in an area where timber extraction is taking place, have multiple factors that affect the relationship. The factor considered here is loss of habitat so higher the flow of provisional timber extraction service lower is the flow of recreational hunting service. The influence is stronger from provisional timber extraction ESS to recreational hunting ESS. The difference in number of icons depicts the decrease in number of animals killed in hunting areas, showing trade-off relationship between these services.

The benefits gained from the actual use of provisional service may either increase or decrease the benefits that can be received from the recreational hunting service in the same area. The volume of timber extracted from an area can lead to the destruction of habitat for many animals which may decrease the presence of game species, thereby decreasing the flow of recreational ESS: hunting. It has a unidirectional relationship as a number of animals killed has no influence on the volume of timber extracted. As per the experts, the factor which is more important to determine the relationship between these services is habitat loss and therefore, it defines and quantifies their relationship in the BBN. This relationship represents trade-off as there is an increase in benefits gained from provisional service timber extraction and a decrease in the flow of recreational hunting service.

These identified relationships helped to get a good understanding of the system components. It helped to identify the nodes, create links between them to show the dependencies and also develop the logic to populate the CPT in the BBN in the Expert Elicitation stage.

4.2. Stage 2: Design stage

Part1: Construction of BBN

i. Selection of software/platform to build BBN

A decision had to be made between selecting R package- "bnspatial"[16] or Netica for implementing Bayesian networks in the geographical space. As the model needed expert inputs at all three stages- knowledge acquisition, design and implementation - Netica was preferred over R package due to better visual presentation and availability of GUI. The experts during CPT elicitation and validation found it easier to understand the network and its connections in Netica than in R whose suitability for participatory modelling purposes is poor (Pérez-Miñana, 2016). Though Netica is commercially available, a licensed version of Netica was available and provided by ITC which provided additional functionality like an option to explore the extension GeoNetica. Therefore, Netica (version 6.07) was selected to construct the BBN and use it to carry out inference.

While working with Netica, it was found that the documentation for usage of GeoNetica was very limited. Therefore, another GUI for integrating spatial information to the non-spatial output of BBN was explored, which is a specialised online application developed by ETH-PLUS (gBay.ethz.ch) that allows running BBNs with spatial data, multiple times. The BBN structure can be created in Netica or any other software, saved as a ".neta" file which can then be directly uploaded to gBay for integration. The maps generated were enhanced for visual interpretation and displayed in ArcGIS Pro. This answers the research question (2.a, What modelling platform is most suitable to construct the BBN for the objectives of this study?).

[16] https://cran.r-project.org/web/packages/bnspatial/index.html

ii. Defining the BBN nodes, it's states and connecting the links

The nodes below have been classified as controlling node, intermediate node and target/objective nodes based on the table (Section:3.1.2.iii. Table 4). The states were defined in this section based on the type of data available to represent the node, and then the data is prepared such that each state represents all values that the node can take. The steps are taken to prepare data are shown in section 4.2. Subpart 1. This answers the research question (2.b: Which variables will be chosen to build the network?)

- **The Input Node**

1. **Seasons Node** is considered as the main input node as the aim is to investigate the likelihood of changes in interactions among the ESS due to changing seasons. Seasons was included as a variable that influences the entire system of ESS interactions and is, therefore, the main driver that changes the flow of ESS, thereby changing their interactions. Therefore, the season is a controlling node. There are four states of the season's node (Table 11).

Table 11: The description of controlling node

Node Type: Controlling Nodes: Changes the system whose system response we want to model: Seasons		
Seasons	**Total: 4 states** Winter, Spring, Summer, Autumn	The seasons are defined as: Winter (December - February) Spring (March-May) Summer (June - August) Autumn (September - November)

- **The Spatial Input Nodes**

Table 12: The description of spatial input nodes

Node Type: Spatial Input Nodes: Area/Route where the ESS is actually utilized (flow)

The model has four spatial inputs representing the routes and the areas of concerned ESS of priority:

1. Canyoning routes represent the routes where canyoning takes place. Out of the eight canyoning routes marked by the expert, seven are analysed since one of them lies outside the study area. These routes get a different number of visitors during different seasons. This node provides direct spatial input to visitors on canyoning routes node, which represents the ESS flow for canyoning. The values that this node can take, i.e. the states of the node are spatial in nature and represent the canyoning routes (Table 13). The raster map preparation steps in section 4.2. SubPart 1 and prepared a raster map of different canyoning routes can be seen in the appendix (C.1.1 Figure A12).

Table 12: Description of spatial input node: Canyoning routes

Canyoning Routes	Total: 7 states: Route 1, Route 2, Route 3, Route 4, Route 5, Route 7, Route 8.	The states represent different routes along which the actual flow of this recreational service varies during different seasons.

2. Hiking routes represent the routes where hiking takes place throughout the year. These routes get a different number of visitors during different seasons based on the preference of the people, accessibility of the routes, trail quality, marking along routes, point of interest along the routes and reasons for hiking etc. So, for this study, eight hiking routes and one special bike marathon route (ITI-Epic marathon) have been modelled, which are visited by a different number of people during different seasons. Some routes which have not been maintained and mentioned by the experts to be closed have been dropped from the study. The marathon takes place in Autumn (in the month of September) and has maximum people visiting at that time. The rest of the year, the accessibility and visits to this route remain low. This node provides direct spatial input to visitors on hiking routes node, which represents the ESS flow for hiking. The values that this node can take, i.e. the states of the node are spatial in nature and represent the hiking routes (Table 14). The raster map preparation steps in 4.2. SubPart 1 and prepared a raster map of different hiking routes can be seen in the appendix (C.1.2 Figure A13).

Table 13: Description of spatial input node: Hiking routes

Hiking Routes	Total: 9 states: Route 1, Route 3, Route 4, Route 5, Route 6, Route 7, Route 8, Route 12, Route 13.	The states represent different routes along which during different seasons, the actual flow of this recreational service varies.

3. Timber Extraction Areas*:* The volume of timber extracted depends on the seasons as the logging of trees located at the highest altitudes can only take place in the Summers. This is due to the fact that accessibility of the area in Winters is low and the chances of rotting of logged trees are high. The area where the timber is extracted tells us the location from where the ESS flow takes place. The quantity tells us how much of the ESS is actually being delivered. As the volume of timber extraction takes place in different quantities and in different areas over the two years, therefore to capture the variability in interactions among services, timber extraction from the year 2019 has been included to model the effects of timber extraction on other services, along with the year 2015. It is assumed that the impact of timber extraction only persists during the season when timber is being extracted (to keep the model simple). Although there are three locations from where timber has been extracted in the study area, the areas have been grouped together based on the quantity of timber extracted per hectare. This node, therefore, has two states A1 and A2 giving information of areas with a low and high quantity of timber extraction per hectare (Table 15). The raster map preparation steps in 4.2. SubPart 1 and prepared raster map of different areas of timber extraction can be seen in the appendix (C.1.4 Figure A15).

Table 14: Description of spatial input node: Timber extraction areas

Timber Extraction Areas	Total: 2 states: A1 and A2.	The states represent different areas in which during Summers, the actual flow of this provisional service varies depending on the volume of timber extracted per hectare per season.

4. Hunting areas: The node hunting areas show areas where hunting takes place. The variation in hunting activity depends on different seasons, type of game species available in those areas and whether they are allowed to be hunted in a season. The game species of importance in the area depending on the expert interview are boars, partridges, birds and hares. These game species are allowed to be hunted during different seasons and in different numbers. When the data was collected from experts through participatory mapping approach, they indicated areas on the map where hunting is difficult during Winters due to low accessibility. Also, they mentioned that some areas might be accessible during Summers (in the month of August), but only some bird species are allowed to be hunted, and the animal species like boars and hares are not allowed to be hunted. Then they marked the areas on the map indicating the duration of hunting allowed for each species of importance, when it is allowed to be hunted and in what quantity depending on daily limits (low, medium or high). Hunting is not allowed in Spring. So, keeping in mind whether hunting is allowed and if the area is accessible, the hunting areas are classified into 57 states (Table 16). The raster map preparation steps in 4.2. SubPart 1 and prepared a raster map of different areas where hunting takes place can be seen in the appendix (C.1.4 Figure A 14).

Table 15: Description of spatial input node: Hunting areas

Hunting Areas	**Total: 57 states:** Area 1 to Area 57	**Area 1 to Area 57:** The states represent different areas in which during different seasons, the actual flow of this recreational service varies depending on the number of animals hunted per hectare of area per season.

- **The Intermediate Nodes – Expert-based inputs**

The four priority ESS are the intermediate nodes, and they link the controlling node to the target nodes called interactions node helping to observe the changes in interactions with seasonal changes. These nodes propagate the information per pixel from the input nodes to the target node. These nodes represent the benefits humans receive during different seasons in different routes or areas.

Table 16: The description of intermediate nodes

Node Type: Intermediate Nodes: The ESS flow nodes that link controlling node to target nodes

1. ESS flow for recreational hiking: Number of visitors visiting the route per ha per season

The actual amount of this recreational ESS flow is gauged by the relaxation gained by hiking in the protected areas. The more people visiting the routes, higher is the flow of ESS; therefore, more benefit received from the ESS on those routes. The indicator used for quantifying this service is Number of people visiting a route per hectare per season. The visitor numbers can fluctuate with seasons due to many factors, but the factors chosen here are based on the inputs from experts. The main identified factors are accessibility and preference of the routes, which vary over seasons and control the visitation of people on a route. These data were collected and prepared in Appendix B.1.2. These factors were then combined to create an index which represented the number of visitors visiting a route in a season. The steps are mentioned in the data preparation section to create three states for the node: low, medium or high in 4.2. Subpart 1.

Table 17: Description of intermediate node: ESS flow of hiking recreational service

ESS flow: Hiking: Number of people per hectare of the route per season	Total: 3 states Low, Medium, High	The number of visitors visiting the route per ha per season can be low, medium or high depending on the accessibility of the route and preference which vary over seasons.

2. **ESS flow for recreational hunting: Number of game species (animals) killed per hectare per season:**

   The actual amount of this recreational ESS flow is the pleasure gained by hunting game species in the area. The higher the number of kills, the higher is the flow of ESS; therefore, more benefit received from the ESS service.

This service is quantified by indicator: Number of game species (animals) killed per hectare per season.

The number of game species killed in an area depends on:

- Whether hunting is allowed in that season, i.e. is it permitted?
- What is particular game species being hunted in that area? (as described before, hunting period for a game species varies seasonally).
- Accessibility of that area during different seasons.

This node has three states: NoKills, LowNumKills or HighNumKills for which the data is prepared in in 4.2. Subpart 1.

Table 18: Description of intermediate node: ESS flow of hunting recreational service

ESS Flow **Hunting:** Number of game species killed per hectare per season	**Total: 3 states** NoKills, LowNumKills, HighNumKills	**NoKills:** The areas show where and during which season most game species are hunted. When hunting cannot take place due to restrictions and policies or due to accessibility being low, there is no hunting in the area and categorised under noKills. **LowNumKills** is based on the expert knowledge of where a low number of animals are killed during a season. In Winters, hunting in higher elevations is difficult as the accessibility is low. The low number is also linked to policy allowance of the number of animals of particular species is allowed to be hunted in a day. Eg. In hunting seasons only one hare can be hunted by one hunter during a day in three days a week when hunting the hare is allowed. **HighNumKills** are the hotspots where most animals are hunted irrespective of the restrictions. The three states are based on expert expressed categories. The scores for accessibility and type

		of game species were linked by the expert to the area

3. ESS flow for timber produced: Volume of timber extracted in tons per ha per season

The actual quantity of this provisional ESS flow is the actual volume of timber harvested from an area. The higher the volume of timber harvested, the higher is the flow of this ESS. The expert was able to provide exact numbers for a volume of timber extracted from an area. The indicator used for quantifying this service is: Volume of timber extracted per hectare per season. So, this node was populated using direct values which were classified based on the quantity of timber extracted per hectare. It has three states: No, Low and High (Table 20), for which the data is prepared in 4.2. SubPart 1.

Table 19: Description of intermediate node: ESS flow of timber extraction provisional service

ESS Flow: Volume of timber extracted per hectare per season	Total: 3 states No, Low, High	As timber extraction only takes place during Summers, it can only happen in two quantities: either low or high. For the rest of the year (Spring, Autumn and Winters), there is no timber extraction. **No:** When there is no timber extraction in Winter, Spring and Autumn, then the state is no representing no extraction. **Low:** When there is a low volume of timber extraction (0-1 ton per hectare), it is categorised as a low state. **High:** When the volume of timber extracted is 24 tonnes per hectare, it is classified in a high category.

4. ESS flow for recreational canyoning: Number of visitors visiting the route per ha per season

The actual amount of this recreational ESS flow is gauged by the relaxation gained by canyoners in the protected areas. The more people visiting the routes, the higher is the flow of ESS, therefore more benefit received from the ESS on those routes. The indicator used for quantifying this service is: Number of people visiting a route per hectare per season.

The expert was able to provide exact numbers for the number of people visiting a route during a season. So, this node got direct values which were classified by normalising the data and categorising it to keep the input to the nodes of the BBN comparable and consistent. Section 4.2. SubPart 1 shows the steps taken to discretise the data into three states: No, Low and High (Table 21).

Table 20: Description of intermediate node: ESS flow of recreational canyoning service

ESS Flow: Canyoning: Number of people visiting a canyoning route per hectare	Total: 3 states No, Low, High	**No:** No visitors on the route in a season **Low:** Low number of visitors on route per hectare in a season **High:** High number of visitors on a route per hectare in a season

- **The Target Node**

Table 21: Description of the target node

Node Type: Target Nodes: The output nodes on which the model outcomes are tested

The interactions among ESS occur when the change in one service can lead to change in the other. The change introduced can again be in terms of supply or demand, which can impact the flow of the service as well. In this study, the ESS share the common space where the beneficiaries receive the benefits from these services. The interactions among these services can represent a trade-off, i.e. they have a negative correlation between spatial occurrences while interactions can also be synergistic. Though the interactions do not need to occur in the same location, however for this case study we can see that the interaction among the ESS is due to physical interaction, where the use of one service causes changes in supply, flow or demand for the other services. All the output nodes show the probability distribution for three kinds of interactions any two services can have in a season. The different combinations of the parent states of these target nodes can be interpreted as having different interactions among these services. Both the parent nodes are influenced by the season nodes and also by the respective spatial inputs. These different combinations have a different probability of occurrence during the four seasons. So, these target nodes help to identify, the changes in the type of interactions between these services in the same location and also highlight changed probabilities of their occurrences over seasons. The target nodes can take either one of the three interactions: trade-off, synergy and no-effect. There are six target nodes representing interactions between the two services (Table 23). All the target nodes receive inputs from intermediary nodes representing respective ESS flows and the states for each of them are described by interaction type states: trade-off, synergy and no-effect.

Table 22: List of all target nodes: pairwise interactions, which receive input from Intermediate ESS flow nodes in pairs

Target Nodes	Intermediate ESS flow nodes
Interactions (Timber & Hiking)	Provisioning service timber extraction and Recreational service hiking
Interactions (Timber & Hunting)	Provisioning service timber extraction and Recreational service hunting (game).
Interactions (Timber & Canyoning)	Provisioning service timber extraction and Recreational service canyoning.
Interactions (Canyoning and Hiking)	Recreational services hiking and canyoning.
Interactions (Hunting & Hiking)	Recreational services hunting (game) and hiking.
Interactions (Hunting & Canyoning)	Recreational service hunting (game) and canyoning.

As the data collected for flow recreational hiking and hunting services was qualitative and expressed categorically as low, medium and high or no, low and high, therefore to maintain consistency and comparability, the quantitative data for the flow of provisioning timber extraction and flow of recreational canyoning service, was decided to be converted into similar categories. Thus, the states were expressed qualitatively as a description which made the network and its interconnections easier to understand. Therefore, different types of data were integrated due to the structure of the network in the way the nodes are linked, and data is prepared to fill the network. (This answers the research question 2.b How will the different data types be integrated?) These nodes, links and states put together to create the structure of the

BBN called the Directed Acyclic Graph. The output of the design stage is the completed structure of the BBN.

SubPart1:Data Preparation

The BBN contained spatial input nodes which represented the areas or routes where the beneficiaries received the benefits from chosen ESS, which represented the actual quantity of service flow. As the structure of the network was quite simple and straightforward, the node preparation required two kinds of processes- preparation of spatial data and data discretisation for non-spatial nodes. The spatial data were collected during the Knowledge Acquisition stage and created into vector files for all services (Appendix: B). The intermediate nodes do not receive spatial input, but their data are prepared in a way such that the states of these nodes represent the combination of their parent state nodes, during different situations. The data for different services was available as qualitative or quantitative.

Quantitative data

The data for provisional timber extraction and recreational canyoning service was quantitative and was converted into categories to keep consistency and comparability in the network.

- **Canyoning routes**

- **Spatial input nodes**

  As the routes were digitised based on expert input, the canyoning routes were created in a vector format in Data Curation part of Stage 1 (Appendix: B.1.1 Figure A 4). It was rasterized to create seven states for a spatial node: Canyoning route node in this stage. The raster input can be seen in Appendix (C.1.1 Figure A12).

- **Intermediate node: ESS Flow node: Number of visitors on canyoning route per hectare node**

The expert gave data on the number of people visiting these routes during different seasons (Appendix: B.1.1 Figure A 3). To prepare data for the states, flowing steps were taken:

1. Normalise[17] the data to 0-1
2. Take mid-value (0.5).
3. As the data were few with very little variation so:

Data-values below 0.5 was set into the low class. (Low: Data-values < 0.5)
Data-values equal to and greater than 0.5 was set in high class (High: Data-values >= 0.5)
Data-values with 0 values set to No visitors' category. (No visitors: Data-values = 0)
This helped to create three states of the node covering all possible values for it during different seasons: No, Low, High.

[17] Normalised data (Zi) = xi-min(x)/max(x) - min(x); where xi=(x1, ..., xn) and Zi is now ith normalized data.

➢ **Timber extraction areas**

❖ ***Spatial input nodes:***

It can be observed that the timber was extracted in different quantities from three areas (Appendix: B.1.4 Figure A10). Based on the volume of timber extraction per hectare in Summers, the areas were grouped into two categories. The two areas (Kastania and Dyo Vouna) with < 1 ton of extraction per hectare were grouped in low timber extraction area, category A1. The third area where timber extracted= 24 ton per hectare was classified under the high category, A2. These categories then represent the two states for spatial input node: Timber extraction areas node. The raster input can be seen in Appendix C.1.4 Figure A15.

❖ ***Intermediate node: ESS Flow node: Volume of timber extracted per hectare node***

The volume of timber extraction data was available in units of cubic meters. The data was prepared to bring it to a common unit by converting the volume of timber extracted to ton per hectare in ArcGIS Pro (Appendix: B.1.4 Figure A9). The states were defined as No, Low and High based on the volume of timber extracted per hectare during Summer season.

Qualitative data

The recreational hiking and hunting services data was qualitative and was collected categorically.

➢ **Hiking Routes**

❖ ***Spatial node:***

The routes were already available in vector format from Management Body in Data Curation part of Stage 1 (Appendix: B.1.2 Figure A 4). It was rasterized to create nine states for the spatial node: Hiking route node. The raster input can be seen in Appendix (C.1.2 Figure A 13).

❖ ***Intermediate node: ESS Flow node: Number of visitors on a hiking route per hectare node***

The indicator of ESS flow for recreational hiking was the number of visitors visiting a hiking route per hectare per season. Based on the expert opinion gained during data collection (Stage 1) the number of visitors depended on two factors: preference and accessibility of the hiking routes during different seasons. The data for accessibility was collected as categorical data, defined by the experts as (low, medium, high) for each route for each season. The preference data was provided in terms of ranking of the route, that informed about which routes were more visited by the visitors during different seasons. The routes were ranked in order from most visited to least visited which used as a substitution for a preference of the people for visiting the routes during the different season as per expert opinion.

Accessibility: The data was already categorized as low, medium and high, and the values were associated with each route for each season.

Preference:

The data was prepared (B.1.2 & Table A16) and categorized into classes low, medium and high.

An index developed by combining these two factors (accessibility and preference) was used to populate the flow indicator for Recreational ESS hiking.

The index was created by:

1. Using spatial join in ArcGIS pro to join data together based on location.
2. Then use equal weight summation to create an index to measure the ESS flow for hiking.

3. The values in index ranged from (1-9) after summation. Using the Equal Interval method in ArcGIS Pro[18], the values were put under three classes: low (1-3) medium (4-6) high (7-9).

These classes then represented the three states for ESS flow for recreational hiking in the BBN as a low, medium, high.

➢ **Hunting Areas**

❖ ***Spatial node:***

The three experts drew polygons of different sizes and in different areas representing similar information about where and what kind of game species are hunted in those areas (B.1.3 Figure A 8). Then the data were merged together (Geoprocessing tool in ArcMap: Union) to form 57 different areas. All these areas had information about game species hunted in those areas and accessibility of those areas during different seasons. These areas were then rasterised to create 57 states for the spatial input Hunting areas (C.1.3 Figure A 14).

❖ ***Intermediate node: ESS Flow node: Number of game species killed per hectare node***

The indicator of ESS flow for recreational hunting was a number of game species killed per hectare per season. Based on the expert opinion gained during data collection (Stage 1) the game species killed depended on two factors: accessibility and type of game species that can be hunted in different seasons. The data for accessibility was collected as categorical data, defined by the experts as low, medium, high for each area for each season. The data for the type of game species was also spatially explicit linked to the polygon description while the expert marked the polygon on the map during data collection (participatory mapping). The data for the type of game species was available as a score provided by the experts who calculated it based on the following information:

1. Whether hunting was allowed in that season: permitted?
2. What particular game species were being hunted in that area? (as hunting period for a game species varies seasonally).

Accessibility: The data was categorized as low, medium and high.

The number of game species hunted: The data was categorized as No, Low and High.

An index developed by combining these two factors was used to populate the indicator for Recreational ESS hunting flow (Appendix B.1.3 & Table A 17).

The index was created by:

1. Using spatial join in ArcGIS pro and using equal weight summation to create an index to measure the ESS flow for hunting

2. The values in index ranged from (0-9) after summation. Using Jenks Natural Breaks method in ArcGIS Pro, the values were put under three classes: No (0), Low (1-5) high (6-9).

These classes then represented the three states for ESS flow for recreational hunting in the BBN as NoKills, LowNumKills, HighNumKills.

iv. DAG

The model development was based on guidelines of (Cain, 2001; Bromley, 2005) and was implemented in Netica. The DAG (Figure 20) shows different coloured nodes which represent different groups of variables.

1. The dark grey node represents the input node: Seasons.

[18] https://pro.arcgis.com/en/pro-app/help/mapping/layer-properties/data-classification-methods

2. The light grey show spatial input nodes- timber extraction areas, canyoning routes, hiking routes, hunting areas.

3. The intermediate nodes with expert-based inputs are in light yellow and represent ESS flows. These ESS flows are then grouped into pairs to look into their interactions and these represent target nodes, colour coded as brown.

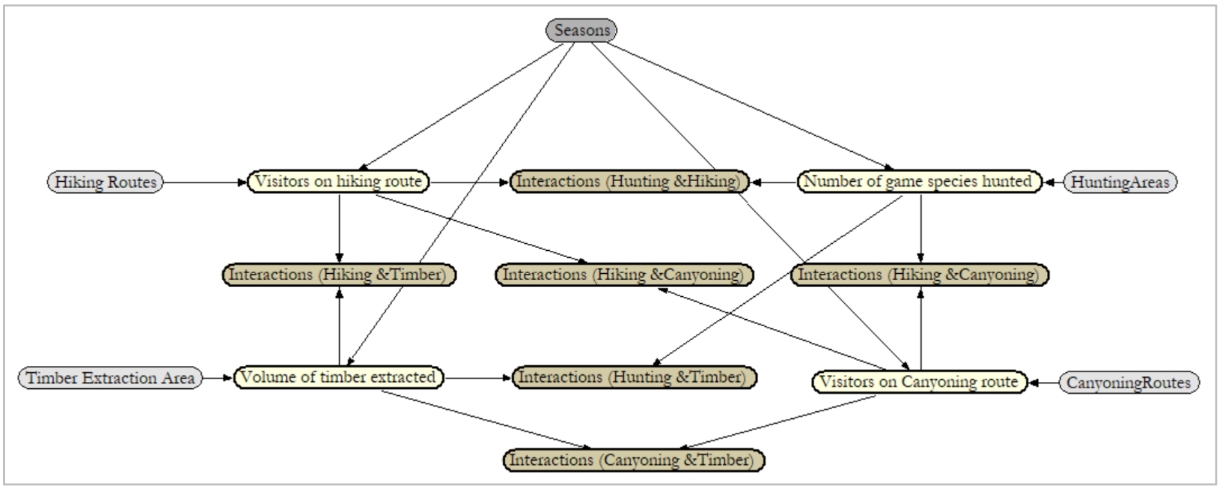


Figure 20: DAG (Structure of the BBN) for modelling ESS interactions

The DAG integrates the GIS layers with ESS flow nodes to depict information about where the consumption of chosen ESS takes place. Now, based on the way the nodes are interconnected tells us about the dependence and independence of nodes. The nodes of importance here are ESS flows and the interactions they have between each other. The complete BBN structure is built by combining different ESS flow nodes representing recreational services like hunting, canyoning and hiking along with food and fibre provisioning service like timber extraction. The structure of the BBN is the main output of Stage 2 Design Stage (Section 3.2.2).

4.3. Stage 3: BBN Operationalisation Stage

<u>Part 1. Expert Elicitation (CPT)</u>

<u>Quantification of ESS relationships using expert knowledge</u>

Once the structure of the BBN was ready, the next step was to populate the child nodes with CPT values. In this network, there are intermediate nodes (ESS flow nodes) and target nodes (Interaction nodes) which receive input from their parent nodes and therefore need CPT to be filled in order to determine the relationship with their parents. This helps to answer the research question (3.a- How will the identified relationship between the ESS be quantified through the expert knowledge?)

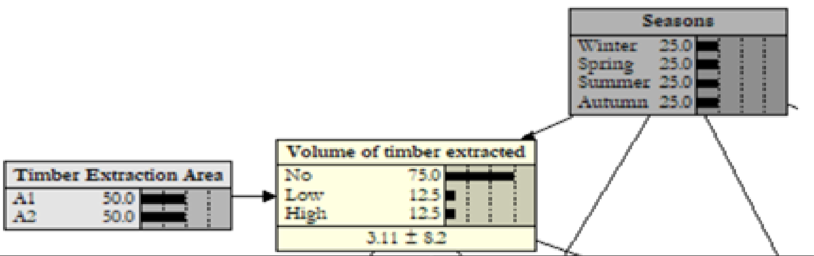
- **CPT for Intermediate nodes: ESS flow nodes**

It can be seen from the DAG, the ESS flow nodes are child nodes for seasons and spatial input nodes. The ESS flow nodes (yellow) therefore have a dependency on their parent nodes expressed as:

1. P (Number of game species hunted (ESS flow) | Seasons, Hunting Areas)
2. P (Visitors on canyoning routes (ESS flow) |Season, Canyoning Routes)
3. P (The volume of timber extracted (ESS flow) |Seasons, Timber Extraction Areas)
4. P (Visitors on Hiking Routes (ESS flow) |Seasons, Hiking Routes)

*(Probability of number of game species hunted given seasons and hunting areas)

An example of how the CPT can be populated and the way the BBN calculates the probability distribution of states of a node has been discussed in Section 3.1.3 Stage 3 Part1, with concepts of marginalization, joint probability distribution and Bayes theorem. Here, on the same principle, taking an example of ESS flow of provisioning service: timber extraction, the process behind entering information to CPT of the node has been described below (Figure 21). As this logic remains the same for other services, therefore details have not been repeated, but their tables have been included in Appendix D for reference.



Conditional Probability Table		Volume of Timber Extracted		
Seasons	AreaofTimberExtraction	No	Low	High
Winter	A1	100	0	0
Winter	A2	100	0	0
Spring	A1	100	0	0
Spring	A2	100	0	0
Summer	A1	0	100	0
Summer	A2	0	0	100
Autumn	A1	100	0	0
Autumn	A2	100	0	0

Figure 21: The figure shows the CPT values filled for the node "volume of timber extracted."

The volume of timber extracted depends on the combination of its parent nodes: Timber extraction area (spatial input) and Seasons. Therefore, the CPT was filled manually based on knowledge about where the different parent combinations of states were true in space. As we know from the map (Appendix: C.1.4 Figure A 15), areas A1 have a low volume of timber extracted, and extraction is only during Summers, so the probability of such an event to occur is 100% only for this combination. Similarly, A2 has a high volume of timber extracted and is only extracted during Summers, so:
Scenarios:

1. **Probability (P) of the volume of timber extracted to be high, given the season is Summer and timber extraction area is A2 is 100% is written as:**

P (Volume of timber extracted =="High" | Season =="Summer", Timber Extraction Area =="A2") = 100% else for all other combinations of the parent nodes, the volume of timber extraction =="High" will be 0%. So, the places where the combination of parent states are known to exist, tell us that the event actually took place, and there is no uncertainty involved in its occurrence.

2. **P (Volume of timber extracted =="High" | Season ="Spring", Timber Extraction Area =="A2") = 0% as the timber extraction does not take place in Spring. This means that the event cannot occur. The following combination holds true for this case:**

P (Volume of timber extracted ==" No" | Season =" Spring", Timber Extraction Area ==" A2") = 100% as the timber extraction does not take place in Spring; therefore there is 100% surety that no volume of timber will be extracted.

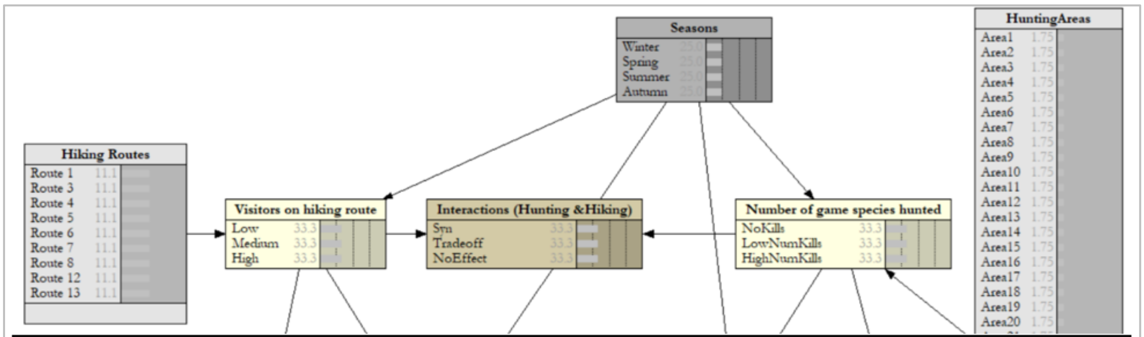
3. P (Volume of timber extracted ==" High" | Season =" Summer", Timber Extraction Area ==" A1") = 0% as the timber extraction from Area 1 cannot be high, based on information gained from data collected. The following combination holds true for this case:

P (Volume of timber extracted ==" Low" | Season =" Summer", Timber Extraction Area ==" A1") = 100% as there is 100% surety that volume of timber extracted during Summer and from area A1 is low.

<u>2. CPT for target nodes</u>

The flowchart (Section 3.1.3 Figure 8) shows the logic used to populate the CPT for pairwise interactions between the ESS flow nodes. This logic was derived based on the common terminology fixed with the Management Body, which defines the interaction types (trade-offs, synergies or no-effect) considered valid for the study (Appendix A 1.3.1).

Figure 22 shows each combination of parent nodes and corresponding values that three states in the Interactions - target node can take. On the left side of the table, all combinations of the two parent nodes are listed while on the right is the conditional probability table with values filled for the three interaction types: synergy, trade-off and no-effect based on the joint probability of the parent nodes. The values are filled for each row such that total is a hundred per cent.



Interactions (Hunting & Hiking)				
Number of Visitors (Hiking)	**Number of game species hunted**	**Synergy**	**Trade-off**	**No-Effect**
Low	NoKills	0	0	100
Low	LowNumKills	0	0	100
Low	HighNumKills	0	100	0
Medium	NoKills	0	0	100
Medium	LowNumKills	0	100	0
Medium	HighNumKills	0	100	0
High	NoKills	0	0	100
High	LowNumKills	0	100	0
High	HighNumKills	0	100	0

Figure 22: The figure shows the CPT values filled for the node "Interactions (Hunting & Hiking)"

The values in CPT are filled based on the pairwise comparison of states of the parents:

1. The probability of no-effect = 100% for all places where either one or both services have no state as values.

2. When ESS1==" High" and ESS2 ==" High", then this combination should result in synergy = 100% based on the definition of synergy as defined by Bennett et al. (2009). But the component of ESS being looked at is flow, which means the benefit of the service is received by the people in the same area (which serves multiple purposes) and therefore interactions will also depend on the interactions among the beneficiaries of the services. So, depending on the combination of ESS being looked at, the interaction identified would depend on the nature of the services to support each other. For example, consider

recreational hunting and recreational hiking. The fundamental nature of these two recreational services is that if there is a high flow of recreational hunting ESS, it will not allow the other service to flow. This is because there is a conflict of interests between beneficiaries of the service. Therefore, this combination of parent states will instead have a 100% probability to be trade-offs. This information is based on the expert knowledge of ESS flow relationships for each pair of services.

3. Similarly, when filling the CPT for parent combinations of ESS1==" Low" and ESS2==" Low", according to the Bennett et al. (2009) definition, this should be accounted as synergy, but depending on the ESS and its component being looked at and based on the expert's definition of such a situation, this combination could get 100% no-effect as in case of recreational hunting and hiking. The reason is that the two services have weak interactions and so the impact is nearly negligible.

The CPT for the other interactions has been filled on similar grounds, and therefore the process has not been repeated, but their tables for reference have been included in (Appendix E). Once all CPT were completed, the BBN became fully functional (Figure 23).

Expert-Elicited (Functional BBN)

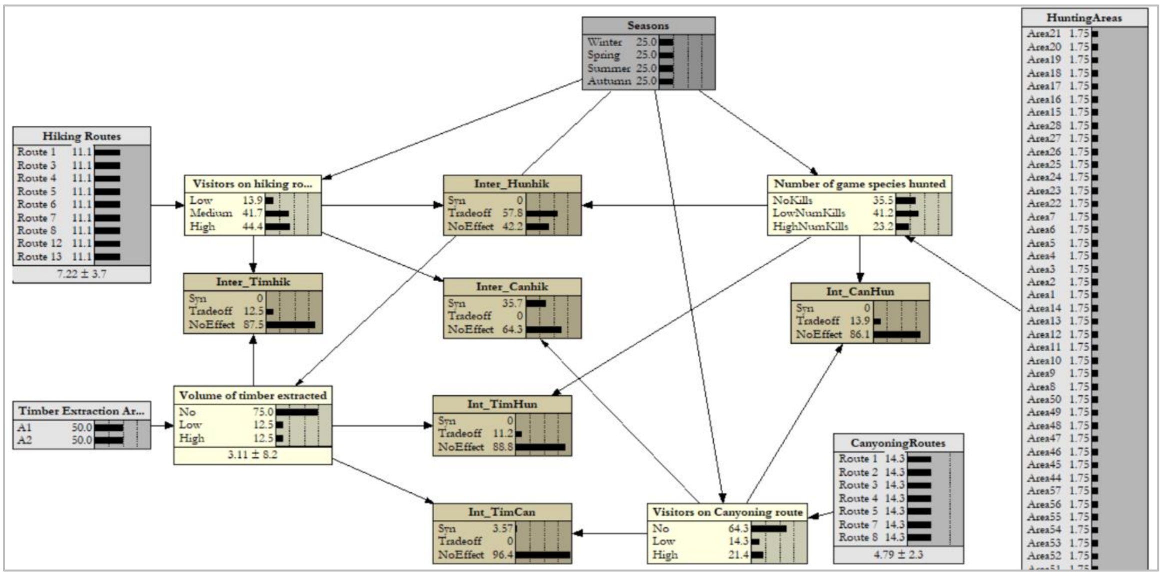


Figure 23: Fully functional BBN that models' seasonal variations in ESS interactions. Only the first 20 hunting areas out of 57 are represented here for better visualisation.

The BBN shows the prior values calculated for each node. The parent (root) node like seasons node and spatial input nodes have no conditional probability tables and therefore have uniform probabilities. The child nodes like ESS flow nodes and target nodes get their probability values using joint probability calculations on CPT values filled according to the combination of parent states (as explained in section 3.1.3 Part 1).

4.4. Stage 4: Spatial BBN application and validation stage

The stage shows the spatial implementation of the BBN that identifies and quantifies the changes in pairs of ESS interactions seasonally and in space which can be beneficial for managers to identify priority areas for management. The maps produced help to visualise the changes in ESS relationships using a BBN. This answers the research question 3.b. (How will the BBN be used to visualise and quantify changes in identified relationships across space and over seasons?)

Part 1: BBN to Spatial BBN

General map layout information for map interpretation.

The map layout, in general, has four sections.

1. Part A represents the background information map which shows the places where the benefits from four ecosystem services are received, like the canyoning routes, hiking routes, hunting areas and timber extraction areas. It also shows nearby villages and the boundary of the study area enclosing two study sites GR2440003 and GR2440004. It sets the base layer for the study. It has been created as a separate map so that the main interactions map is better visualized.
2. Part B shows a map of the kind of interaction an ESS pair can have – trade-off or synergy in a season. There is a range of probability values associated with the interaction being represented. The trade-offs are represented in colour shades of blue, the synergy in green and uncertainty in a palette of red.
3. Part C illustrates the spatially explicit uncertainties associated with the estimates of the quantification of the ESS interaction in Part B at a pixel level.
4. Part D is the legend representing map symbols used in all the parts A, B and C.
5. The orange coloured ellipse is used to highlight areas to focus on a map.

The maps below show the probability distribution of trade-offs and synergy for ESS interactions based on the outputs derived from the BBN. The legend for Part B is shown as the probability distribution values of each state for a target node, and Part C shows the probability distribution of uncertainty values associated with that target node. The output is derived from gBay, which associates the probability distribution values calculated in BBN with the spatial inputs, thus providing probabilistic spatial output. The probability values are associated with each pixel of a raster. The outputs have been classified into six ranges which lie between 0%, 1-25%, 26-50%, 51-75%, 76-99% and 100%. The uncertainty is quantified by Shannon's index:

$$J = H'/H_{max}. \qquad \text{.......(14)}$$

The values 0% indicate that there is 100% surety that the interaction type being investigated does not take place in that area while 100% shows that the interaction definitely takes place. For example, in the case of the probabilistic map of synergies, the places where there is no possibility of synergy, get 0% synergy values. The places where there is an overlap between canyoning and hiking routes and have visitors on both, get 100% synergy value. But in the places where there is not enough information to say that interaction is synergy, (non-overlapping areas of canyoning and hiking routes in this case), then those pixel can get values in ranges between 1-25%, 26-50%, 51-75% and 76-99%, depending on the joint probability distributions in the BBN. This shows the uncertainty in the level of knowledge available for the area. If synergy value is 1-25%, it means that the probability of synergy to occur in that area is low on the other hand if it is 76-99% it means there is high probability of synergy to occur in the area.

In case of the uncertainty map, if the uncertainty is 0%, it tells us that there is complete certainty of interactions node to be in a particular state for example synergy, while 100% shows maximum uncertainty which is depicted as the uniform distribution between all possible states.

The values of 0% and 100% exist almost in all maps and express same information about an event to either happens with 100% certainty or the event not happening at all depicted by 0% certainty. Therefore, they have been excluded from the ranges. The four ranges are created between 1 to 99% to make interactions and uncertainty values in different maps comparable and easy to relate.

1. **Visualization of pairwise interactions between ESS flow for Recreational Canyoning and Recreational Hiking Services for all seasons**

The interaction between recreational canyoning and hiking in all the seasons varies in space, as shown by figures 24, 25, 26, 27, The changes are in probability distribution between synergy and no-effect. No-effect is observed when there are no people visiting canyoning routes in any season. It can be observed from all the seasons that hiking route R5 and canyoning route Rodokalos (highlighted by orange dashed ellipse) have 100% synergy which represents that these routes are the highest visited and maximum ESS flow takes place in these routes all throughout the year. It can also be seen from the uncertainty map which shows for these areas during all seasons, 0% uncertainty. Therefore, there is 100% surety of having 100% synergy in the area all throughout the year.

From the background map, it can be observed that is the only overlapping area where the synergy between canyoning and hiking can take place. Yet, the way the CPT defines the relationship between canyoning and hiking, i.e. the flow of recreational canyoning has a stronger influence on interactions than the flow of recreational hiking, so it is observed that canyoning routes get a probability of having synergy during different seasons, even though there are no specific hiking routes overlapping them. The reasons can be: 1. As canyoning includes multiple activities and hiking is inherent while canyoning, therefore even though the hiking routes do not exist in places where canyoning takes place in study area, yet there is a probability for synergy. 2 Also, there is no condition set to look into interactions only where hiking and canyoning routes overlap, so based on unidirectional relationship described by the experts, the canyoning routes which get visitors during any season, show probability of synergy. This information can be useful for the experts if they plan to increase tourism in the area by constructing the hiking routes in these specified areas giving a probability of synergy.

During Winter (Figure 24), all the canyoning routes have probability of synergy to be 0% with probability of uncertainty to be 0% that this information is true except for Rodokalos canyon which has probability of synergy to be 100% with probability of certainty = 100% for this event to occur. During Spring (Figure 25), all other routes have a probability of 100% synergy except Gorgopotamos and Stenovouni canyoning routes which have no visitors so, probability of synergy to occur =0%. In Summer (Figure 27) and Autumn (Figure 26), Gorgopotamos route has a probability of 100% synergy.

It can be inferred from the map generated that though the BBN is able to map the interactions of where they actually happen on the ground (Rodokalos canyoning route and hiking route 5), it also generates a lot of information for other services as they are a part of the same network. This extra information does not make sense and also creates confusion. The uncertainty map helps to identify these areas which have high uncertainty. The contribution of recreational hiking services to the interactions between hiking and canyoning services can be observed to be highly uncertain from the uncertainty maps for all season especially during Autumn where uncertainty is reported to be 100%.

Therefore, it can be observed that a place can have same interactions all through the year (example Rodokalos) or there can be a change in magnitude and interactions among pair of services over season and in space (example Gorgopotamos).In this case the change in interactions is reflected as synergy and no-effect but with a different choice of services or a different ESS component being looked at, the switch might be between synergy and trade-off. This can be explored in further studies.

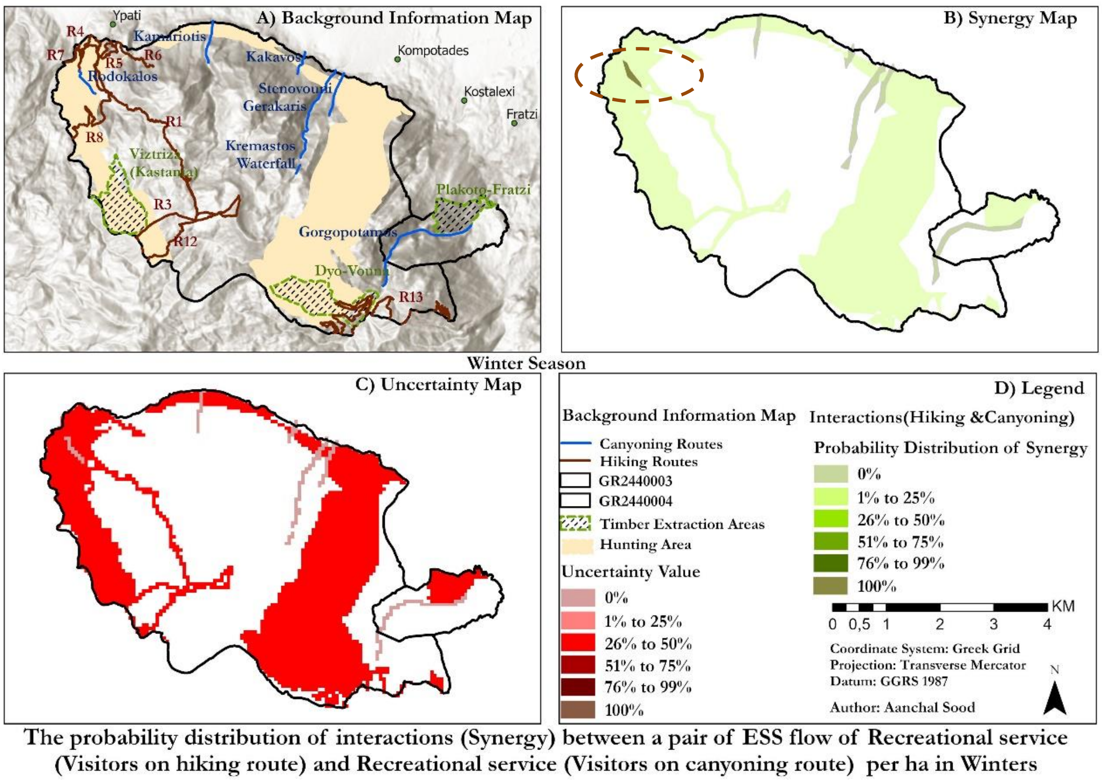


Figure 24: Probability distribution of interactions between Recreational Canyoning and Hiking service along with the quantified uncertainty in their relationship, in Winter

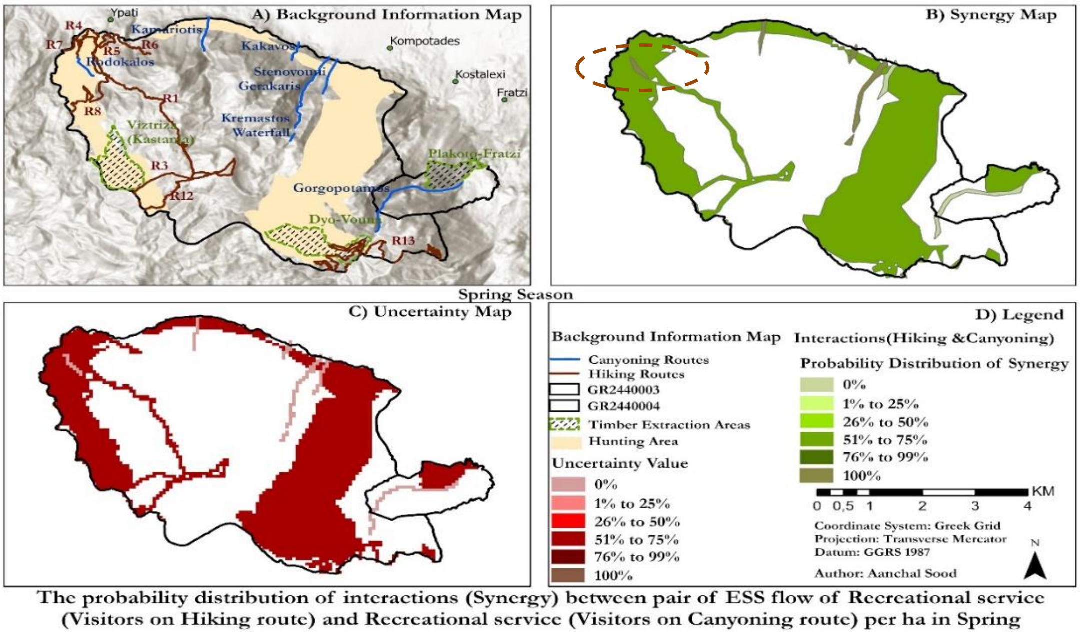


Figure 25: Probability distribution of interactions between Recreational Canyoning and Hiking service along with the quantified uncertainty their relationship, in Spring

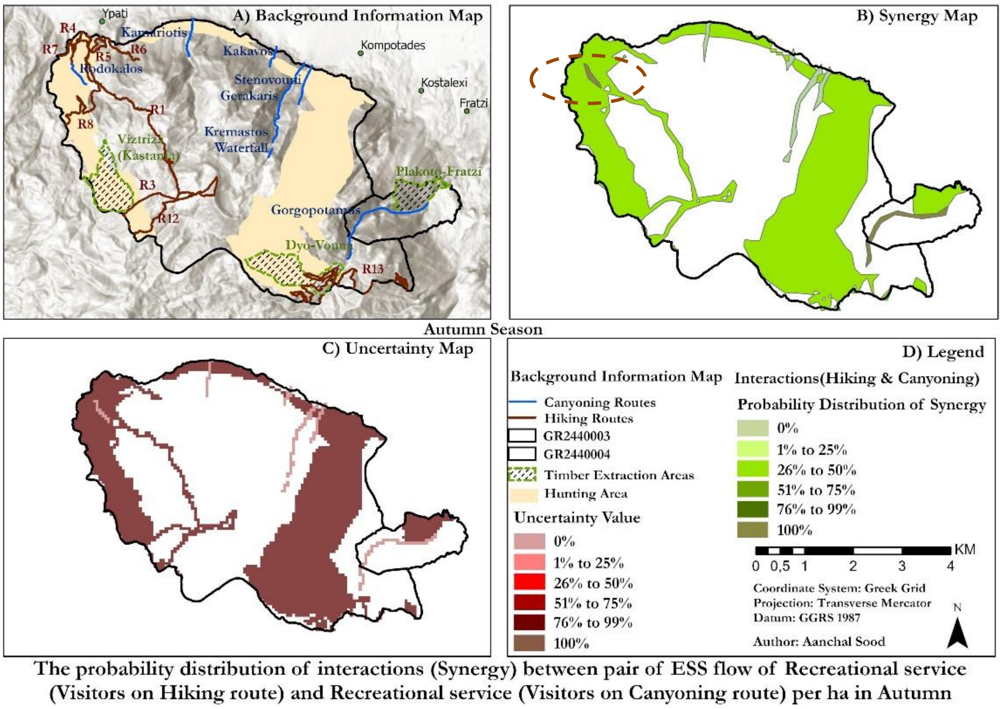


Figure 26: Probability distribution of interactions between Recreational Canyoning and Hiking service along with the quantified uncertainty in their relationship, in Autumn

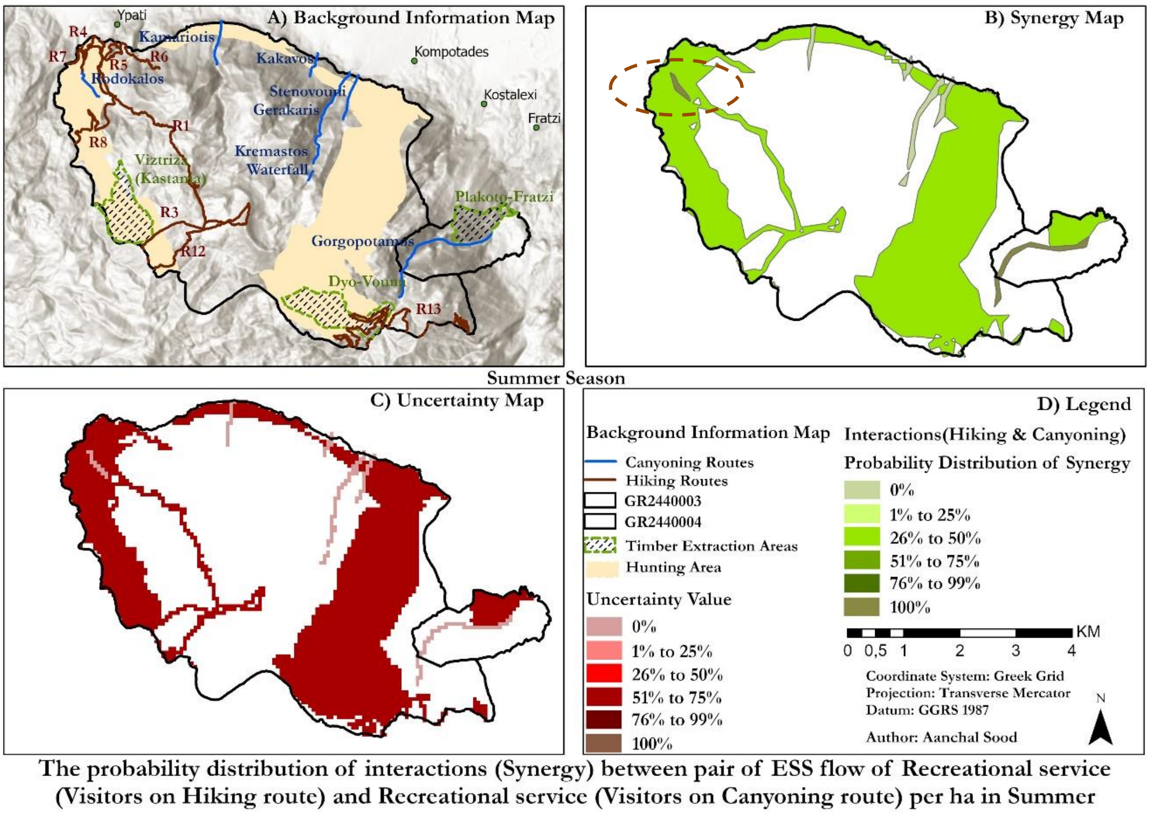


Figure 27: Probability distribution of interactions between Recreational Canyoning and Hiking service along with the quantified uncertainty in their relationship, in Summer

2. Visualization of pairwise interactions between ESS flow for Recreational Canyoning and Recreational Hunting Services for all seasons

The interaction between recreational canyoning and hunting in all the seasons varies between trade-off and no-effect. No-effect is observed when there are no people visiting canyoning routes in any season or hunting does not take place in Spring. In these cases, the probability of having trade-offs is 0% with a probability of certainty = 100% that no interactions occur. The map has not been generated as the entire area only shows the probability of no-effect=100%.

The uncertainty involved in working with the hunting data is the highest, which can be seen from the range of uncertainty values in the uncertainty map for all the seasons. From figures 28, 29, 30 it can be seen that at canyoning route Rodokalos, there is 100% trade-off probability with recreational hunting in all seasons except Spring when no interaction takes place.

As there is no condition applied to restrict the interactions to areas where an overlap among the services takes place, therefore, the BBN shows trade-off at places like Gorgopotamos canyoning route where there is no hunting reported. The BBN shows a trade-off to occur 100% in Summer (Figure 29) when Gorgopotamos has a high number of visitors and 76 to 99% trade-off in Autumn when there are the low number of visitors on this route. But the uncertainty map is useful here as it shows the uncertainty of trade-off to occur in these locations is high. In Winter, when there are no visitors on the route, therefore the BBN shows 0% probability of trade-off with 0% uncertainty.

It is also observed that the hunting ESS flow changes in space and magnitude over a season. In Winter (Figure 28) and Summer (Figure 29), no interaction takes place in the grey areas. Therefore, the probability of having an interaction is 0% and is shown by the probability of 0% uncertainty in the uncertainty map. Same areas during Autumn (Figure 30) have 51-75% chance of having trade-off with canyoning ESS. Though this information is not correct as there are no canyoning routes in these areas, it highlights the fact that during different seasons, the ESS flow for recreational hunting (also for other ESS flow in general), vary over space and in magnitude.

The recreational hiking gets probability distribution values for different seasons, although the interactions being looked at are between recreational hunting and canyoning. This is because all these interactions are a part of the network and have an influence on each other. In order to not show results which are not valid for particular interactions, some conditions need to be set to restrict the outcomes only to pair of ESS being considered.

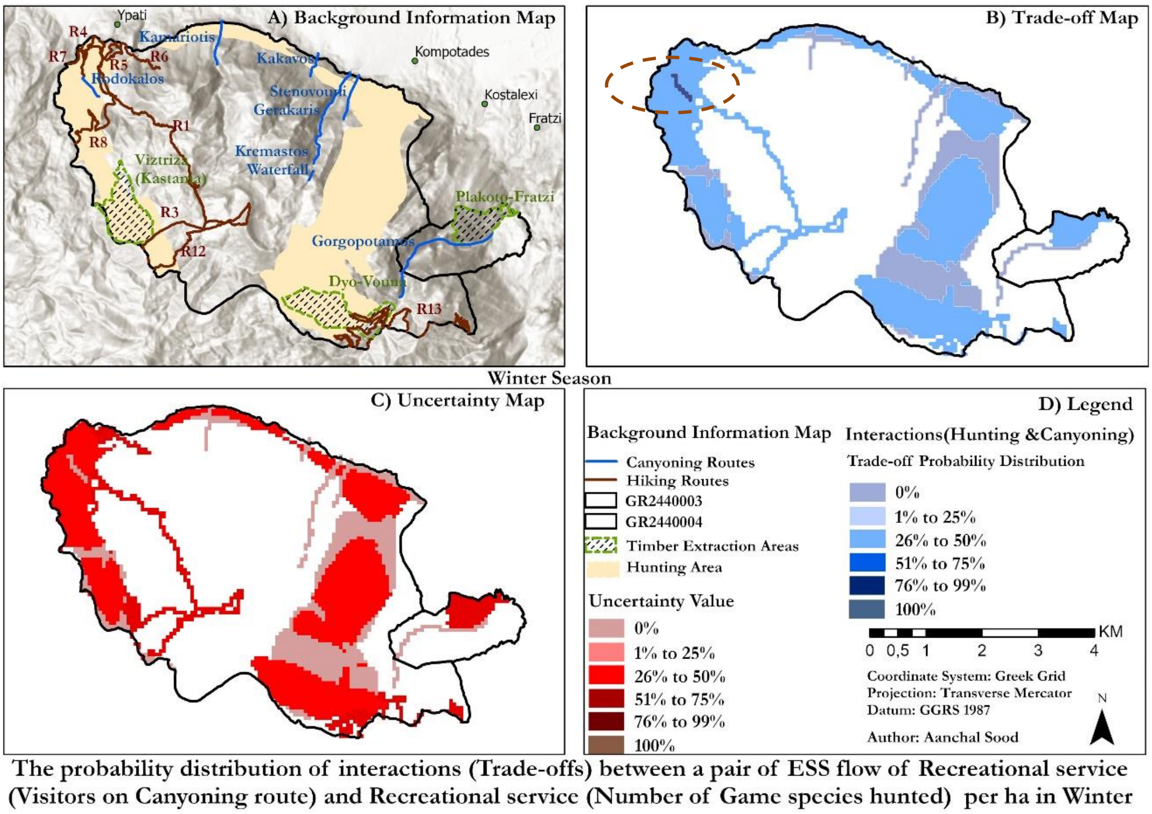


Figure 28: Probability distribution of interactions between Recreational Canyoning and Hunting service along with the quantified uncertainty in their relationship, in Winter

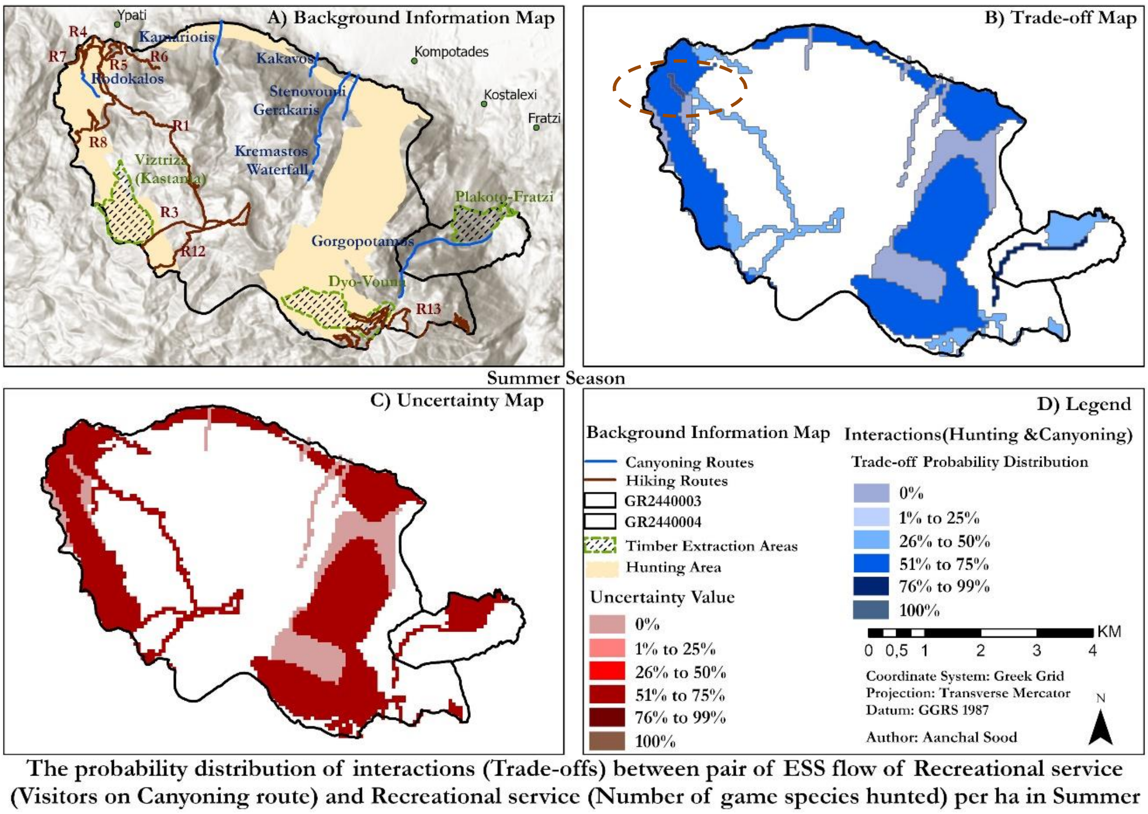


Figure 29: Probability distribution of interactions between Recreational Canyoning and Hunting service along with the quantified uncertainty in their relationship, in Summer

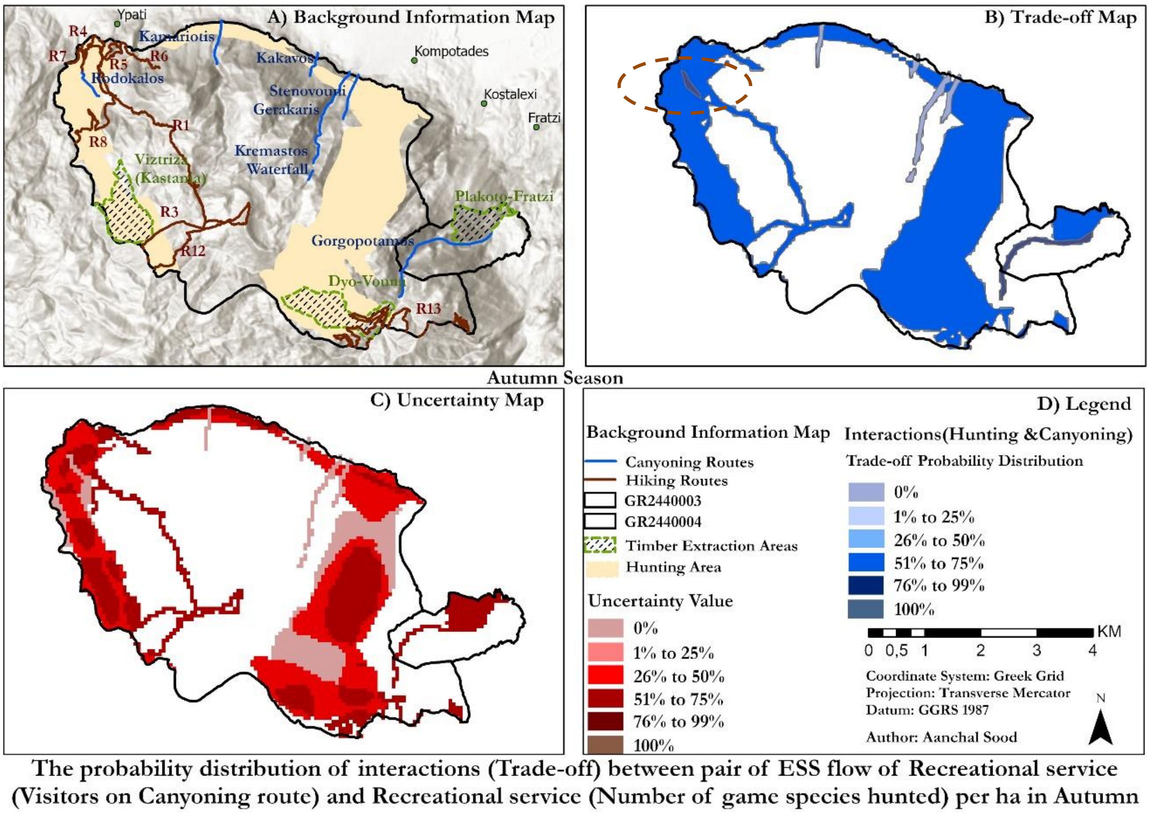


Figure 30 :Probability distribution of interactions between Recreational Canyoning and Hunting service along with the quantified uncertainty in their relationship, in Autumn

3. Visualization of pairwise interactions between ESS flow for Recreational Hiking and Recreational Hunting Services for all seasons

The interaction between recreational hiking and hunting in all the seasons varies between trade-off and no-effect. No-effect is observed when hunting does not take place in Spring. In these cases, the probability of having trade-offs is 0% with 100% certainty no interactions occur. The map has not been generated for Spring season.

The uncertainty involved in interactions between recreational hiking and hunting are the highest as the data collected for both the services was qualitative and has a lot of uncertainty and bias. The uncertainty map shows a range of uncertainty values for all the seasons showing hunting data has the highest uncertainty. Figure 32 shows that some hunting areas do not have hunting in Winter (ones in grey) and so the probability of interaction is 0%, and the uncertainty map shows 0% uncertainty. However, it is observed that recreational hiking has a different magnitude of a trade-off with recreational hunting in different areas. Also, hunting areas and hiking routes overlap in many places. Depending on the flow of the two ESS and the season, the magnitude of trade-offs is assigned to those areas.

In Winter (Figure 32), R1 and R5 have high visitors and hunting in those areas is also high; therefore it can be seen that probability of trade-offs at R5=100% as it completely overlaps with the hunting area and the uncertainty map shows 0% uncertainty of the trade-off occurring in that area. The probability of trade-off at R1 is 76-99% as there is partial overlap with the hunting area. The other routes R12, R6 and R13 have a low number of visitors; therefore, it can be observed that the probability of trade-off at these locations is low, 1-25%. Even though R3, R4, R7 and R8 have a medium number of visitors, but as hunting in those areas is high so these routes have a high probability of trade-offs (76-99% and 100%).

Similar observations are made during other seasons, with trade-off always being high at R1 and R5 and lowest in R6, R12, R13; except in Autumn (Figure 31), where during Autumn, the trade-off is high among ESS hiking and hunting (76%-99%) for R13 as ITI-Epic marathon has high visitors on a route in that season. Overall, it is found that there is a lot of variability in a trade-off between ESS of hiking and hunting over different seasons.

As there is no condition applied to restrict the interactions to areas where an overlap among the services takes place, therefore, the BBN shows trade-off at places like Gorgopotamos canyoning route and Plakoto Fratzi where there is no hunting or hiking yet BBN shows a high probability for a trade-off to occur, i.e. 76-99% in Summer (Figure 33) and Autumn (Figure 31) but the medium (51-75%) trade-off in Winter. Here the uncertainty map shows the uncertainty of trade-off to occur in these locations is high.

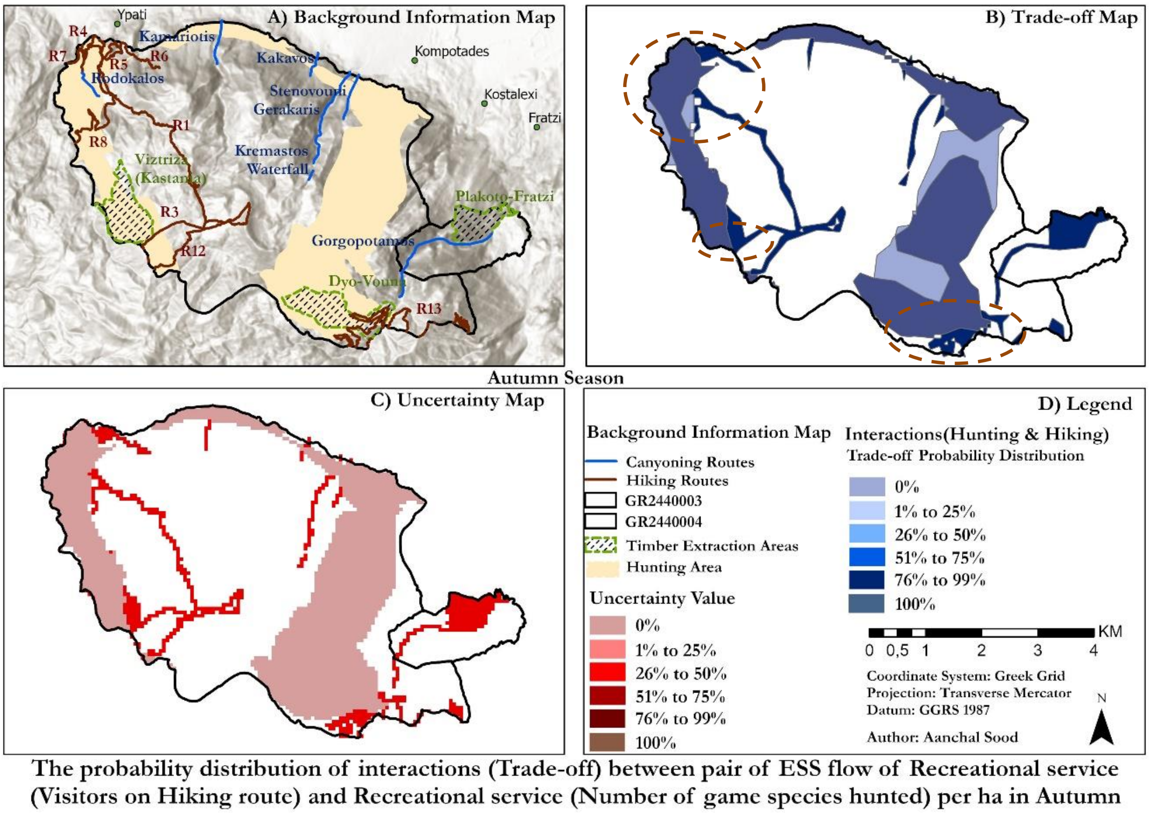


Figure 31: Probability distribution of interactions between Recreational Hiking and Hunting service along with the quantified uncertainty in their relationship, in Autumn

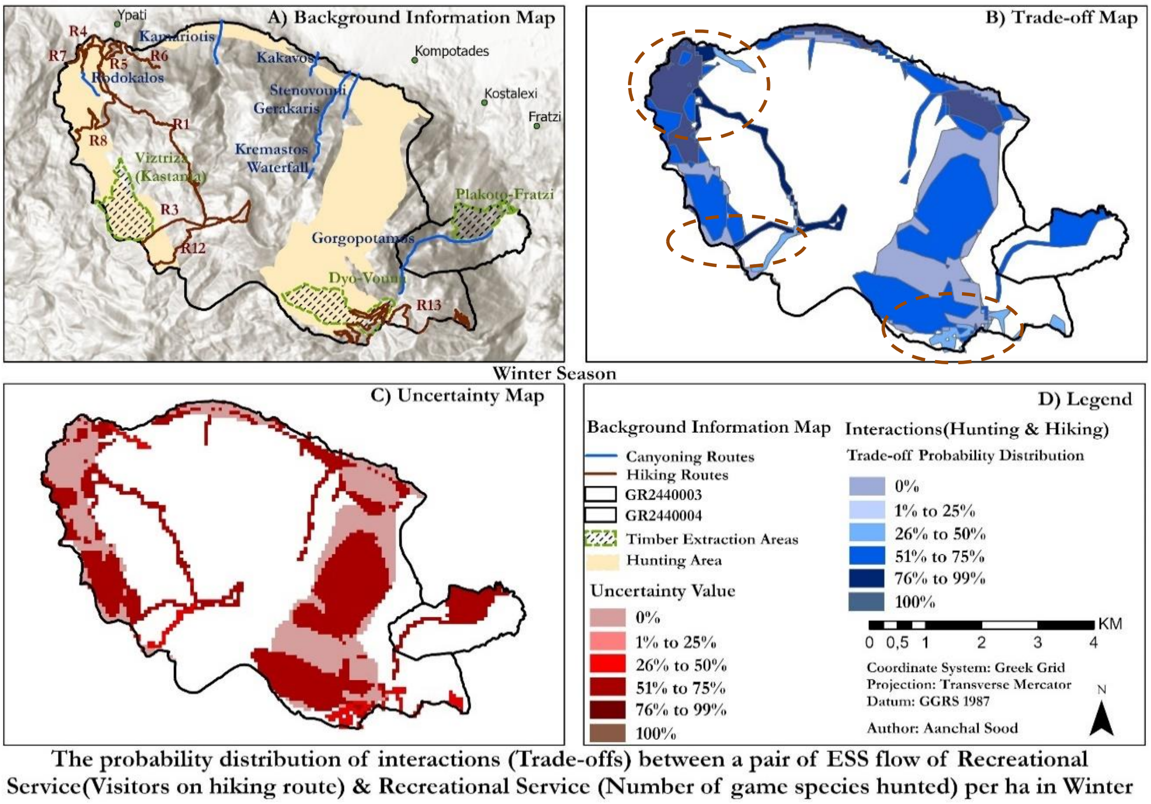


Figure 32: Probability distribution of interactions between Recreational Hiking and Hunting service along with the quantified uncertainty in their relationship, in Winter

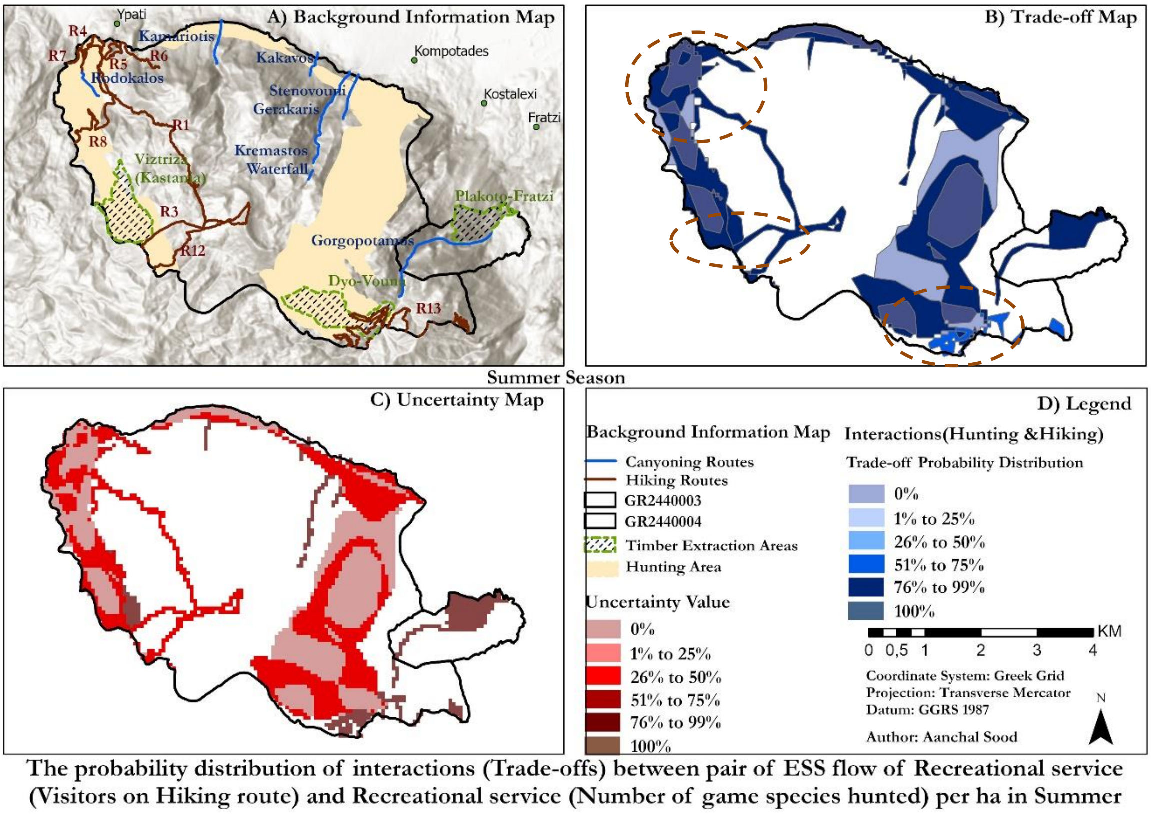
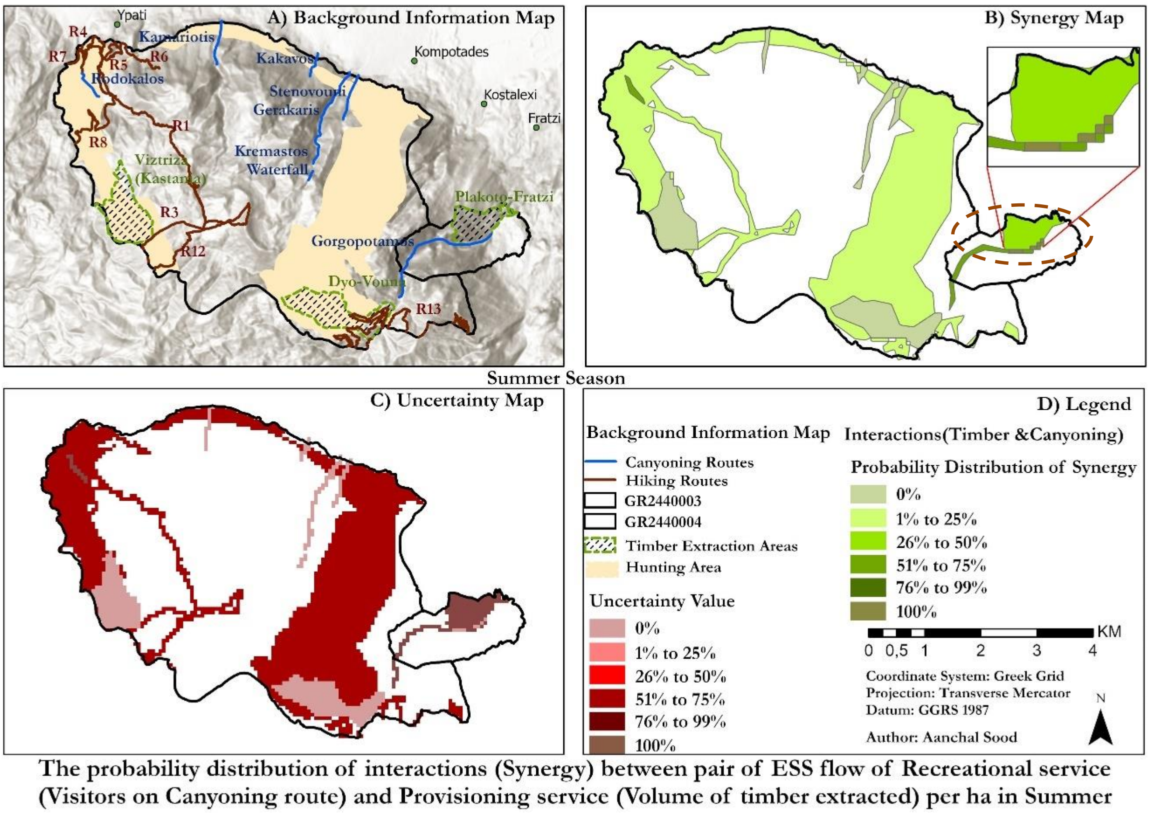


Figure 33: Probability distribution of interactions between Recreational Hiking and Hunting service along with the quantified uncertainty in their relationship, in Summer

Provisional Timber extraction and Recreational Canyoning Services

The provisional service timber extraction and recreational service canyoning only have interaction during Summer (Figure 34). There is no map produced for interactions of services with provisioning service: Timber extraction for Autumn, Winter and Spring as timber extraction doesn't take place in those seasons. The inset map shows the places where timber and canyoning routes intersect; they have a probability of synergy values = 100%. The surrounding areas of timber and canyoning routes which have no spatial overlap have 51-75% probability of synergy. This place (Plakoto Fratzi) has a high volume of timber extracted, and as mentioned more, the timber extracted better accessibility which favours recreational canyoning service. The A1 area of timber extraction has no overlap with the canyoning route, so there is no interaction, which is shown by the probability of synergy = 0% or probability of no-effect=100%. The canyoning route Rodokalos which also overlaps with the hiking route R5 shows 50% chance of synergy although there is no timber extraction in the area. This is again due to the way the network is structured and can be seen to have a high probability of uncertainty associated with. Therefore, this result should be ignored along with the probability values displayed along with the hunting areas. The timber extraction areas A1 and the other canyoning routes are accurately showing no interactions, i.e. probability of synergy = 0% and the associated uncertainty map shows the probability of certainty of this event to be true is 100% for the interaction. Therefore, overall, it is found that due to the assumption that ESS of timber extraction only has an impact when the timber is being extracted, therefore, the interaction during Summer has synergy with recreational service canyoning.

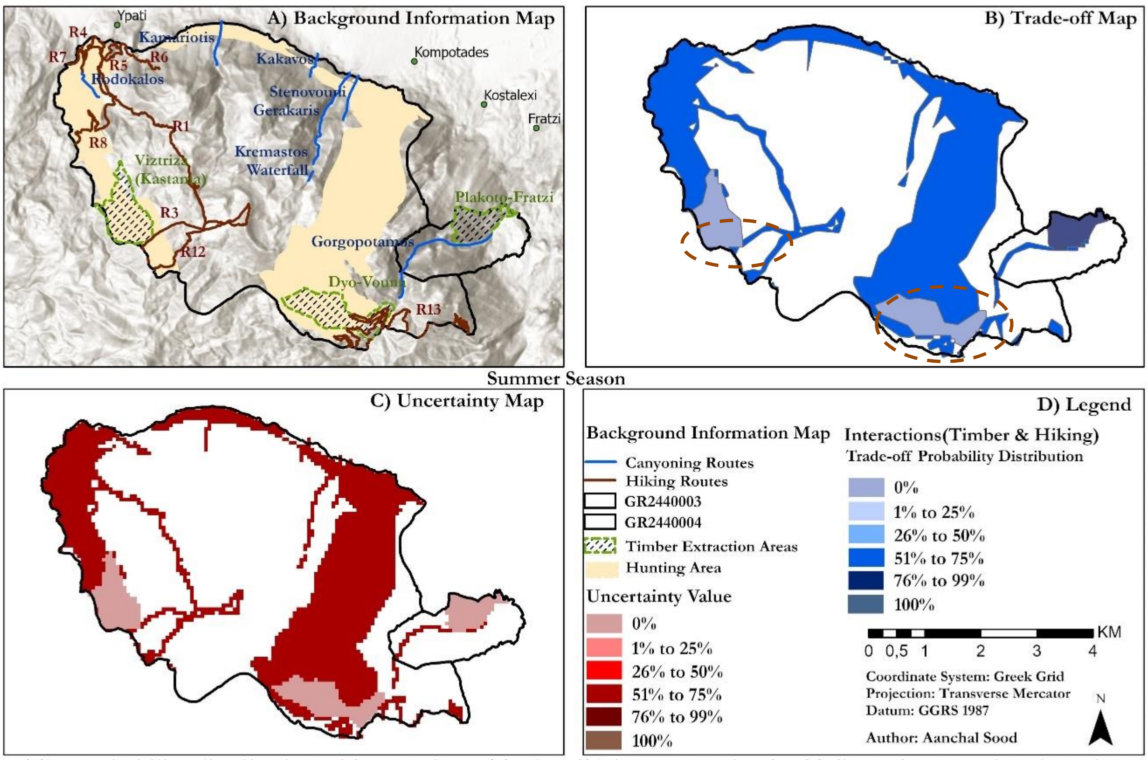


The probability distribution of interactions (Synergy) between pair of ESS flow of Recreational service (Visitors on Canyoning route) and Provisioning service (Volume of timber extracted) per ha in Summer

Figure 34: Probability distribution of interactions between Recreational Canyoning and Provisional ESS timber extraction along with the quantified uncertainty in their relationship, in Summer

Provisional Timber extraction and Recreational Hiking Services

These services only have interaction during Summer (Figure 35). There is no map produced for interactions of services with provisioning service: Timber extraction for Autumn, Winter and Spring as timber extraction doesn't take place in those seasons. The places where timber and hiking routes slightly intersect are at Kastania with R3 hiking route and Dyo-Vouna with route R13. The number of visitors on route R3 is high, and R13 is low during Summers, but as explained before, timber extraction has a stronger influence on a number of visitors on hiking routes, so the chances with low timber extraction having trade-offs are low. Therefore, even though there is a spatial overlap among the two services, still there is a no-effect relationship as probability of no-effect=100% at both these overlapping areas. The uncertainty map also shows there is 100% certainty for this relationship to be true in these areas. The area A2 where a large volume of timber extraction takes place has no hiking routes in the area though it gives trade-off probability with canyoning route Gorgopotamos. This should be ignored as again this is not a correct result which can be confirmed from the probability of uncertainty to be 51-75% associated to it. Therefore, overall, it is found that due to the assumption that ESS of timber extraction only has an impact when the timber is being extracted, therefore, the interaction during Summer is mostly no-effect with recreational service hiking.



The probability distribution of interactions (Trade-offs) between pair of ESS flow of Recreational service (Visitors on Hiking route) and Provisioning service (Volume of timber extracted) per ha in Summer

Figure 35: Probability distribution of interactions between Recreational Hiking and Provisional ESS timber extraction along with the quantified uncertainty in their relationship, in Summer

Provisioning service: Timber extraction and Recreational Hunting Services

There is no map produced for interactions of services with provisioning service: Timber extraction for Autumn, Winter and Spring as timber extraction doesn't take place in those seasons. Map for Summer is generated and shown in Figure 36. The areas showing 0% probability of trade-off are areas where hunting doesn't take place during Summers. Therefore, even the uncertainty value associated to those pixels is 0% which means high certainty of this event to be true. As during Summer season, the ESS hunting is low where they overlap with low timber extraction areas. Therefore there is no trade-off observed. Instead, the areas show a 100% probability of having no-effect (0% trade-off) with 0% uncertainty value in uncertainty map indicating the interaction type to be true. The Plakoto-fratzi timber extraction area has a high volume of timber extracted, but there is no hunting in the area. The probability values of the trade-off between ESS of hunting and timber extraction in those areas are high, 76-99% but do not represent reality and should be ignored. The uncertainty map shows 51-75% probability of uncertainty (medium uncertainty) of providing this information about these interactions. Though there is a huge overlap between hiking and timber ESS yet the interaction outcome is no- effect as the two areas hightlighted either do not have hunting in those areas or have a low number of animals killed in those areas during Summer. Also, the timber extracted in those areas is low. So overall provisioning ESS timber extraction has a no-effect relationship with cultural, recreational hunting ESS during Summer.

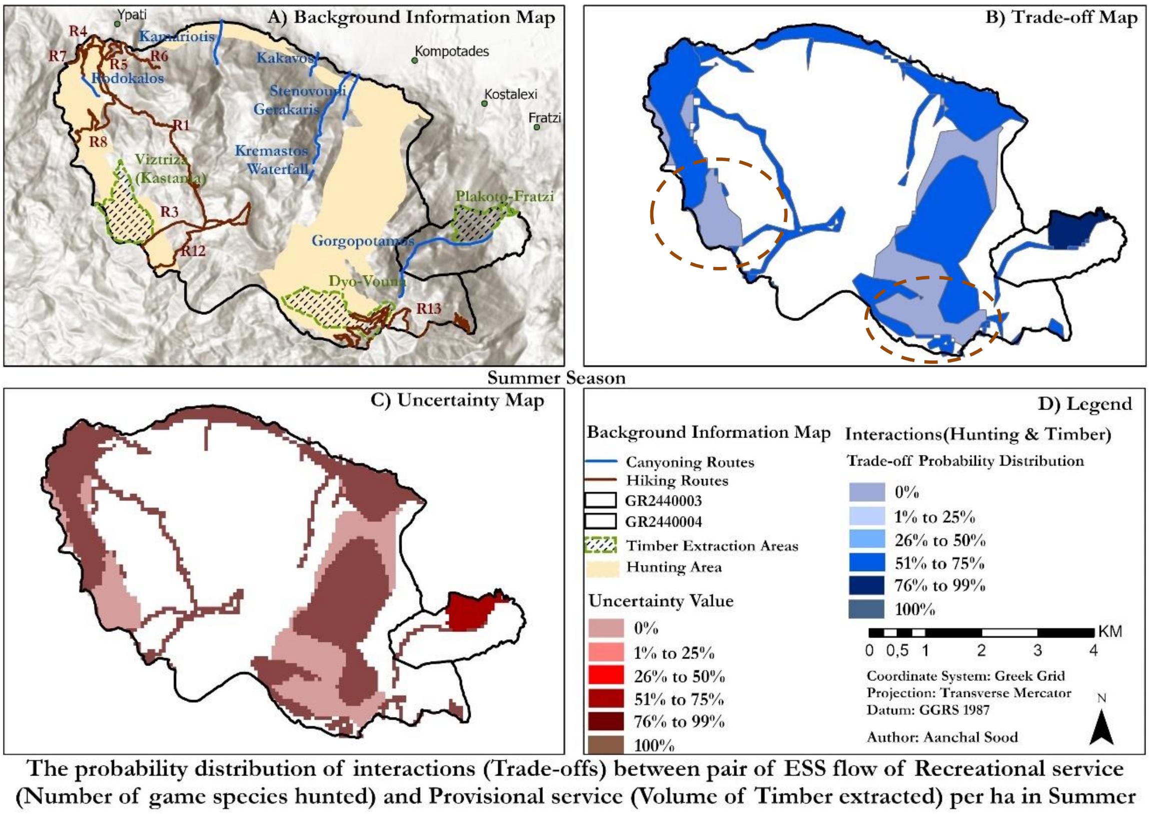


Figure 36: Probability distribution of interactions between Recreational Hunting and Provisional ESS timber extraction along with the quantified uncertainty in their relationship, in Summer

The uncertainty maps can help make a choice among several alternative decisions by looking at the level of certainty about an output. The hunting data mostly can be seen to have high uncertainty; therefore, the Management Body can decide to collect more information about hunting activities and also make decisions keeping in mind the level of certainty they have in an area to have interactions.

Cumulative interactions (trade-offs and synergy) maps over four seasons

The cumulative maps of interactions show the areas where the probability of having synergies and trade-offs is high (75-99%, 100%) in a season. It integrates information on the quantity of ESS produced in the area. These maps help to identify areas of priority management as there is a high certainty of these interactions to happen in those locations. The Management Body has been mentioned to have limited resources available to manage huge areas. In such a case, maps like these can help the Management Body to identify places of priority management during different seasons, who can then prioritise the management actions to these areas to decrease the trade-offs and enhance the synergy looking at the overall impacts of their decisions using the BBN.

The cumulative probability maps show areas having either trade-offs or synergies above a threshold value of 75%. The 75% value was chosen such that it represents higher certainty of being in a particular state, an example being 75% sure to have synergy in that pixel. Besides that, as discussed before, there was a limitation in the network the model assigns probability values to areas where particular interactions cannot happen. Looking at the uncertainty map, such areas have high uncertainty values associated with them so a choice was made to represent only those areas which have high certainty of events to occur by checking the uncertainty maps and also looking at the interaction types whose probability to happen with certainty in the area is high. The cumulative map has a pixel's value calculated as a sum of probabilities of two states (trade-offs and synergies) greater than a threshold value. The dark violet colour shows areas for high priority management during all seasons, and the light purple shows priority areas for management. High priority areas are those areas which have a probability of interaction = 100% while priority areas are those which have a probability of interaction = 75-99%.

An area with one ESS bundle was identified among recreational ESS of hunting, hiking and canyoning (area of Rodokalos canyoning and route R5 of hiking) which have a high probability of interactions happening. This result was expected as it can be seen that it overall seasons there are always visitors on the hiking as well as on canyoning routes. The hunting also takes place in all seasons except Spring. So from maps (37, 38, 39, 40), this area is seen to have a high priority for management purpose in seasons.

Another ESS bundle area was identified with normal mapping which has ESS of hunting, hiking and timber extraction (Hiking routes R3 and R13, timber extraction area A1). But based on the trade-offs and synergies identified and their quantification, it was found that the ESS bundle of hunting, hiking and timber extraction all through the seasons have no-effect as the flow of these services over the seasons is not high. Thus, the Rodokalos canyoning route – Hiking route R5 area has the highest amount of interactions and incase of prioritization this area should be of utmost importance. This shows us the advantage of quantifying the relationships and identified ESS bundle areas over normal mapping as it helps to make well informed decisions and saves lot of time and resources.

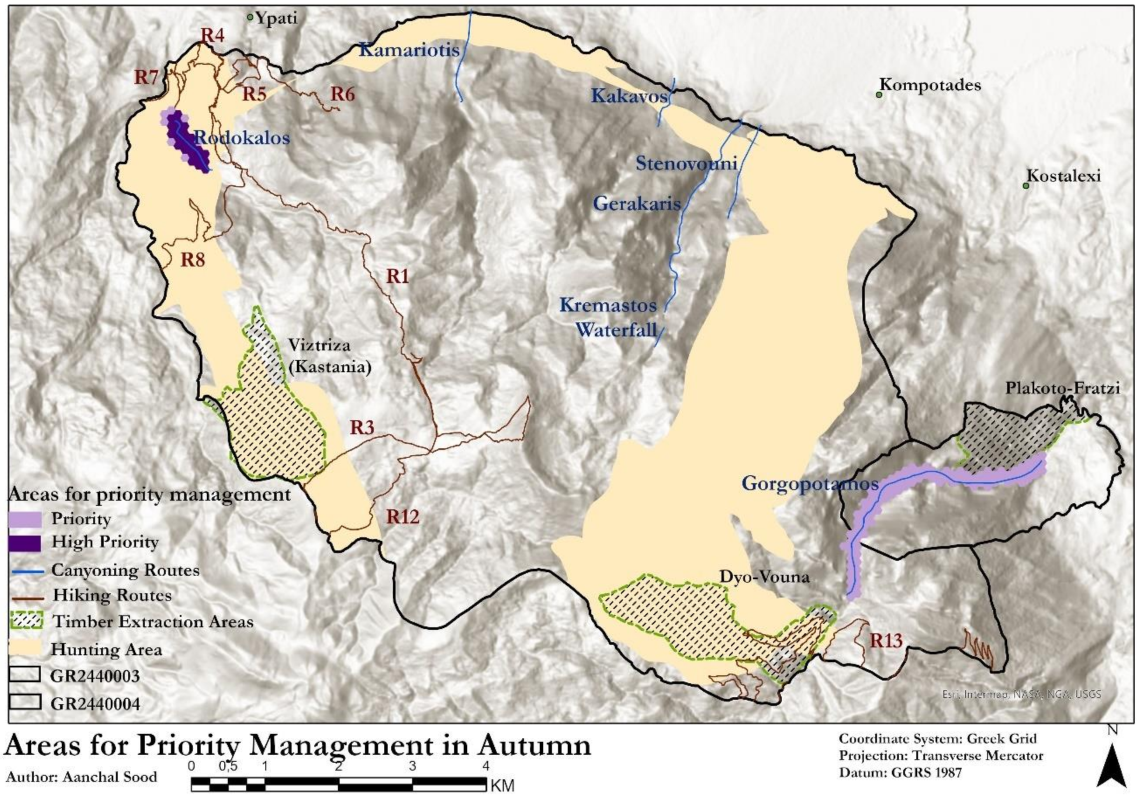


Figure 37: Priority and High priority area for management identified by creating a cumulative map for Autumn in the study area

During Autumn (Figure 37), the area around the Rodokalos canyoning route and Route 7 for hiking needs high priority management. This is because this area provides three ESS whose magnitude is high. Though ESS of hiking and canyoning have synergy and both services, have high ESS flow during Autumn, yet this place also has a high number of kills taking place in the area. Hunting ESS has trade-off with canyoning ESS and also hiking ESS. So overall, it can be said that though the area is a hotspot of ESS, yet all the services cannot occur together due to the nature of activities and interactions among the beneficiaries. This area, therefore, has the possibility of high trade-off and might need priority management decisions in Autumn.

The Gorgopotamos canyoning route, on the other hand high flow of recreational canyoning ESS but there is no interaction with any other service in that area during that season. So that result shows inaccuracy and can be ignored.

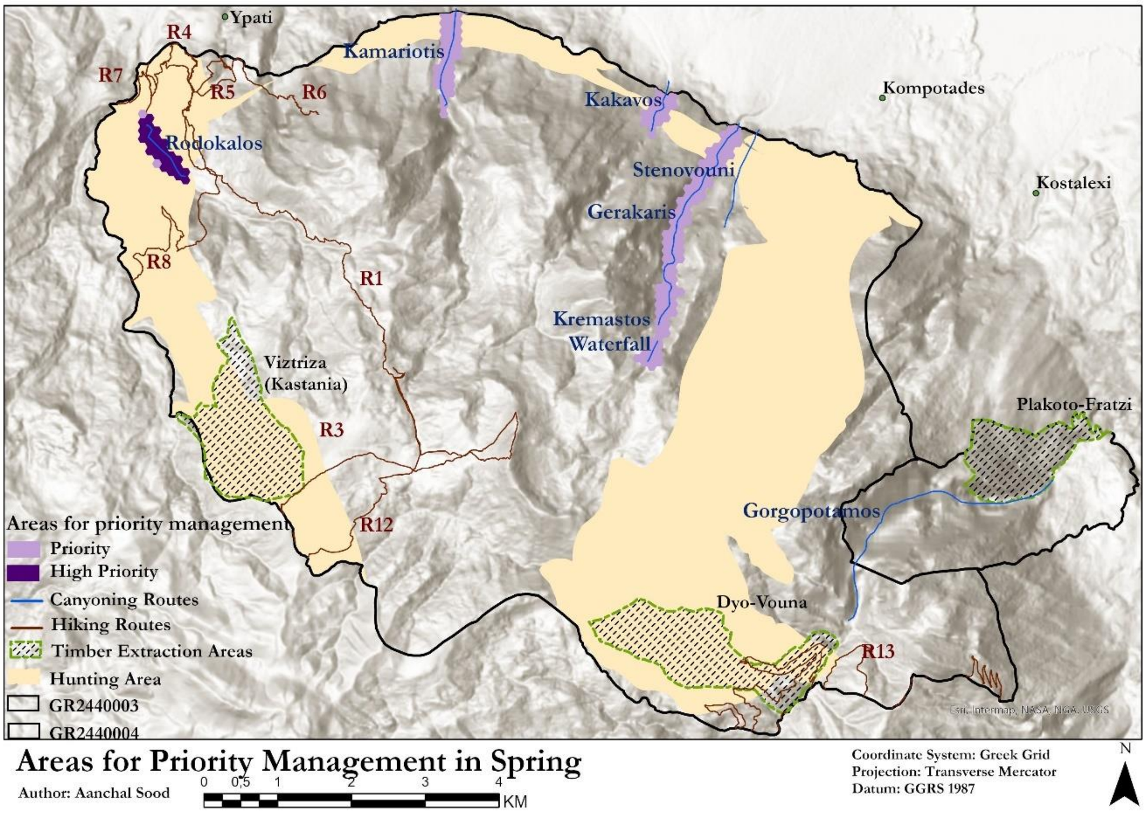


Figure 38: Priority and High priority area for management identified by creating a cumulative map for Spring in the study area

During Spring (Figure 38), the area around the Rodokalos canyoning route and Route 7 for hiking shows that it needs high priority management. There is only two ESS interacting in that area with high magnitude, i.e. ESS of hiking and canyoning. Due to the nature of activities and interactions among the beneficiaries, the two activities have a synergistic relationship. Landuyt et al. (2016) had mentioned that a place could attract a lot of visitors, but beyond a threshold, it may have a negative or a repulsive effect. As mentioned by the experts that people like to visit those routes which are far away from human influence, so having a greater number of visitors can have a negative effect on both hiking and canyoning ESS. Therefore, the area might need to be managed with priority during Spring.

Some canyoning routes towards the North of the study area have a high flow of recreational canyoning ESS, but there is no interaction with any other service in that area during that season. So that result shows inaccuracy and can be ignored.

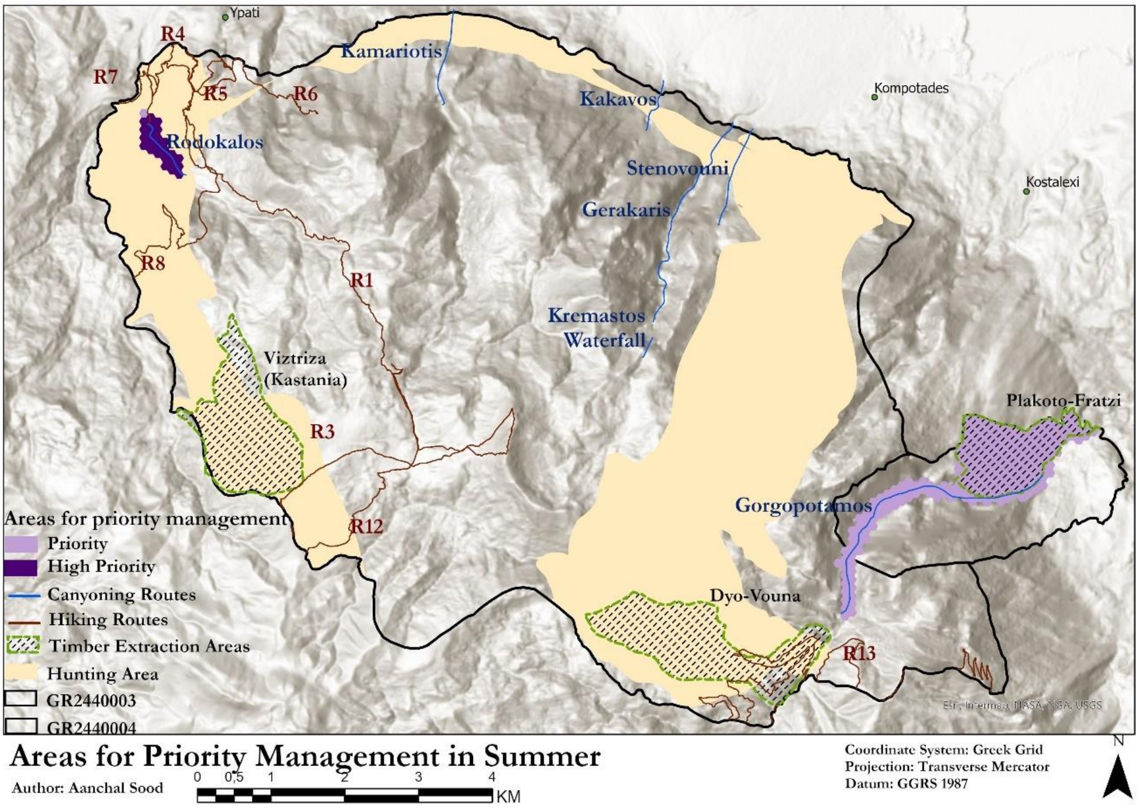


Figure 39: Priority and High priority area for management identified by creating a cumulative map for Summer in the study area

During Summer (Figure 39), the area around the Rodokalos canyoning route and Route 7 for hiking shows that it needs high priority management. There are three ESS interacting in that area during Summer. The two with high magnitude, i.e. ESS of hiking and canyoning and one which can be low or not occurring in that area at all during Summer. Due to the nature of activities and interactions among the beneficiaries, the two activities have a synergistic relationship. Although with recreational hunting ESS, both the other services have a trade-off relationship, as the magnitude of recreational hunting ESS is low or zero, so the interaction is no-effect. Therefore, the management actions need to be similar to Spring season depending on the magnitude of synergy the two services: recreational hiking and canyoning have with each other.

The other location that has a synergistic relationship during Summers is the area around Plakoto Fratzi. Due to high volume of timber extracted from the area, the accessibility to the Gorgopotamos canyon might have increased (need more information on that part) which might have led more people to visit the route for enjoyment. Therefore it shows synergy, but as mentioned before, a repulsive effect can be generated if a large volume of timber is extracted as the landscape beauty is destroyed the area might not be preferred by canyoners anymore.

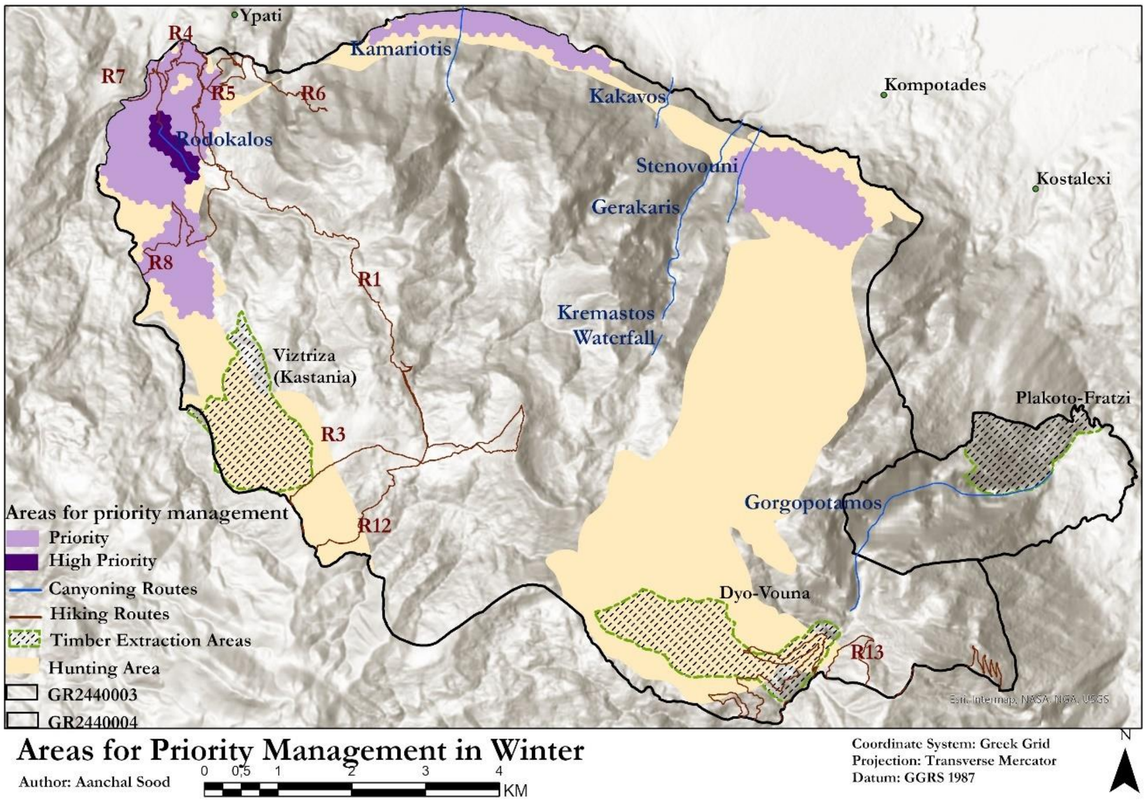


Figure 40: Priority and High priority area for management identified by creating a cumulative map for Winter in the study area

During Winter (Figure 40), the area around the Rodokalos canyoning route and Route 7 for hiking needs high priority management. This is because this area provides three ESS whose magnitude is high. Though ESS of hiking and canyoning have synergy and both services, have high ESS flow during Winter, yet this place also has a high number of kills taking place in the area. Hunting ESS has trade-off with canyoning ESS and also hiking ESS. So overall, it can be said that though the area is a hotspot of ESS, yet all the services cannot occur together due to the nature of activities and interactions among the beneficiaries. This area, therefore, has the possibility of high trade-off and might need priority management decisions in Winter.

The priority areas, on the other hand, show the high flow of recreational hunting ESS but during Winters no other canyoning route has visitors. So, the result in the north top of the study area can be ignored as they are inaccurate. The hiking route 8 has a medium number of visitors and hiking is high in Winters in that area. Therefore, there can be some trade-off in that area which is shown as a priority area for Winter management purpose on the map.

Part 2: Model Validation

1. Face Validation

The validation happened with one expert from Management Body as described in section 3.2.4 Part 2.i. The expert was not familiar with the working of the BBN and therefore acknowledged the BBN walkthrough was helpful. As the expert was one of the two who had helped during initial discussions to define terminology and collect data, she was able to quickly understand the interlinkages between the nodes and the causal structure of the network. She found the structure of the model straightforward and easy to understand. The only comment she had was about the way the ESS flow nodes were feeding the interactions node independently. Instead, she had expected the ESS flow nodes to have links in between them if they directly impact each other and also some other factors to be included in the network when the ESS flow nodes did not have direct relationships. She was informed about the limitation of the BBN to handle feedback loops and was informed about the assumptions that had to be made to keep the model simple and workable. Once the working of BBN was explained to her along with assumptions made, she agreed with the present structure of the BBN.

She also found discussing the CPT values, as percentages rather than values varying between 0 and 1 was more understandable. The logic for CPT was based on expert's definitions of the interactions, and therefore she could relate to the way the CPT was filled. There were no comments or suggestions regarding the CPT.

The expert found it difficult to understand the map in first go as the map gave probabilities of interactions associated with areas. Then a brief example was given to her about the way the map was needed to be interpreted, and she found the results to be very useful. She acknowledged that she was very familiar with the study area, yet the map provided a more detailed insight into different places that during different months would need their attention. She said the quantified interactions map could help in prioritising the areas to manage better in a well-informed manner based on the results. The information about uncertainty was initially confusing, but on explanation, she appreciated the model output. She said the map and the BBN could be useful for framing opinions and have these modelled quantified outputs as evidence to back their opinions.
She said that the model produced a good representation of accumulated expert knowledge, and the map helped to validate the results as the expert was able to relate the outputs with the local knowledge thereby increasing the trust in the output of the model.

Therefore, face validation of the results with the expert-led to checking the output of the network that it behaves in a logical way. The effects of seasons on the interactions and the places were identified by the expert.

2. Sensitivity analysis using mutual information

In general, the resulting maps had a different value of uncertainties and sensitivity analysis identified its key influencing factors. The change of influences was observed when the states in seasons node were selected and when no evidence is set on the season node (i.e. the network has no additional information input to it). As expected, when any state in the season node is selected, an overall decrease in uncertainty of target interaction nodes was observed. Due to a multitude of outputs, only one example is explained in detail below related to Interactions (Hunting & Hiking) node while the rest of the charts are appended into the Appendix E.

➢ **Target Node: Interactions (Hunting & Hiking) node**

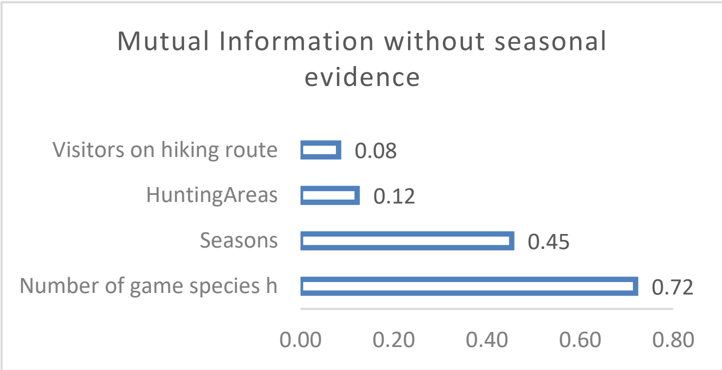


Figure 41: Mutual Information of node Interactions (Hiking & Hunting) with no evidence on seasons node

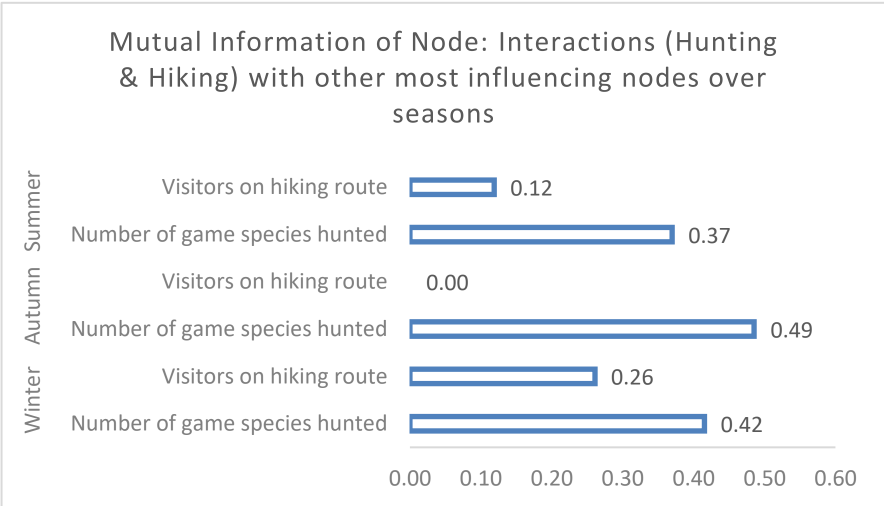


Figure 42: Comparison of mutual Information of node Interactions (Hiking & Hunting) with evidence of Winter, Summer and Autumn on seasons node. No hunting during Spring so no interaction, therefore not used

Interactions (Hunting & Hiking)

Figure 41 shows that the target node Interactions (Hunting & Hiking) is more sensitive to the node number of game species hunted than the node number of visitors on hiking routes. It can be observed from Figure 41, the mutual information of game species hunted node is the highest (0.72), which tells us that number of game species hunted node has the strongest impact on the interactions among the two services followed by seasons and volume of timber extracted. The visitors on hiking route has a relatively very small influence (0.08) on the Interactions node. Seasons node has great influence as well (0.45).

This information about ESS: recreational hunting being more influential is in accordance with what the experts had described during the interviews. They had mentioned that if there are a high number of animals being hunted, which means the flow of ESS is high, it has a greater impact on visitors on the routes, who have to leave the area. Therefore, visitors on hiking route receive low/no benefits from the recreational service (hiking) in this case. On the other hand, if there are a large number of visitors on the hiking route, in the same area as the hunters, it causes inconvenience to the hunters, but they do not stop their sports activity. So, there is still a flow of recreational hunting ESS.

Once the evidence is set on the season's node (Figure 42), the changes in the information provided by the nodes can be observed when Season is provided evidence: Season = Autumn, then the mutual information of interactions with Visitors on hiking route node = 0. This means that there cannot be any entropy reduction using the visitors on hiking node as it has no more information available to contribute to interactions anymore, however, as the mutual information for the number of game species node is 0.49 (high) which means that this node can further explain the interactions. It can be inferred that in order to answer more accurately about the interactions between the two services, most useful data to be collected would be about a number of game species hunted so as to decrease the uncertainty involved in the prediction of the interactions. The difference in contributions during different seasons can be observed from the BBN.

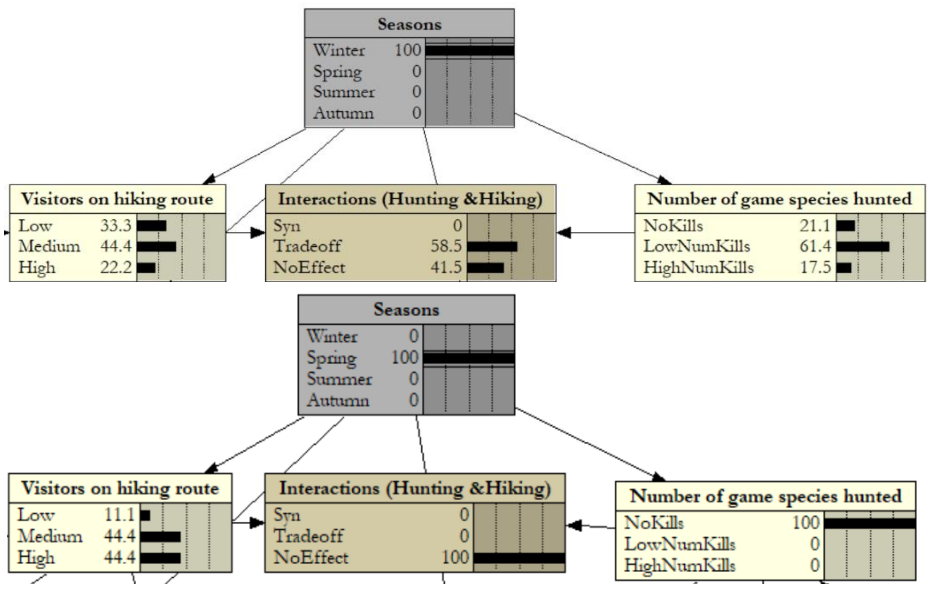


Figure 43: The probability distribution values among states of ESS flow nodes and interaction node (hunting & hiking) for winter and spring

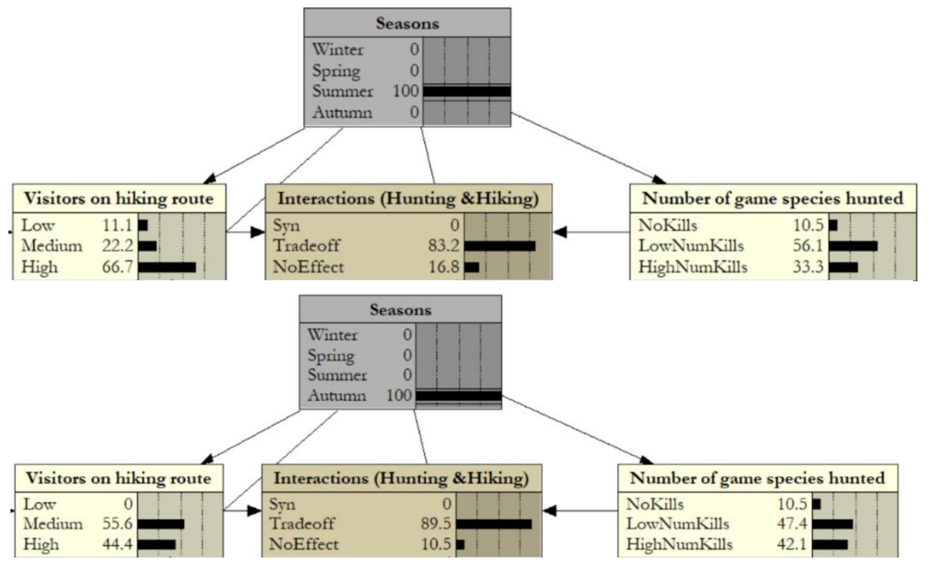


Figure 44: The probability distribution values among states of ESS flow nodes and interaction node (hunting & hiking) for autumn and summer

It can be observed that the probability distribution of a number of game species node for different seasons varies and is rather flat for the season's evidence: "Autumn " when compared to a probability distribution in "Summer" (Figure 44). If the probability distribution is uniform, then it represents maximum uncertainty. As certainty increases, the node will tend to have a peek at one state. This can be observed for "Spring" season where due to ban in hunting, the number of game species that can be hunted is certainly 100% NoKills. Therefore, if new evidence was entered into the game species node for the season of Autumn, the game species node has higher uncertainty for Autumn, so more changes in interaction will be observed in the target node. Similarly, if the variability in output node is small, then it is likely that there is less uncertainty about that value in the node. Therefore it is observed that a number of game species node has a greater contribution to probability values of (Interactions) target node and this information can later help the end-user to take adequate measures to reduce/enhance the probabilities of the target node events as desired. Other studies (Nicholson & Jitnah, 1998; Landuyt et al., 2016; Zou & Yue, 2017) that performed a sensitivity analysis using mutual information to detect the influential nodes have suggested that the most informative nodes should be selected while carrying posterior probability computation as this node provides the most information about target node, which has also been observed in this study. The result of the mutual information for the rest of the interactions are attached in appendix E.

Taking another example of Interactions (hiking and canyoning), the CPT can also be validated from another aspect. The mutual information figure A 23 & 24, show that the number of people on hiking route node has little to zero contribution to the interactions node which can also be tallied from the fact that the interaction between canyoning and hiking is unidirectional and direct (4.1.Part 2. Figure 14) from recreational canyoning to hiking. The mutual information agrees with the fact, thus validating the CPT. Therefore, the BBN shows the difference in the strength of causal relationships between the two variables (the ESS flow nodes) and highlights the sensitivity between the variables. Similar results were obtained for the other services which had a unidirectional relationship, and no exception was found.

Also, the expert who validated the model was informed about the Bayesian network having the capability to find out the factors that had more influence on the output by using mutual information as an indicator. The expert mentioned that this feature too, would be very useful as it would help to relate their knowledge with the model output. In case of any discrepancy in results and belief of the experts would help them to understand the system even better once the underlying CPT for those nodes is checked. Also, this feature would be useful to know during which seasons which factors have a higher influence on the target node so that well-informed decision could be made.

The mutual information helped to validate the logic used to fill in the values into CPT as described in detail in the Results (4.4.1. Part2). The node with the strongest influence with respect to a target node was identified and the outputs generated through sensitivity analysis matched with the description provided by the experts, therefore, validating the CPT values and working of BBN. This was the case with all the interaction nodes.

5. DISCUSSION

This study demonstrated the use of spatial BBN to show seasonal changes in ESS interactions over space and across seasons and produce maps for their visualisation. A choice of the study sites was made to implement the study. As the chosen sites to work on were Natura 2000 sites of protected habitats, the choice of the selected sites gave an opportunity to work with the less assessed ESS. It was highlighted by Vlami et al. (2017) that cultural ESS in Greek protected areas have not been assessed and discussed the importance of assessing these services in order to stop the degradation of cultural landscapes, spread awareness and promote cultural services in Greece's protected areas. Out of the initial list of eight selected ESS, a final four were chosen out of which three ESS of priority for the Management Body of Mt. Oiti were cultural services of recreational hunting, hiking and canyoning. Even though Crouzat et al. (2016), looked into the relationship between the different components (supply, flow and demand) of ESS like wood production, leisure hunting and nature tourism but they used an influence diagram to describe the relationships between ESS. This is the first time where a study is conducted to model the seasonal variations in ESS interactions focusing on flow component among the above mentioned cultural ESS and provisional service like timber extraction.

Due to low availability of data, which has been mentioned by many studies (Uusitalo, 2007; Landuyt et al., 2013; Landuyt et al., 2015; Kleemann et al., 2018) data was collected through expert interviews, which has been mentioned by Kleemann et al. (2018) & Aguilera et al. (2011) as one of the most commonly used methods in data collection and validation processes of BBN. The initial plan was to organise focus group discussions to obtain expert knowledge, but due to the low availability of the experts, face-to-face interviews had to be conducted. This saved time and resources, but the interviews were based on the opinion and judgment of individual experts and therefore, might have added a lot of bias to the study. Schmitt & Brugere (2013) mention that consulting diverse experts increases the robustness of the model. Landuyt et al. (2016) suggested that multiple experts from within multiple research domains should be interviewed for collecting data through BBN's can be built easily from knowledge acquired from a single expert Single expert-based BBN can be perceived as subjective or unscientific thus threatening the credibility of BBNs. However, for this study, care was taken to include experts from different departments for interviews, which allowed an overview of system components, their relationships and understanding of the system from different perspectives.

Similar to the findings of Crouzat et al. (2016), it was found that experts from different departments had different knowledge and perceptions about the same socio-ecological factors in the area. Therefore, to come to a common ground, common terminology had to be introduced, which might have added some bias during the data collection process. In similar terms, Landuyt et al. (2016) mentioned that the data collected can have uncertainty associated with people's preference and demand for ESS. Further data classification for analysis and visualization could add higher value to uncertainty. These sources of uncertainty are identified in the study, and the uncertainty maps provide a spatial representation of uncertainty related to the interaction. The study exploits the advantage of using BBN, which accounts for uncertainty explicitly. Communication of uncertainty helps the decision-makers to be aware of the risks of certain decisions, who can then decide to choose or refrain from making those decisions.

The creation of the influence diagrams has brought forward a lot of interesting findings. The aim was to develop a model structure that represented the system as close to reality as possible. During the interviews, information about different ESS components (supply, flow and demand) was discussed so as to get the understanding of system components and their relationship. The findings are in accordance with Crouzat et al. (2016), who mentions that some relationships would not have been revealed if these components were not considered. This can be understood from the fact that the same ESS pairs can have different relationship depending on the factor of influence being considered. For example (4.4.1.Part 2.ii), influence diagram (Figure 17) shows the relationship between the flow of provisional timber extraction service and recreational hiking service. A choice had to be made about which factor should be considered in order to model the relationship between the two services to keep the model simple. The experts were asked to choose one factor which they thought was the most influential that would define the most realised relationship between the services. Therefore, it is important to highlight that if the choice of factors was different from what was selected by experts, the type of interactions among the services might be different. The output, in that case, can be a very different representation of interactions. For example, the volume of timber extracted leads to increased accessibility of the inaccessible area, which can increase the number of people going for hiking. This has a positive effect, and therefore the two services can have a synergistic relationship. But the factor that the experts considered was most influential in defining the relationship between provisional ESS timber and recreational hiking ESS, was the destruction of hiking paths. This leads to a decrease in the number of visitors on the route, thus affecting the flow of recreational hiking service. So, the choice of influential factor played an important role in defining the type of interactions between the services. These factors are drivers of change, and from a study, it can be seen that it is important to investigate them along with the interactions. The scope of this study limited to look into the season as driver of change, but the studies in future can explore the impact of different drivers alongside season to get a bigger and detailed picture of interactions among mentioned services. Mouchet et al. (2014) and Landuyt et al. (2016) mention the importance of investigating drivers along with the interactions among services mentioning how knowledge on drivers can influence interactions among services. Also, Bennett et al. (2009) mentioned that without the knowledge on drivers that cause changes in ESS, the research on interactions is incomplete as, without knowledge on what causes interactions and how they can be changed, the synergy and trade-offs cannot be managed.

Also, the interactions between ESS were described based on the kind of relationship the experts thought the stakeholders had with each other rather than the relationship between ESS, as the component of focus was ESS flow. Small, Munday & Durance (2017) also mention that the ESS might have many different beneficiaries who share the ESS, yet, the most significant source of trade-offs could rather be due to multiple uses of ecosystems, than sharing of the ESS (As observed from the relationship between Recreational hunting and hiking). Depending on the ESS of priority for different experts, the experts view the relationship among different ESS differently. As this makes the interactions context-dependent, therefore coming up with a general trend becomes difficult. So, a similar ESS assessment would need to be adapted to local data and the local context.

The interactions were defined like synergy, trade-off and no-effect based on Bennett et al. (2009). While identifying the relationships between the services with the experts it was realised that there was a mismatch of definitions of these services as this research looks into social-ecological systems in which the social interactions also influence the relationships along with the ecological changes in ESS. Therefore, the definitions were adjusted to fit with the situations on the ground among the receivers of the benefits. While filling in the CPT, if the states of the two parents are high, according to the ecological framework, it should represent synergy. But looking at the flow of recreational ESS, the interaction among services also depends on the user group characteristics and their relationships with each other. Therefore, as seen from the influence diagram, that relationship between recreational hunting and hiking or recreational hunting and canyoning is inverse. Therefore, any these services have trade-offs. Similarly, recreational hiking and canyoning have synergy. Also, as these interactions have been defined for these services, therefore the parent node combination gives a probability of the interaction node to be in one of the states, i.e. trade-off, synergy or no effect depending on how the relationship of these services is on the ground. The no-effect also has a different definition. It includes those parent combinations of ESS which show a weak relationship with each other. For example, if there are a low number of visitors on hiking routes and a low number of hunters in the same area, then though it causes inconvenience to both the user groups, it does not cause one to increase and other to decrease. It becomes a weak association and therefore put in the no-effect category.

It was also observed from the fully functional BBN (Section Figure 23), that based on the way the CPT for the target nodes was defined, either trade-off or synergy was assigned a zero chance of occurring when no evidence was provided in-network. This result shows the reality of interactions between the pair of ESS on the ground and also reflects on the choice of factors selected to represent the most influential factors which determine the relationship between the services. When the evidence is added to the network, it is observed that a change in interactions among the services only takes place either between trade-off and no-effect or synergy or no-effect but not trade-off and synergy as the CPT have been defined according to the relationship between the beneficiaries of two services on the ground. The relationships are based on user group characteristics, so a trade-off does not transition to synergy and vice-versa but to no-effect based on the change in the magnitude of occurrence of both the service flows.

As uncertainty means lack of knowledge, therefore, areas with high uncertainty can be chosen as grounds for more collection of data and monitoring. This can help the decision-makers to be familiarised with the area and develop a better understanding of ESS provided by the area and their interactions. The uncertainty map provides quantified information about the certainty of an ESS interaction happening at a location. It can be helpful to Management Body with a limited number of resources to prioritize areas with a high certainty of trade-offs for paying immediate attention to the ground. Once solutions for such areas are in place, then the Management Body can focus on other areas which have higher uncertainty of the relationship between ESS. Also, as the data is collected through interviews, it informs the experts about the knowledge they have about locations in the study area.

Large uncertainty is observed in the area for each season for recreational hunting and hiking as the data for these services was qualitative and collected from expert interviews. These uncertainties could not be improved as no other data was available with the experts except what they had already shared. Similar results were observed by Grêt-Regamey et al. (2013) in their study for the recreational model.

Crouzat et al. (2016) mentioned that it would be interesting to note whether ESS interactions change due to seasonal fluctuations. It is evident from the results that relationships observed between services in space do not remain the same across seasons. Similar to the findings of Hou et al. (2017), this study shows that for different ESS, the interaction patterns change over seasons. These patterns depend on the ESS being modelled along with information about the component being looked at. ESS can have different interaction patterns due to various factors controlling its supply or demand which control the flow. Therefore static assessments cannot give a complete picture of interactions as mentioned by Lautenbach et al. (2019). The results also show that there is a change in the magnitude of ESS during different seasons with the increase and decrease in the flow of service. Example, the canyoning routes during different seasons have a different number of visitors on the same route. It can be observed from Appendix B Figure A3, that during different seasons ESS flow of recreational canyoning service varies in magnitude and in space (different location of routes). Route 7 has a high flow of ESS throughout the year while route 1 has low flow during Autumn, high flow during Summer and no flow during Winter and Spring. Therefore the results show that seasonal changes introduce changes in management decisions (as in case of timber and hunting) and social practices and preferences (like in case of hiking and canyoning) which may lead to change in magnitude and relationship among the services in space. Thus, the model is able to show that seasonality can help to understand different characteristics of socio-ecological dynamics.

Another important thing to keep in mind is that different ESS behave differently over time. So, the appropriate temporal scale needs to be selected in order to observe the changes in interaction patterns. This has been discussed by Hou et al. (2017) who mentioned that interaction patterns of services could differ in temporal scales like seasons, months, years or decades due to variations in the intra-annual and annual provision of services. In this study, it is observed that different areas have more people visiting them during different seasons and no of visitors from no to high visitors. If such information was observed over the year, all these variations would be lost as an average for the year would show visitors on all routes in a year, which would definitely not show the reality.

6. LIMITATIONS AND RECOMMENDATIONS

- The study was conceptualised to model all type of ESS, i.e. provisioning, cultural and regulatory services but besides the limited time and resources available to conduct the study, selection of ESS was controlled by data availability, expert availability for interviews, spatial overlap between services and services of priority for Management Body. As there were more services identified in the protected area, if there were more time and data available, a different set of ESS could be chosen which would lead to the selection of different priority areas and generate different ESS interaction results. Landuyt et al. (2013) also mention that choice of ESS to be included or ignored makes a strong impact on the results of the model.
- In order to build a BBN, experts need to be involved in the design phase and throughout the construction of the BBN. The involvement of experts needs to be an iterative process with their inputs flowing in several times (Höfer et al., 2020). But due to limited time available for a field visit, the expert involvement was more limited. Data collection was done during Winters when many of the experts were on Christmas break.
- Also, while collecting data from experts of different expertise and background, although most of them had similar views on relationships among services, some experts had different views. If a larger group of experts from the same department as well as more diverse departments could be interviewed, the insights for relationships among services could have been more comprehensive and different from what was accepted for the study. Though it would have added variability, it would also help cover values for all expected states, would have led to a triangulation of data and identify sources of uncertainty, thereby increasing the trust in the model. Kleemann et al. (2018) also mention in their study that having experts from diverse disciplines increases the chances of getting a complete picture of the study and the contradictive findings help to identify uncertainty.
- A lot of time had to be spent working on data curation. For example, a lot of hunting data was shared by the Hunting Organisation of Athens in Greece. The problem was that the data were in Greek, and it could not be easily interpreted. Besides that, it was difficult to get in touch with the experts for any other clarifications time and again. Most of the experts could not speak in English; therefore, the communication was restricted, and data collection was dependent on translators. It limited the cross-questioning part while conducting interviews; therefore, the data can be thought of having a lot of bias. Therefore, it seems necessary to be able to contact experts when data has been prepared for the nodes rather than just collecting data in one go and not being able to discuss the progress with them later.
- Only pairwise interactions between services could be operationalised because of the complexity of the relationship between the chosen services. Also, to keep the size of CPT minimum, only two services were observed for looking into their interactions as target nodes. Filling in CPT for more than two services together needed more information about their mutual influence when all three or four services occur together in different state combinations. But that information could not be collected within the timeframe of the study and would not be straightforward to derive. However, as all the services were a part of the Bayesian network, therefore even though the services were not directly connected, the change in one service reflected the change in the other.
- Based on the time and data available, the interactions among the ESS were presented in a simplified way describing them as trade-offs, synergies and no-effect. While filling the CPT, it was realised that these three states were not representative enough (not exhaustive) to show the level of quantification between these interaction types. Based on the logic used to fill in the CPT, it was realised that the level of trade-off or synergy could further be classified one step more to include values which showed a

difference in magnitude of those types. For example: While filling in CPT for interaction (hiking and canyoning) node, based on the combination of the two parents, the information on the difference in magnitude of synergy was lost.

Table 23: CPT for interaction (hiking and canyoning) node showing how the difference in magnitude of synergy is lost.

Number of visitors on hiking routes	Number of visitors on canyoning routes	Interactions (Hiking & Canyoning)
Low	Low	Synergy
Low	High	Synergy
Medium	Low	Synergy
Medium	High	Synergy
High	Low	Synergy
High	High	Synergy

Table 24 shows a low number of visitors on hiking route and high number of visitors on canyoning route represent synergy in same way as high number of visitors on hiking route and high number of visitors on canyoning route. If there was another level, maybe low synergy and high synergy to represent these differences, then on the map the areas of low synergy could be identified, and management decisions could be made so as to improve the low synergy to high synergy areas. This can be addressed in further research as due to time and data limitation and unavailability of experts for further questioning, and it could not be considered in this study. It can lead to an improved understanding of conditions behind variations in interactions in space. It can help to generate maps to visualise areas with similar conditions and magnitude of interactions which can be helpful to apply similar management decisions in those areas.

- Many of these ESS is received in the area which is designated as areas of high conservation priority. Due to shortage of time and complexity of the relationship of these ESS, the impact of the relationships of the ESS on these priority habitats in areas of special conservation could not be modelled. This aspect can be looked into by future studies that take place in the area.
- Due to limited time, a static image representation of the uncertainty map was produced, but in a future study, dynamic or animation-based uncertainty maps can be produced for better visualisation.
- Though the maps were extremely helpful in viewing the changes happening in space yet their static representation of the changes of the interactions is a limitation of this study. The results would be better understood and change better visualized if the evidence was inserted in the BBN in one node and the posterior probability changes could be visualized in the map for all the target nodes with an updated probability distribution. It would make the comparison of the changes easy and also show the trends of change of the interactions over seasons. Another way of visualisation of spatial variations in ESS over seasons is like May et al. (2019) who provide a web interface of a spatially explicit BBN which would allow more elaborated comparisons between changes in interactions which would leads to their enhanced understanding.

- There is a possibility to add more details to the network by collecting more spatial and non-spatial data to include socio-economic variables that were dropped from the BBN. The influence diagram showed the multiple factors that could define the positive or negative relationship between the flow of two services. In order not to lose information and under-represent the relationship that two services can have, more nodes can be added to model those factors and update the structure to better represent reality. Example, more information about topographic viewshed, points of wildlife observation, distance from a road, distance from nearest village etc. can be used as inputs to a node landscape attractiveness which can then be input to model the flow of recreational hiking ESS along with the qualitative data (preferences and accessibility) used in the model for determining the flow. Then the CPT can be filled with these two different inputs and weights can be provided to determine the influence these factors have in determining their contribution to the node.
- It can be inferred from the generated maps that though the BBN is able to map the interactions correctly (For example, Rodokalos canyoning route and hiking route 5), it also generates a lot of additional information for other services as they are a part of the same network. This extra information for this study does not make sense and also creates confusion. It was observed from all the maps that along with the required interactions, some unexpected outputs were shown on the maps. Example, Section 4.4.Part 1 Figure 24 shows interactions (synergy) among canyoning and hiking and a low probability of synergy is found along all hunting areas. The hunting areas do not have hiking and canyoning routes all over the place so those areas showing probability of having synergy between canyoning and hiking is incorrect. This has been mentioned by Ellison et al. (1998), that in the absence of evidence for the nodes in BBN, the prior probabilities values get associated with those nodes, in a way to deal with the missing data. As there is no condition set that the BBN should only look into overlapping areas for identifying specified interactions, therefore, while calculating the probability distribution of interactions for the selected ESS pair, the BBN also calculates probability distribution of same interactions for other nodes in network. As the information needed to calculate interactions between canyoning and hiking is missing in other nodes therefore the BBN associates prior probability values with those nodes and displays it like probability of having that interaction in those areas. There is a need to handle these within the network while filling in the CPT or by making certain structural changes This error can be solved by adding a state to the spatial input nodes specifying that when interactions between hiking and canyoning take place, then prior probability of hunting area/timber area should be zero. This is the case with other interactions as well. This is the shortcoming of the network based on the way it was designed and can be improved in future studies. This is the major limitation of the network constructed and due to shortage of time, the improvements could not be made. But the uncertainty map is helpful in this case as it shows such unwanted areas to have high uncertainty and therefore while validating the results with the experts, these areas were decided not to be given importance.
- In this study, it was assumed that the effects of timber extraction are valid only in that season, to keep the model simple. But in order to model the effects of timber extraction over time, feedback loops need to be taken into account. The dynamic BBN could be explored in order to study the feedbacks into the system. This is similar to Landuyt et al. (2016), who highlights the drawbacks of the linear structure of the model which cannot incorporate feedback loops therefore either assumptions need to include the ESS in modelling or ESS have to be dropped.
- Due to time and data constraints, the model validation could not be carried out in more detail. As the approach that could be followed due to limited data availability is mostly based on expert knowledge, therefore it is subjective. Besides that, during review and validation, only one expert from Management Body could be contacted. The reliability of the network would increase with

the availability of more data and if the model was validated by different experts. The face validation took place from the viewpoint of an expert from Management Body (the biologist) who has knowledge of the entire area and good understanding of the system and its dependencies yet the validation of the model would have benefitted more and model could be deemed more reliable if other department experts were available. The model could also have been tested with the data if it was available and it would be more accurate as suggested by Landuyt et al. (2016) as the experts mostly will not go against what they have said already or may agree to all the results based on reviewing a few places that they are familiar with.

- The BBN could be used for representing future scenarios and predict how, over time, the interactions among ESS could change. For this, more information about past years could be collected to observe if there were any trends in presence and absence of services or increase or decrease over the years, how these have changed over years and then predict how they could change over time. This would require a lot of new data to be collected and can be taken up by future studies.

7. CONCLUSION

The study aimed at exploring the capability of a BBN to map seasonal changes in ESS trade-offs and synergies. In the previous studies, the BBN's have been used to assess and quantify trade-offs and synergies arising due to interactions between ESS, yet the application of BBN's have not yet been fully explored for mapping those interactions. Besides that, not much research is available that looks into seasonal variations in ESS interactions, specifically looking at the flow component of ESS. Therefore, the aim of this research was to fill in these identified gaps and explore the capability of BBN to produce ESS interactions maps.

The BBN was able to model together with the flow of different kinds of ESS – a tangible-provisioning ESS- timber extraction and three intangible recreational ESS- Recreational hiking, hunting and canyoning services. Being able to combine these different values together helps to compare the effects of different services on each other and get an overall understanding of the system, its interconnectedness, and its dependencies. However, as mentioned before, these interactions are subjective, based on experts' experiences of the relationship among services, and their influence can change based on addition or subtraction of more different ESS to the network.

The BBN showed its ability to efficiently represent the dependence and independence relationship among the different variables. These quantified dependencies can assist the end-user in taking effective measures to reduce/enhance the likelihood of occurrence of events represented by the target node. It can also assist them by helping to identify the most influencing variables in each interaction. The interactions among the ESS may also change based on which services have been selected to be modelled, what ESS component is being looked at and definitions considered to classify a relationship as trade-off or synergy or no-effect. The structure of the BBN is flexible enough to add any new nodes and states to the BBN thus making it useful for the experts to update the evidence and check influences of new variables on the existing system. The conditional probability tables, though, would need to be updated accordingly. The model and its output can also help the Management Body to visualize the implications of their decisions by understanding how their decisions can change the flow of one ESS and how that can affect multiple linked ESS using the BBN.

As seen from the results, the aim was to identify areas where trade-offs and synergy occur in order to minimize the risk of trade-offs and to maximize the benefits retrieved from nature. By considering trade-offs and quantifying and mapping them, it might become easier for the Management Bodies in finding patterns of occurrence of trade-offs. The Management Body can identify the areas that need special attention during different seasons. The identification of locations for better management and knowing that the location of these interactions' change over seasons, can help to determine necessary steps to apply appropriate measures for optimal utilization of resources. They can thus provide alternative management options which otherwise is difficult due to lack of time, certainty and funds. Also, the cumulative maps can help to identify areas of high priority for management during different seasons. The spatial quantified uncertainty values give confidence in making decisions and while suggesting alternatives for management purposes. This can save time, resources and energy by providing appropriate and efficient management solutions to places facing similar problems and having similar conditions. As mentioned before, there is limited personnel working in the Management Body. Therefore the maps can help the Management Body to identify when and where more efforts are needed to apply targeted management techniques, promoting better-informed decisions and leading to sustainable resource management.

This study is first of its kind to model the seasonal variations in interactions among the four chosen ESS focusing on their flow component. It paves the way for the development of models that investigate ESS interaction, considering that their interactions change over time and across space. Therefore, for taking this first step, a lot of assumptions had to be made, and a lot of improvements can be made to build a better network. Improvements to this study can be made by including more services, collecting more data, interviewing more experts from the same and different departments. The model can be replicated and improved by following the steps included in the methodology and by making use of the knowledge gained from this study. The output can especially be improved by making necessary changes in the structure and adding conditions to remove the unnecessary information being generated by BBN, which later is displayed on the map and adds confusion. Also, some more thought can be put to understand whether sub-categorisation of interaction type (low synergy, high synergy, low trade-off, high trade-off) would be a beneficial and better representative of changing the magnitude of interactions in space. Then the model can be applied to new sites under the jurisdiction of the Management Body. With the future fieldwork and data collection, the model can be refined with the new-found observations and then can be updated to identify interactions among the same or different ESS in other areas.
It can be concluded that the BBN can be used for mapping interactions between ESS which vary across space and in magnitude over the seasons.

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APPENDIX

A. System Analysis

1.1 List of ESS based on CICES classification

Table A 1: List of ESS in the study area based on Natura 2000 and review of related literature for initial discussion with the personnel from Management Body of Mt. Oiti National Park.

CICES classification system		
	Group	**Class**
Provisioning: Nutrition	Biomass	Cultivated crops
		Reared animals and their outputs
		Wild animals and their outputs
	water	Surface water for drinking
		Ground water for drinking
Regulating: Mediation of waste, toxics and other nuisances	Mediation by ecosystems	Control of erosion rates
	Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations
	Atmospheric composition and climate regulation	Micro and regional climate regulation
Cultural: Physical and intellectual interactions with biota, ecosystems, and landscapes, physical, chemical, biological conditions	Physical and experiential interactions Experiential use of plants, animals and land	Scientific
		Educational
	Intellectual and representative interactions	Heritage, cultural
		Entertainment/Sports
		Recreation
		Aesthetic

1.2. Data Already available with the Management Body

Table A 2: List of datasets already available with Management Body

Data Set	Format	Usage
All Natura2000 sites boundaries - within jurisdiction of Management Body	Individual ESRI polygon shapefile	As the spatial extent or boundary of the study area
Natura2000 habitat maps for all sites along with the SDF files	Individual ESRI polygon shapefile	Preliminary exposure to study area characteristics
Core area, Wildlife refuge boundaries	Individual ESRI polygon shapefile	Boundaries of core of protected area and wildlife refuge
Roads and rivers	Individual ESRI line shapefile	Location roads and rivers in the study area
Hiking routes in GR2440004	ESRI line shapefile	Tracks in study area used for hiking purposes
Oiti Toposheet map	Hardcopy: B1 size: 70cm by 100 cm; Raster file (.tif): Softcopy: Scale of 1:35000	Used as reference map while conducting interviews and digitization
Livestock in GR2440004	ESRI point shapefile	Location of place of shelter for livestock during Summers in study area
Forest Property boundaries	ESRI polygon shapefile	The forest property classified as public private disputed or co-owned along with the forest name

1.3. Questionnaires: Participatory Mapping and semi-structured face-to-face interview

1.3.1 Common terminology

Based on discussion with Management Body: the definitions were fixed for low, medium, and high accessibility.

1. **Accessibility**: It means how easily someone can reach their destination. Accessibility is controlled by obstructions in path like fallen trees, high bushes, landslides, path being covered with snow or is muddy and slippery during different seasons, not having directional signs etc. Therefore, accessibility of a route or an area can control how many people can visit a route or an area in any season.

2. **High accessibility**: When the route is well maintained, clean, requires very few physical and technical ability to hike. This route is such that anyone can easily walk through in a season.

3. **Medium Accessibility**: is clear route which required more technical skills and is intermediate ascend.

4. **Low Accessibility**: is a route which has many obstacles, is challenging and cannot be easily walked through.

Defining relationships between services

5. **Trade-offs:** When the flow of one ESS increases and it leads to decrease in the flow of the other ESS, then a trade-off occurs.

6. **Synergy:** When the increase in flow of one service increases the flow of the other to create a cumulative effect. This is also applicable in case when there is a decrease in flow of one service and it leads to decrease in the flow of the other, such that the overall picture has higher decrease represents synergy.

7. **No-Effect:** When there are weak interactions, that is when the flow of both the ESS is low such that it has very low or negligible impact on the other, the experts called it no-effect. It aligns with the explanation (Bennett et al., 2009) gives for weak interactions among the services. Therefore, in such cases, the services have no-effect although in ecological perspective the situation where both services have increase and decrease in flow together, they should be considered as synergy.

1.3.2 Recreational Service: Hiking

Part 1: To capture seasonal variations in ESS flow of a service

Aim: The aim of this activity is to collect information about hiking routes which have more people visiting them and why. Also, information about seasonal variations in number of people visiting a route will be collected. As expert in the area, you are going to answer the questions based on general perception of the people and not your own personal experiences alone.

Q1. After looking at the map and familiarising yourself with the routes, write down in the space below which routes are more visited during different seasons/months? Please fill in the table with the route codes in order of the visitation to those routes.

Table A 3: Hiking route codes and route names

Route Codes	Route Name
R1	Ypati -Perdikovrysi - Oiti Refuge
R2	Oiti Refuge - Karitsa - Loutra Ypatis
R3	Oiti Shelter - Greveno, Alikena, Pyrgos_Neochori
R4	Ypati - Castle
R5	Ypati - Kremastos waterfall (The trail of Pharmacides)
R6	Ypati - Perivolia – Arsali
R7	Kastania - Kapnochori – Ypati
R8	Kastania - Petrotos Top – Ypati
R91011	Sarakatsanoi
R12	Katavothra - Pyrgos – Livadies
R13	Argyrochori -Ambelaki

Table A 4: Table structure to capture ranking of most to least visited hiking routes based on seasons, in interviews by expert

	Most visited to least visited routes			
Seasons	**Winter(S1)**	**Spring(S2)**	**Summer(S3)**	**Autumn(S4)**
Rank (Route codes)				

Q 2. Why are some of these routes more visited than others?
*only to be hinted if no answers provided: Factors like Accessibility during seasons, Level of difficulty

Mention reasons for some routes more visited than others

Q3. Fill in the table below mentioning the accessibility of the routes during different seasons (which includes sign availability, path quality etc.) and difficulty level (based on perception of how difficult the route is in general: maybe depending on length of route, elevation gain etc.)

Table A 5: Ranking of routes based on accessibility in different seasons

Seasons code: S1= Dec, Jan, Feb S2 = Mar, Apr, May S3= Jun, July, Aug S4= Sept, Oct, Nov	**Accessibility of the route (Low, medium, high)**				**Reason for no. of visits change over seasons?**
Route Name	**S1**	**S2**	**S3**	**S4**	
Ypati -Perdikovrysi - Oiti Refuge					
Oiti Refuge - Karitsa - Loutra Ypatis					
Oiti Shelter - Greveno, Alikena, Pyrgos-Neochori					
Ypati - Castle					
Ypati - Kremastos waterfall (The trail of Pharmacides)					
Ypati - Perivolia - Arsali					
Kastania - Kapnochori - Ypati					
Kastania - Petrotos Top - Ypati					
Sarakatsanoi					
Katavothra - Pyrgos - Livadies					
Argyrochori -Ambelaki					

Q4. Are any routes used for special events like: marathon, mountain biking or any other group activities? If yes, which ones? When-seasonal/annual/monthly?

Table A 5: Capture special information for each route during different seasons

Route Code	Route Name	Special events Y, N	When (Season/month)
R1			
R2			
R3			
R4			
R5			
R6			
R7			
R8			
R91011			
R12			
R13			

Part 2: To capture relationship of recreational service: hiking with other services

Q1. Are you aware of the following activities taking place in the study area?

1. Hunting
2. Conservation of plant and animal species
3. timber extraction
4. canyoning
5. Livestock grazing
6. Education
7. Ground Water Extraction

Q2. Do you think that presence of these activities affects positively or negatively number of people going for canyoning? Mention for each activity: Type of affect and give a reason for the same.

Table A 6: Relationship of different ESS with Recreational Hiking ESS

Activity type	Affect Type	Reason
Timber extraction		
Canyoning		
Conservation of plants and animals		
Hunting		
Ground water extraction		
Education and scientific studies		
Livestock Grazing		

1.3.3. Recreational Service: Canyoning

Part 1: To capture seasonal variations in ESS flow of a service

Aim: Collect data through mapping and face-to-face interview to know which canyoning routes people value, if there is a seasonal preference to the route and does accessibility change over seasons. The expert will also be asked about other activities in the area and how do those activities impact the canyoners.

Q1. If there are no routes available to use directly, then can you please mark on the map-draw a line-marking the starting point and end point of the Canyoning routes? Also, in table below, please write down the name of the routes:

Table A 7: Canyoning route codes and route names

Route Codes	Route Name
R1	
R2	
R3	
R4	
R5	
R6	
R7	
R8	

Q2. Please write down in the space below which routes are more visited during different seasons/months? You can write the route codes in order of their visitation (ranks).

Table A 8: Table structure to capture ranking of most to least visited canyoning routes based on seasons, in interviews by expert

	Most visited to least visited routes			
Seasons	**Winter(S1)**	**Spring(S2)**	**Summer(S3)**	**Autumn(S4)**
Rank (Route codes)				

Q3. Why are some of these routes more frequented/visited than others? (*only provide a hint when expert doesn't answer: Accessibility during seasons, Cost, Duration, a greater number of attractions/uniqueness?)

Table A 9: Capture special information for each route during different seasons

Route code	Winter	Spring	Summer	Autumn
R1				
R2				
R3				
R4				
R5				
R6				
R7				
R8				

Part 2: To capture relationship of recreational service: canyoning with other services

Q1. Are you aware of any of the following activities that take place in the area of interest?

Activities such as:

1. Timber extraction
2. Hiking
3. Conservation of plants and animals
4. Hunting
5. Ground water extraction
6. Education and scientific studies
7. Livestock Grazing

Q2**.** Do you think that presence of these activities affects positively or negatively number of people going for canyoning? Mention for each activity: Type of affect and give a reason for the same.

Table A 10: Relationship of different ESS with Recreational Canyoning ESS

Activity type	**Affect Type**	**Reason**
Timber extraction		
Hiking		
Conservation of plants and animals		
Hunting		
Ground water extraction		
Education and scientific studies		
Livestock Grazing		

1.3.4. Recreational Service: Hunting

Part1: To capture seasonal variations in ESS flow of a service

Aim: The aim of this activity is to collect information about prime locations of where most of the animals within the boundary are hunted. Need to mark on the map, the places where hunting takes place the most, where it varies with season along with the number and type of animals hunted in those areas.

Q 1. After looking at the map and familiarising yourself with the area under study, please mark on the map all places where particular species is hunted during a season (not all species are likely to be found and hunted in the same areas). Give the name of the area you draw a name like p1, p2 etc.

Q2. What are the reasons that you think affect the hunting of the animals during different season? Only mention these if the hunters are unable to answer the question to give hints (eg. Accessibility, Policies etc)

Table A 11: Factors that affect hunting of different animals during different seasons

Q3. Once all places are marked on the map, for each place write down if the place is accessible (low, medium, high) during different seasons.

Table A 12: Rank accessibility of the polygons drawn on the map according to seasons

Hunting places	**Accessibility of the area**			
Seasons	**Winter (S1)**	**Spring (S2)**	**Summer (S3)**	**Autumn (S4)**
P1				
P2				
P3				
P4				
P5				

4. Rank these places according to a greater number of animals hunted from them. Also mention the season in which you find most animals hunted, along with which animals are hunted during that season.

Table A 13: Ranking of polygons based on the greatest number of animals hunted in a season

Part 2: To capture relationship of recreational service: hunting with other services

Q1. Are you aware of any of the following activities that take place in the area of interest?

Activities such as:

1. Timber extraction
2. Hiking
3. Conservation of plants and animals
4. Canyoning
5. Ground water extraction
6. Education and scientific studies
7. Livestock Grazing

Q2**.** Do you think that presence of these activities affects positively or negatively number of people going for hunting? Mention for each activity: Type of affect and give a reason for the same.

Table A 14: Relationship of different ESS with Recreational Hunting ESS

Activity type	**Affect Type**	**Reason**
Timber extraction		
Hiking		
Conservation of plants and animals		
Canyoning		
Ground water extraction		
Education and scientific studies		
Livestock Grazing		

1.4. Expert face-to-face mapping exercise

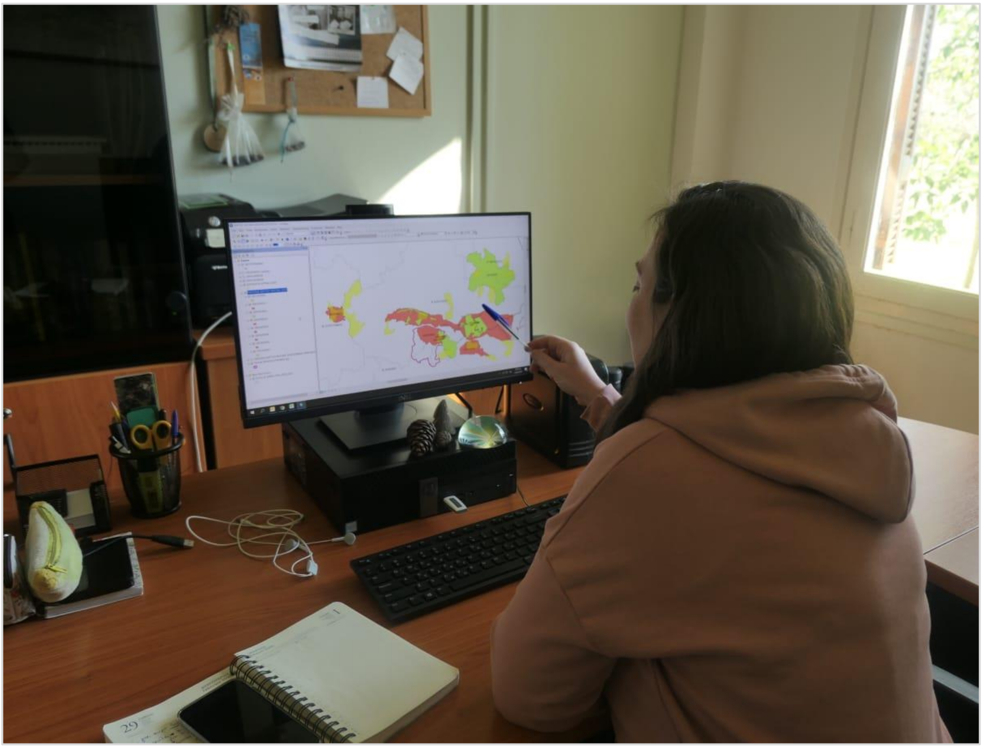


Figure A 1: Discussion with the personnel from Management Body about choice of study area and ecosystem services in those sites

Figure A 2: Expert from Water department digitising and answering questions during mapping exercise

1.5. Services not considered for study

1. Reared animals and their products, animals by amount. Flow Component Indicator: Livestock (number of Cattle, Sheep, Goats and Pigs) per ha per season: Provisioning service,

Although, the data for livestock was available from Management Body as point dataset, no expert was available to be interviewed so no other information could be collected.

2. Environmental/Scientific education: Flow Component Indicator: Number of events or no of receivers/route/season: Cultural Service

It was found after interviewing the expert- the director of KPE - Environmental Educational Centre at Stylida, Central Greece, that out of the three hiking routes used for providing education, two were outside the study area. Also, the experts mentioned that they consider this information about education activities on the routes while providing input for number of visitors on a hiking route in a season. The education related activities only take place along one route in Summers, so they mention it by ranking the route accordingly.

3. Groundwater for nutrition, materials, or energy. Flow Indicator: Volume of water withdrawn from source for consumption per village per season: Provisioning service,

The Water Department of Lamia (DEYAL) were able to provide spatial and non-spatial data as requested. The data was processed to get the volume of water indicated by the meter per season for each village. Then a map was created to see, where the water is being supplied from, where it is being consumed and in what quantity. The flow lines indicate the volume of water supplied for consumption, in this case annually. The reason for dropping this service is that even though the water is being supplied from the study area, the consumption takes place outside the study area. There is no spatial overlap with any of the other services therefore there is no direct interaction. Also, on interviewing the experts, it was found that the water extraction takes place in a sustainable manner and the mountain has abundant water so there are no conflicts with or impacts on any other services being considered already.

B. Data Curation

1.1 Canyoning Routes and seasonal variations in number of visitors

Canyoning routes (Attribute Data)

The chart shows eight routes where route Stenovouni has no visitors in any season. The route Rodokalos has visitors in all seasons with maximum of 120 people during Autumn and minimum of 20 people during Winters, making it the most visited route. The next most popular route is Gorgopotomos route which has equal number of visitors during Autumn and Summers. The same data can be visualised in chart where we can observe most routes have visitors during Spring season.

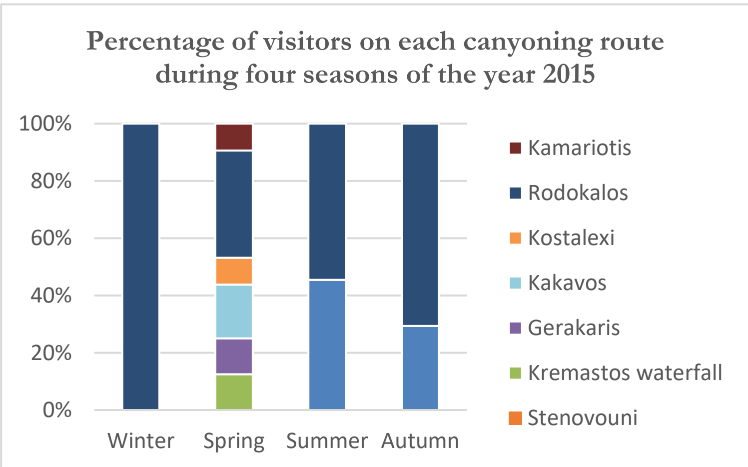


Figure A 3: The variation of visitors on all eight canyoning routes during different seasons. The chart shows percentage of visitors visiting each route in the four seasons and also shows how the visitor numbers differ on the same route in each season. Rodokalos (Route 7) has the maximum visitors all throughout the year but in different numbers varying over season and Spring season has the many visitors visiting many routes.

Canyoning Routes (Spatial data)

As mentioned before the expert gave the location of the start and end locations of the canyoning routes. A canyon can have multiple entry points and have been shown by green triangles in map. The out locations are shown by red squares. The canyoning expert also shared a book from which a lot more information was available about canyoning.

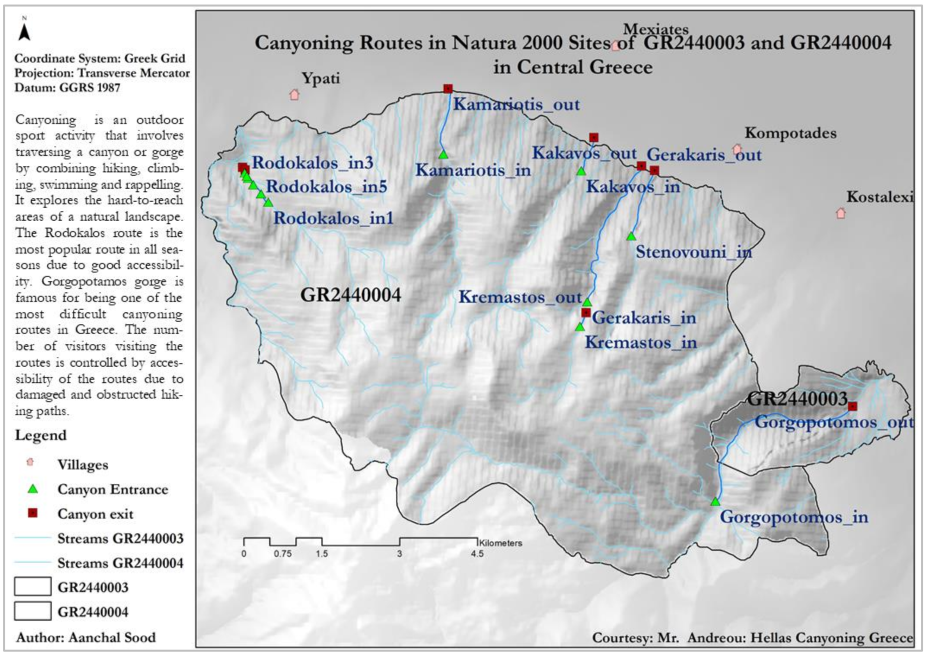


Figure A 4 : The seven canyoning routes with entrance and exit in case study area

1.2 Hiking Routes and seasonal variations in number of visitors

Calculating Preference of each route

Preference of the routes: A ranking of the routes by seasons was provided by the experts to understand which routes people are mostly like to visit in different seasons. The interview was conducted in a way to understand which routes are more frequented/visited by the people and used as a proxy for their preference of the hiking route. The subjectivity of the factor under consideration reflects the degree of uncertainty and bias of a particular person at a particular time. All information collected by interviewing the three experts was analysed and ranks were provided to each route based on each expert's perception of number of visitors visiting each route in each season. Each route was given maximum score of eight, where eight represents the route with first rank (representing it has highest number of visitors). The ranking of the routes done in order of a greater number of visitors on a route to least number of visitors on a route. For example, if a route was ranked 1 by all the three experts meaning the route had highest visitors then the total score of this route was 24 (the highest: here route 5). Similarly, the total sum of all scores for each route was calculated and the final rank was assigned to each route for each season. This is the cumulative rank for visitation based on different seasons calculated by summing up ranks provided by each expert to each route.

Table A 15: Ranking of hiking routes by three hiking experts and cumulative ranking of the hiking routes over different seasons

Cumulative rank:

Person 1

Winter (S1:)	Spring (S2)	Summer (S3)	Autumn (S4)
R5, R1, R8, R3, R4	R5, R1, R8, R3, R4	R5, R1, R8, R3, R4	R5, R1, R8, R3, R4

Person 2

R5, R1, R8, R7, R4	R5, R1, R8, R7, R3, R4, R12, R6	R5, R1, R3, R4, R7, R8	R5, R1, R3, R4, R7, R8

Person 3

R5, R7, R3, R1, R6, R8	R5, R1, R12, R7, R8, R4, R3, R6	R5, R1, R3, R4, R7, R8, R6, R12	R5, R1, R4, R7, R8, R6, R12

Winter (S1)	Spring (S2)	Summer (S3)	Autumn (S4)
R5>R1>R8>R3>R7>R4 >R6>R12	*R5>R1>R8>R3>R7>R4 >R12>R6*	*R5>R1>R3>R4>R8>R7 >R6>R12*	*R5>R1>R4>R3>R8>R7 >R6>R12*

Based on the scores of each of the routes, the data was prepared by normalising it and then categorising into Low, Medium and High preference. The minimum score was 6 and maximum was 24.
1. Normalise[19] the data to 0-1
2. Link nonspatial preference score to routes for each season.
3. Using Jenks Natural Break method in ArcGIS Pro, the values were put under three classes: low, medium, high preference.

The chart shows the variation in number of people along the same route in the four seasons. The number of people visiting route R5 is always the highest and therefore is the most frequented route in any season.

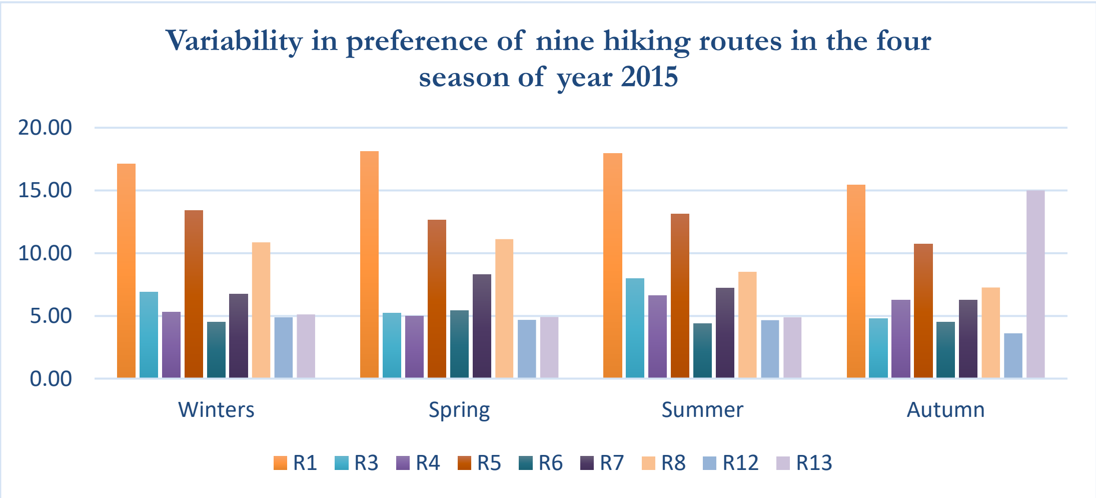


Figure A 5: Variation in preference of nine hiking routes in each season

[19] Normalised data (Zi) = xi-min(x)/max(x) - min(x); where xi=(x1, ..., xn) and Zi is now ith normalized data.

Accessibility of the routes: The hiking expert mentioned that their experience of hiking on a route depends on beauty, accessibility and safety. They mention a route is accessible if it can take the visitors to all accessible, attractive places available on a site through an unobstructed and complete path. Accessibility is controlled by obstructions in the path like fallen trees, high bushes, landslides, path being covered with snow or is muddy and slippery during different seasons, not having directional signs etc. Therefore, the accessibility of a route can control how many people can visit a hiking route in any season. This definition was common for all experts and based on these factors, they categorised the accessibility of a route into three classes: low, medium and high and associated to each route for each season in ArcGIS Pro.

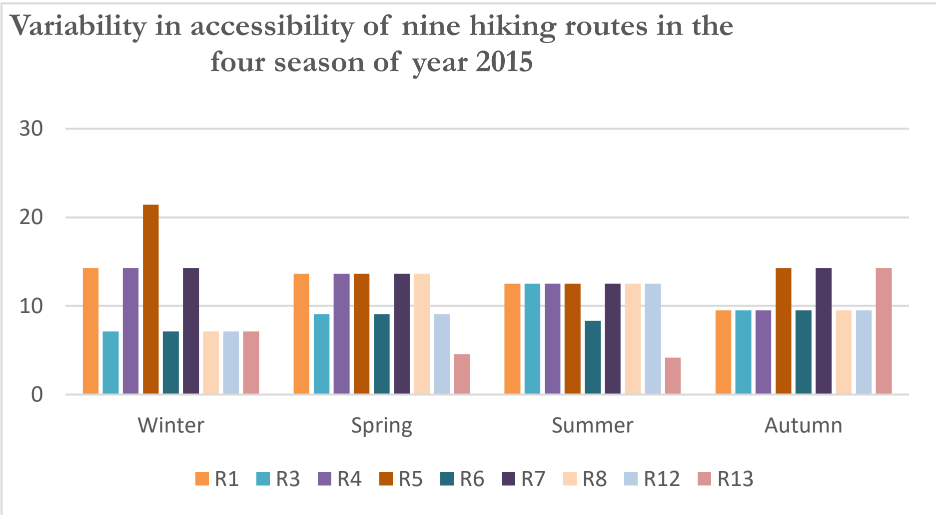


Figure A 6: Variation in accessibility of nine hiking routes in each season

Hiking Routes (Spatial data)

The spatial data was provided in required format by Management Body of Mt. Oiti National Park.

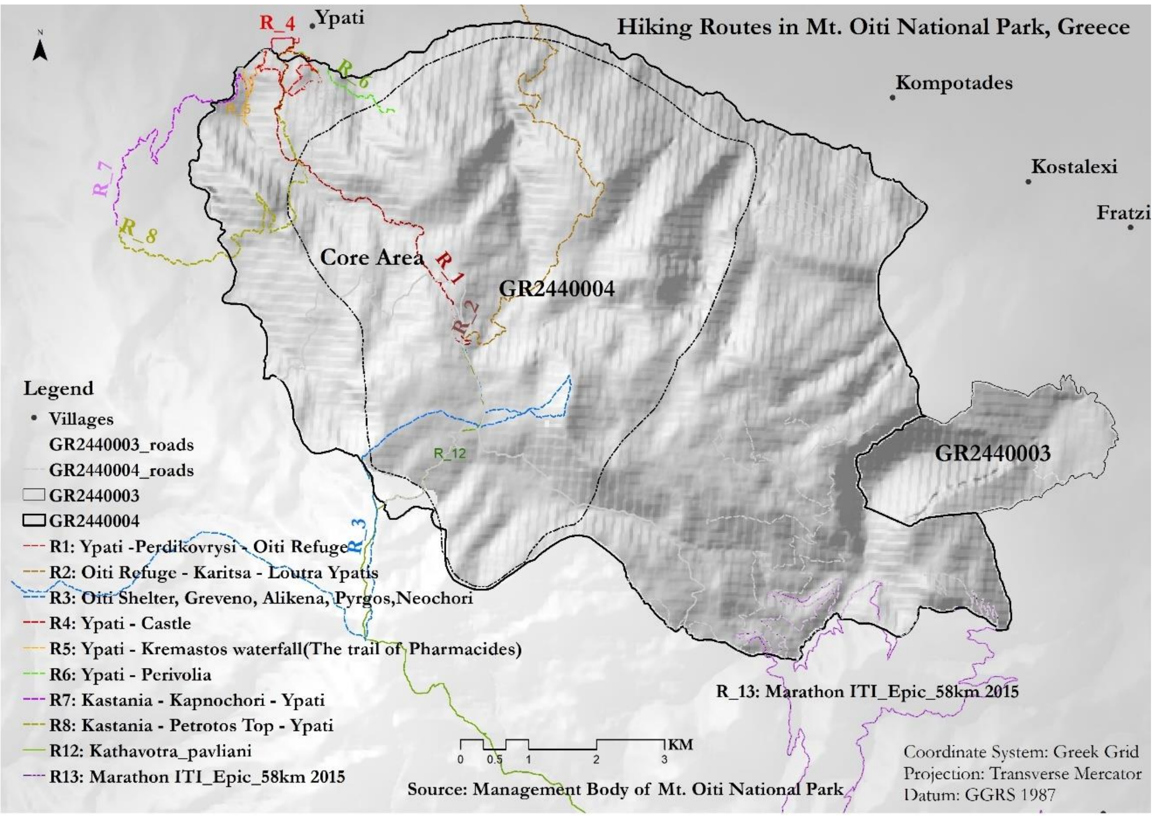


Figure A 7: The nine hiking routes in the study area.

1.3. Hunting areas and seasonal variations in number of animals killed per season

The tables show : scores given to different polygons marked by three key-informants based on their knowledge about where maximum kills for a particular game species takes place during different seasons. They also provided information about accessibility of those areas during these seasons. Hunting is prohibited during Spring, so no information was provided for that month.

Hunting areas (Spatial Data)

The areas for hunting were digitized during participatory mapping exercise where the three hunters drew polygons for where the maximum animals are killed during a season based on their experience of where a kind of game species can be hunted in study area. The hunters identified areas where hunting is banned in all seasons like core and wildlife refuge. They also mentioned the important animals exercise based on where a particular type of animal is hunted in that season and accessibility of the place in that season. The polygons marked by the three hunters have been outlined with different colors with polygon codes they provided while describing about those areas.

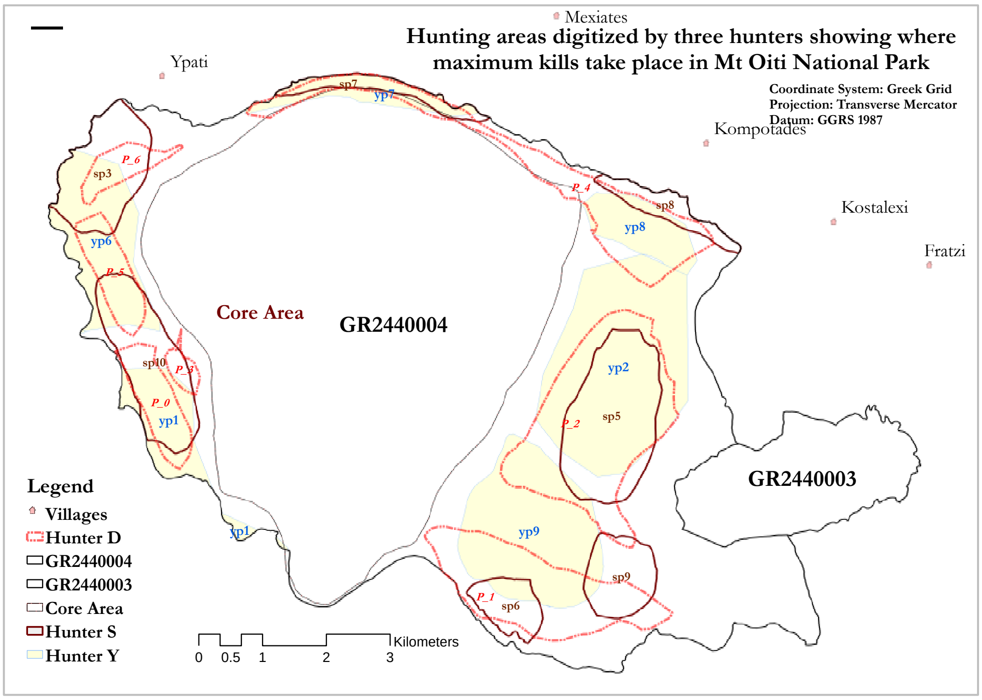


Figure A 8: Hunting areas based on three key-informants' knowledge of places with maximum kills in Mt. Oiti National Park

Hunting areas (Attribute data)

As can be seen from figure A 8 above, the three hunting experts marked polygons showing hotspots for hunting. They also provided the non-spatial information for each polygon (Table A 17 below). All the spatial and non-spatial data from respective hunters were first related together to create three vector datasets.

Table A 16: These table show the data collected from the three hunters

Accessibility of polygons			Person S	Rank based on where animals are most hunted in a season		
Winter	**Summer**	**Autumn**	**Polygon Name**	**GameScore(Wi)**	**GameScore(Su)**	**GameScore(Au)**
high	high	high	p1 - boars	Medium	No	High
low	medium	medium	p2 - hare	Low	No	Medium
low	medium	medium	p3 - boars	Low	No	Medium
high	high	high	p4 - birds	High	High	High
low	medium	medium	p5 - boars	High	No	High
low	medium	medium	p6 - boars	Low	No	Medium
low	medium	medium	p7 - partridge	Medium	No	High

Accessibility of polygons			Person D	Rank based on where animals are most hunted in a season (score)		
Winter	**Summer**	**Autumn**	**Polygon Name**	**Game Wi**	**Game Su**	**Game Au**
low	medium	high	P1 – partridges, hare	Medium	Low	High
low	medium	high	P2 - hares, bird	Medium	Low	High
medium	high	high	P3 - boars	High	No	High
low	medium	high	P4 - boars, hare	Low	No	Medium
high	high	high	P5 - boars, birds	High	High	High
medium	high	high	P6 - hares	Low	No	High

Accessibility of polygons			Person Y	Rank based on where animals are most hunted in a season		
Winter	**Summer**	**Autumn**	**Polygon Name**	**Game Wi**	**Game Su**	**Game Au**
low	medium	high	p1 - Partridge	Low	Medium	High
low	medium	medium	p2 - boars, hare	Low	No	Medium
medium	high	high	p3 - hare, boars	Medium	No	High
high	high	high	p4 - birds	High	High	High
medium	high	high	p5 - boars	High	Low	Medium
low	medium	medium	p6 - boars	No	No	Low

As seen from figure A 8 the areas marked by the experts on the map represent hunting hotspots for particular species were not the exact same locations. Also, the species they mentioned being hunted in the same spot were sometimes different. Therefore the 57 areas were created that represented all the information from the different experts by combining them together using ArcGIS Pro Geoprocessing tool-> Union. The categories were changed to numbers to perform summation so that final scores for accessibility and number of game species could be calculated and then classified into categories again after joining in all data from three experts. So, No=0, Low=1, Medium=2 and High =3. As there were 57 areas created, the accessibility values from each expert for each polygon was added together to form final accessibility score that ranged from 0-9 and similarly for game species, it ranged from 0-9. Based on Equal interval Classification in ArcGis Pro, the final accessibility categories were created: Accessibility (low, medium, high). Jenks Natural Break was used to categorise final game species score for each 57 areas as Final game species categories (No, low, high)

1.4.Timber Extraction (Attribute data)

This table gives information about the volume of timber extracted during the two years. The areas where the extraction was allowed during 2015 are Plakoto-Fratzi (in GR2440003) and Pavliani-Dyo Vouna (in GR2440004) and in in 2019 in forest of Vistriza (Kastania).

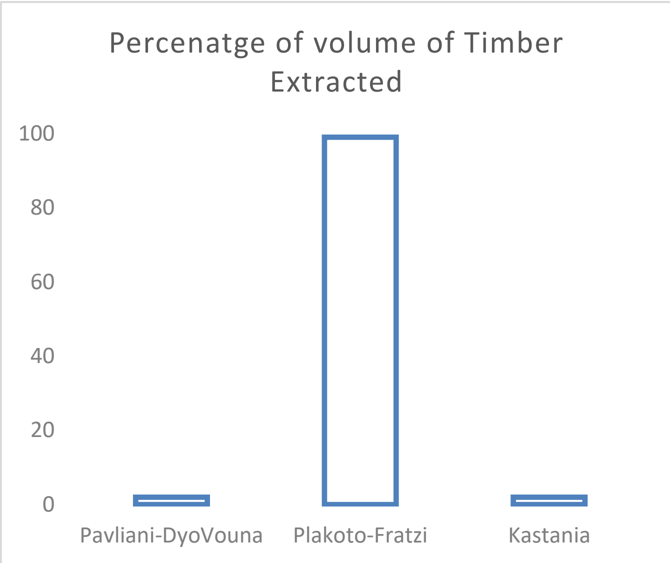


Figure A 9: Comparison of volume of timber extracted in Summer season from three areas

Timber Extraction: Spatial Data

These areas Plakoto-Fratzi (in GR2440003), Pavliani-Dyo Vouna and Kastania in forest of Vistriza (in GR2440004) were digitised as per the information provided by the forest official.

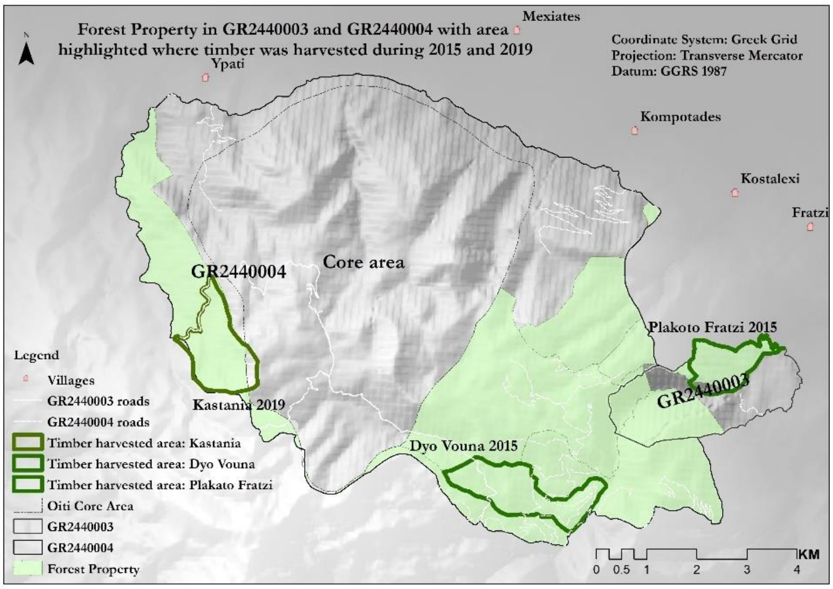


Figure A 10: Timber harvested in case study area year: 2015 and 2019.

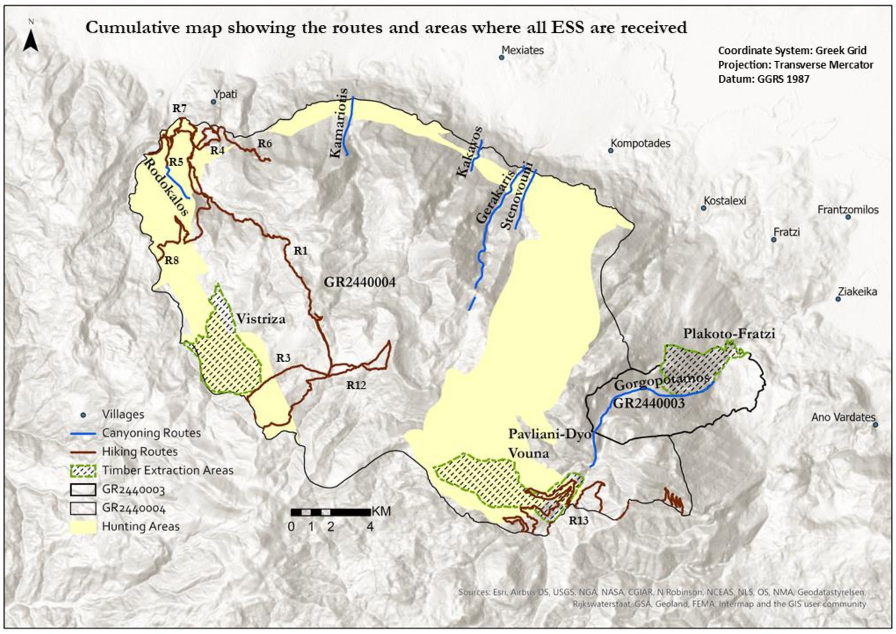


Figure A 11: The cumulative map showing locations where different ESS are received

1.5 Legend for figures used in Identification of ESS relationships

Figures	Description	Reference
	Visitor enjoying canyoning.	("Free Clip art", n.d.)
	Visitors enjoying hiking.	("Free Clip art", n.d.)
	Timber harvest from a forest	("Timber Harvesting In The Forest Stock Vector - Illustration of vehicles", n.d.)
	Hunters enjoying hunting	("Free Clip art", n.d.)
	Increased accessibility in remote inaccessible areas in forest due road construction for timber harvest	("Autumn Harvest -Image Id: HPAD3C", n.d.)
	Destruction of existing hiking routes due to timber extraction and transportation	(Carey, 2019)
	Habitat Loss which leads to migration of animals to other areas	("Invasive species and habitat loss our biggest biodiversity threats", 2018)

Table A 17: The legend for figures used in identification of ESS relationship

C. Design Stage

1.1 Spatial Input node: Canyoning Routes

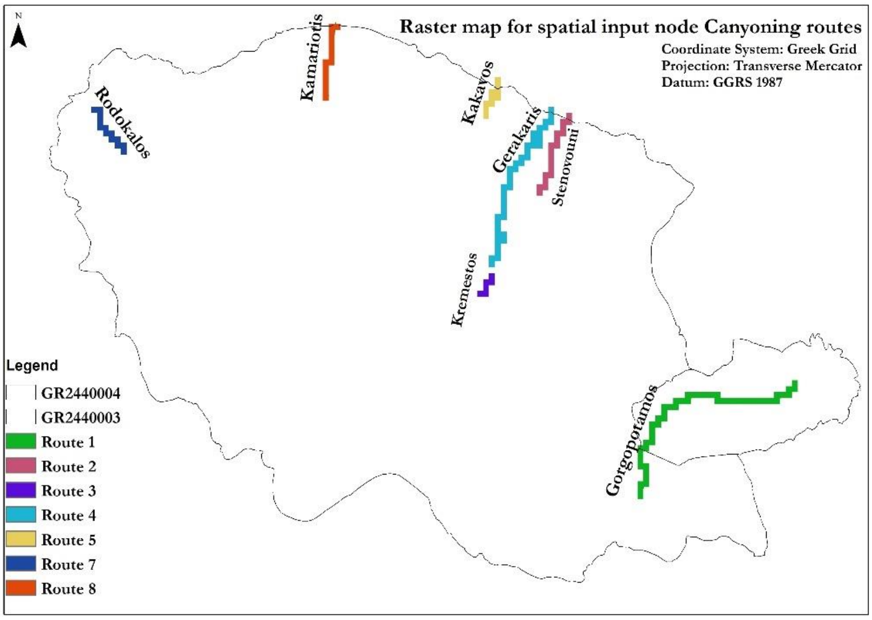


Figure A 12: Canyoning routes as input to spatial node in BBN at 100m raster resolution

1.2 Spatial Input node: Hiking Routes

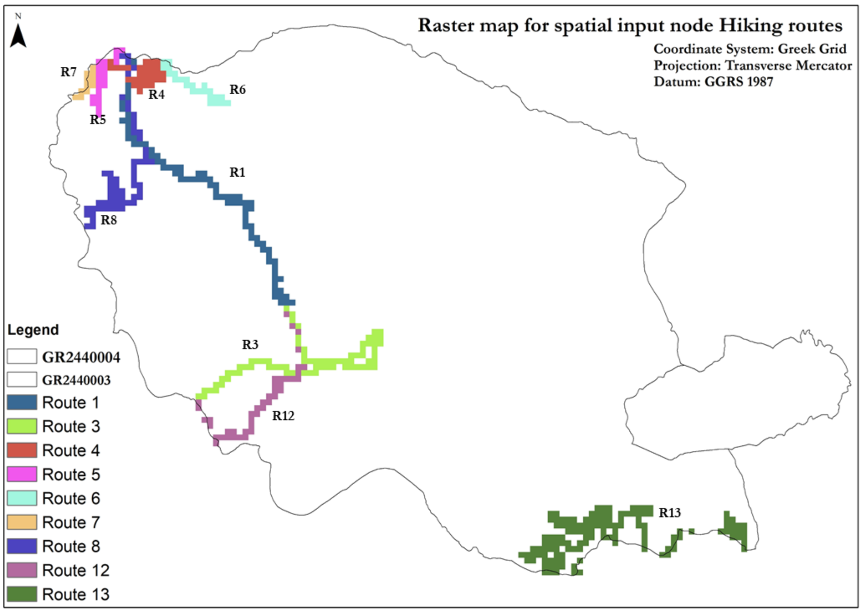


Figure A 13: Hiking routes as input to spatial node in BBN at 100m raster resolution

1.3 Spatial Input node: Hunting Areas

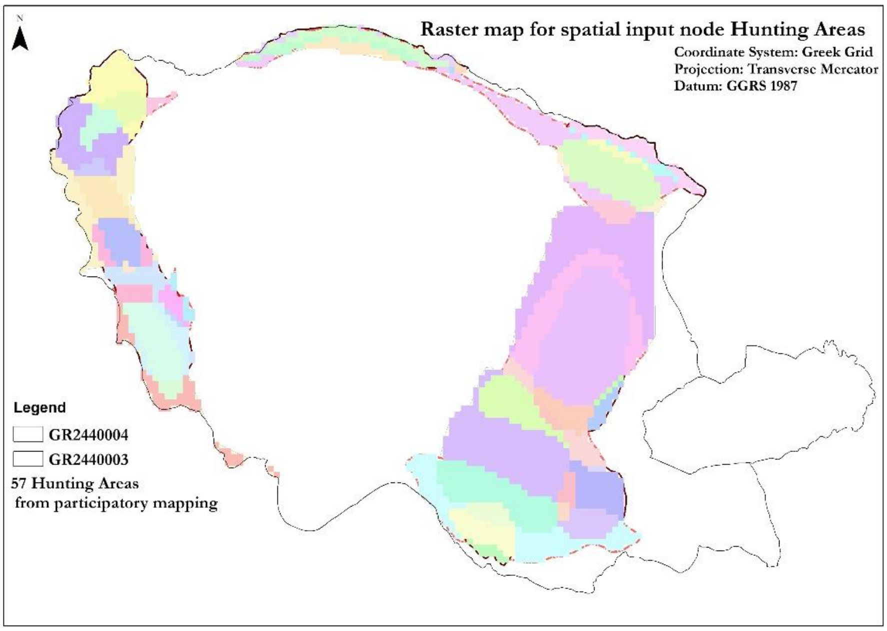


Figure A 14: Hunting areas as input to spatial node in BBN at 100m raster resolution

1.4 Spatial Input node: Timber Extraction Areas

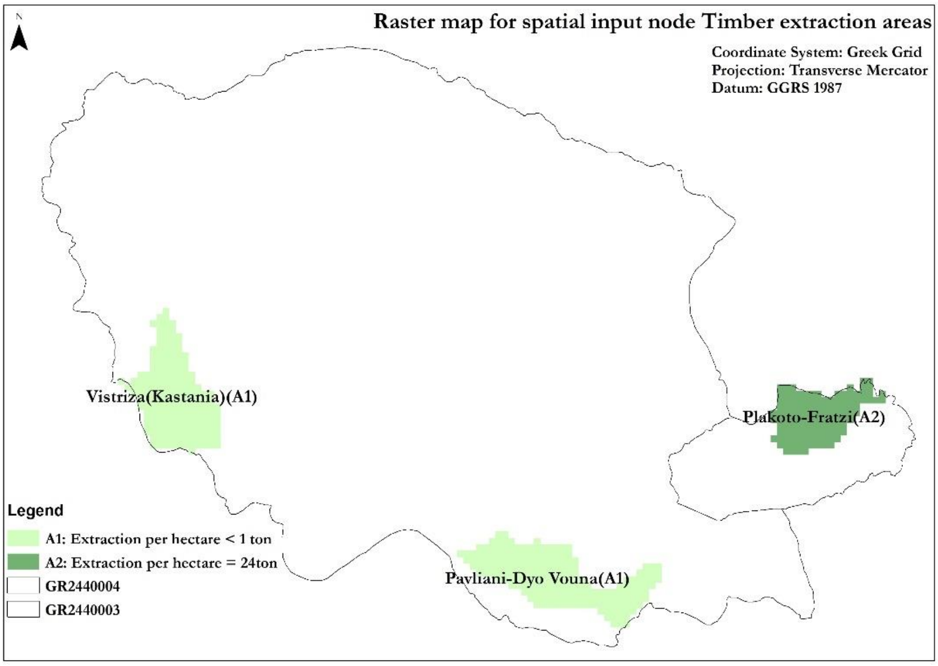


Figure A 15: Timber extraction areas as input to spatial node in BBN at 100m raster resolution

D. CPT for intermediate nodes (ESS flows)

Table A 18: CPT for ESS flow of hiking recreational service

ESS Flow		No. of visitors on hiking route		
Hiking Routes	**Seasons**	**Low**	**Medium**	**High**
Route1	Winter	0	0	100
Route1	Spring	0	0	100
Route1	Summer	0	0	100
Route1	Autumn	0	0	100
Route3	Winter	0	100	0
Route3	Spring	0	100	0
Route3	Summer	0	0	100
Route3	Autumn	0	100	0
Route4	Winter	0	100	0
Route4	Spring	0	100	0
Route4	Summer	0	0	100
Route4	Autumn	0	0	100
Route5	Winter	0	0	100
Route5	Spring	0	0	100
Route5	Summer	0	0	100
Route5	Autumn	0	0	100
Route6	Winter	100	0	0
Route6	Spring	0	100	0
Route6	Summer	0	100	0
Route6	Autumn	0	100	0
Route7	Winter	0	100	0
Route7	Spring	0	0	100
Route7	Summer	0	0	100
Route7	Autumn	0	100	0
Route8	Winter	0	100	0
Route8	Spring	0	0	100
Route8	Summer	0	0	100
Route8	Autumn	0	100	0
Route12	Winter	100	0	0
Route12	Spring	0	100	0
Route12	Summer	0	100	0
Route12	Autumn	0	100	0
Route13	Winter	100	0	0
Route13	Spring	100	0	0
Route13	Summer	100	0	0
Route13	Autumn	0	0	100

Table A 19: CPT for ESS flow of canyoning recreational service

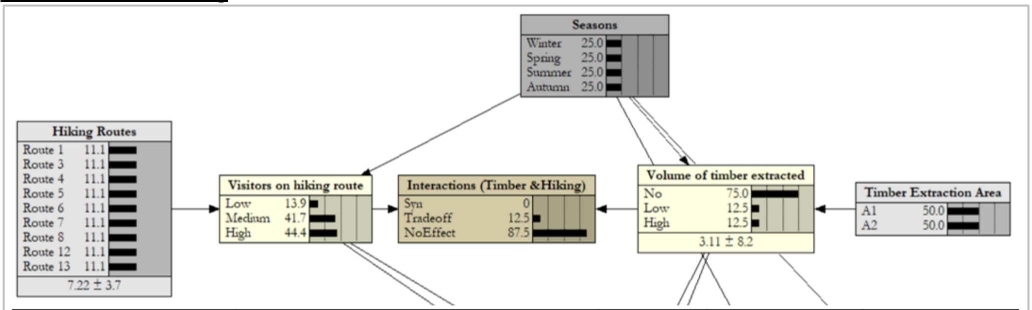
Seasons	**Canyoning Routes**	**No**	**Low**	**High**
Winter	Route1	100	0	0
Winter	Route2	100	0	0
Winter	Route3	100	0	0
Winter	Route4	100	0	0
Winter	Route5	100	0	0
Winter	Route7	0	0	100
Winter	Route8	100	0	0
Spring	Route1	100	0	0
Spring	Route2	100	0	0
Spring	Route3	0	100	0
Spring	Route4	0	100	0
Spring	Route5	0	0	100
Spring	Route7	0	0	100
Spring	Route8	0	100	0
Summer	Route1	0	0	100
Summer	Route2	100	0	0
Summer	Route3	100	0	0
Summer	Route4	100	0	0
Summer	Route5	100	0	0
Summer	Route7	0	0	100
Summer	Route8	100	0	0
Autumn	Route1	0	100	0
Autumn	Route2	100	0	0
Autumn	Route3	100	0	0
Autumn	Route4	100	0	0
Autumn	Route5	100	0	0
Autumn	Route7	0	0	100
Autumn	Route8	100	0	0

Table A 20: Table A 19: CPT for ESS flow of hunting recreational service

ESS Flow		**No. of game species killed**		
Season	**HuntingArea**	**NoKills**	**LowNumKills**	**HighNumKills**
Winter	Area1	0	100	0
Winter	Area2	100	0	0
Winter	Area3	100	0	0
Winter	Area4	0	100	0
Winter	Area5	0	100	0
Winter	Area6	100	0	0
Winter	Area7	100	0	0
Summer	Area47	0	0	100
Summer	Area48	0	0	100
Summer	Area49	0	0	100
Summer	Area50	0	0	100
Summer	Area51	0	0	100
Summer	Area52	0	100	0
Autumn	Area5	0	100	0
Autumn	Area6	100	0	0
Autumn	Area7	0	100	0
Autumn	Area8	100	0	0
Autumn	Area9	100	0	0
Spring	Area7	100	0	0
Spring	Area8	100	0	0
Spring	Area9	100	0	0
Spring	Area10	100	0	0
Spring	Area11	100	0	0
Spring	Area12	100	0	0
Spring	Area13	100	0	0
Spring	Area14	100	0	0
Spring	Area15	100	0	0

E. CPT for target nodes (Interactions)

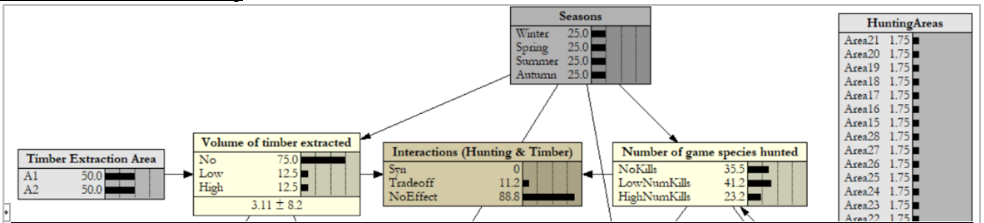
1.1 Timber and Hiking



Timber Extraction	No.of Visitors on Hiking Routes	Synergy	Trade-off	No-Effect
No	Low	0	0	100
No	Medium	0	0	100
No	High	0	0	100
Low	Low	0	0	100
Low	Medium	0	0	100
Low	High	0	0	100
High	Low	0	100	0
High	Medium	0	100	0
High	High	0	100	0

Figure A 16: CPT for Interactions node (Timber & Hiking)

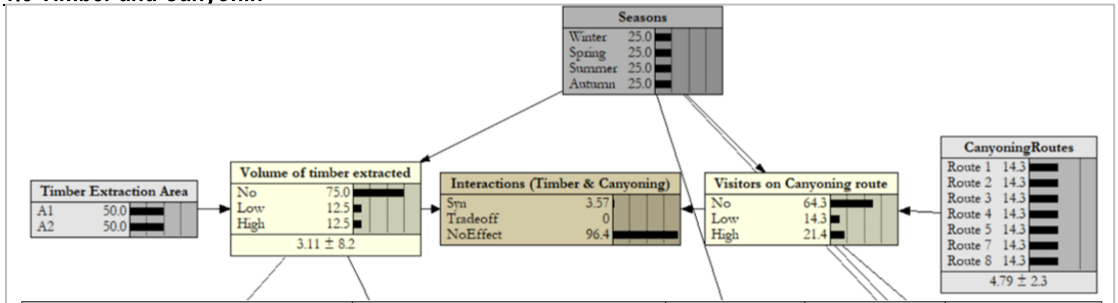
1.2 Timber and Hunting



No. of Game Species killed	Vol. of Timber Extracted	Synergy	Trade-off	No-Effect
NoKills	No	0	0	100
NoKills	Low	0	0	100
NoKills	High	0	0	100
LowNumKills	No	0	0	100
LowNumKills	Low	0	0	100
LowNumKills	High	0	100	0
HighNumKills	No	0	0	100
HighNumKills	Low	0	0	100
HighNumKills	High	0	100	0

Figure A 17: CPT for Interactions node (Timber & Hunting)

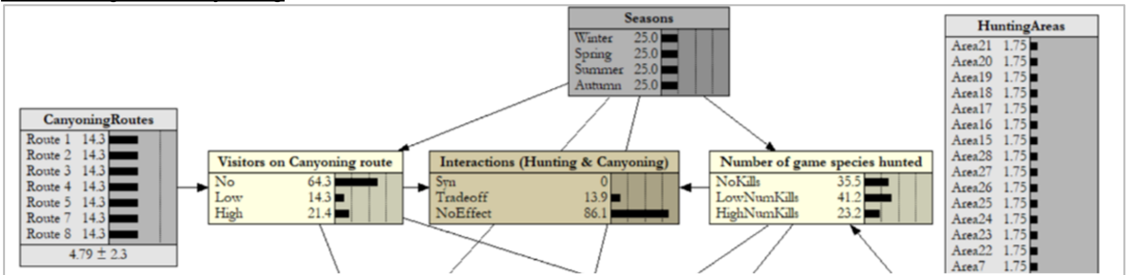
1.3 Timber and Canyonin



Volume of Timber extracted	No. of Visitors Canyoning Route	Synergy	Trade-off	No-Effect
No	No	0	0	100
No	Low	0	0	100
No	High	0	0	100
Low	No	0	0	100
Low	Low	100	0	0
Low	High	0	0	100
High	No	0	0	100
High	Low	0	100	0
High	High	100	0	0

Figure A 18: CPT for Interactions node (Timber & Canyoning)

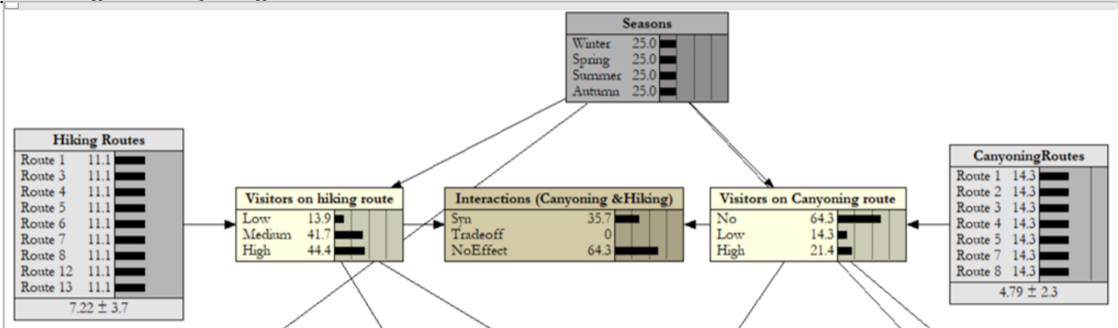
1.4 Hunting and Canyoning



No. of Game Species killed	No. of Visitors Canyoning Route	Synergy	Trade-off	No-Effect
NoKills	No	0	0	1
NoKills	Low	0	0	1
NoKills	High	0	0	1
LowNumKills	No	0	0	1
LowNumKills	Low	0	0	1
LowNumKills	High	0	1	0
HighNumKills	No	0	0	1
HighNumKills	Low	0	1	0
HighNumKills	High	0	1	0

Figure A 19: CPT for Interactions node (Canyoning & Hunting)

1.5 Hiking and Canyoning



No.of Visitors Hiking Route	No.of Visitors Canyoning Route	Synergy	Trade-off	No-Effect
Low	No	0	0	100
Low	Low	100	0	0
Low	High	100	0	0
Medium	No	0	0	100
Medium	Low	100	0	0
Medium	High	100	0	0
High	No	0	0	100
High	Low	100	0	0
High	High	100	0	0

Figure A 20: CPT for Interactions node (Canyoning & Hiking)

E. Mutual Information charts

1. Target Node: Interactions (Timber & Hiking)

As timber is extracted in Summers and it is assumed that the influence of timber extraction takes place only when it happens and does not last after extraction has taken place, so the mutual information is available only for Summers.

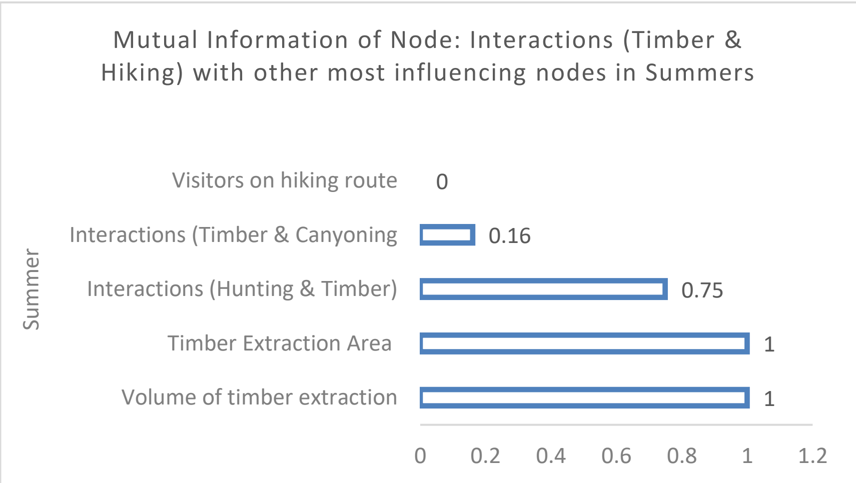


Figure A 21: The mutual information for Interactions (Timber & Hiking) node with seasons evidence being Summers

From Figure A 21, it is observed that the degree of dependence between the target node Interactions (Timber & Hiking) and volume of timber extracted is the highest (0.54), which tells us that volume of timber extracted node has the strongest impact on the interactions among the two services followed by interactions (hunting and timber) node and seasons node. The visitors on hiking route has relatively very small influence (0.02) on the Interactions node. This information about ESS: timber extraction having most influence is similar to what the experts had described during the interviews and helps validate the CPT filled in the BBN. It is observed that as expected when the season is Summer, volume of timber extraction has the highest impact on interactions (timber and hiking) and this node can further be used to provide more information about the interactions node while the number of visitors on hiking route becomes independent and does not contribute any more information for interactions node. When the evidence is set to Summers for seasons node, it is observed that the degree of dependence between the target node Interactions (Timber & Hiking) and volume of timber extraction (ESS flow of timber) is the highest (1: total dependency), which tells us that number of volume of timber extraction node has the strongest impact on the interactions among the two services followed by Interactions (Hunting and timber). The visitors on hiking route has no influence (0) on the Interactions node.

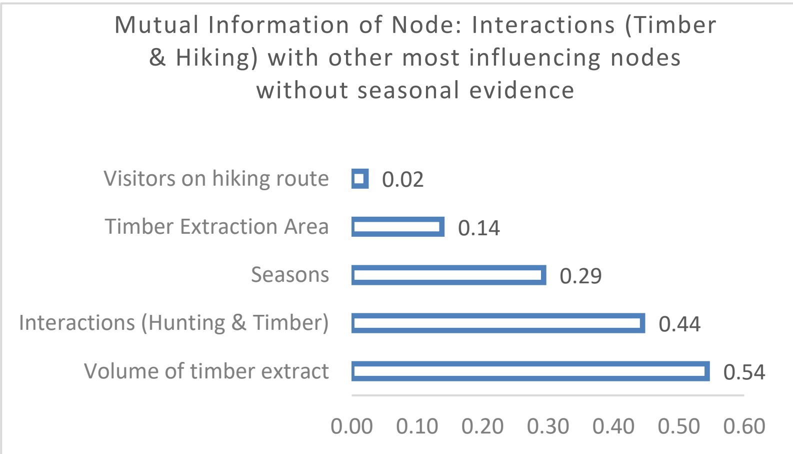


Figure A 22: The mutual information for Interactions (Timber & Hiking) node without seasonal evidence

This information about ESS: recreational hiking not influencing volume of timber extracted is what the experts had described during the interviews while when the volume of timber extracted is known, the information about interactions between timber and hiking will be known too as the dependence is complete (1).

2. Target Node: Interactions (Canyoning & Hiking)

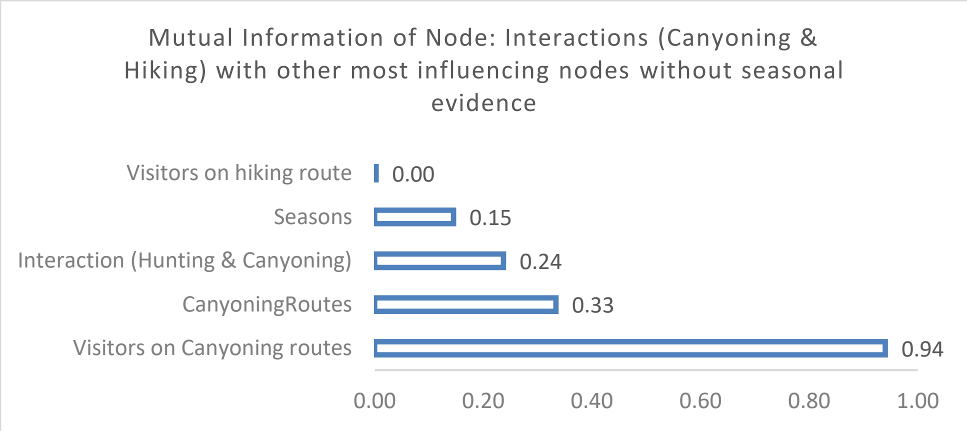


Figure A 23: The mutual information for Interactions (Canyoning & Hiking) node without seasonal evidence

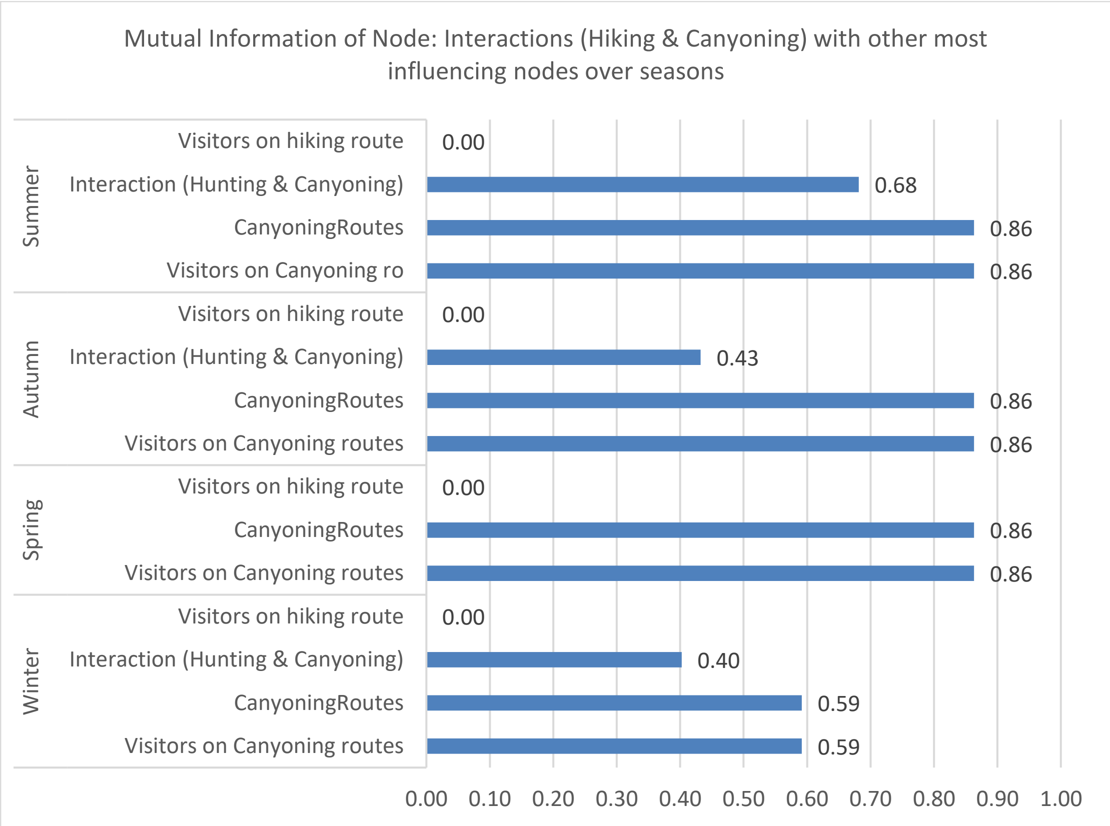


Figure A 24: The mutual information for Interactions (Canyoning & Hiking) node with season evidence of winter summer spring and autumn individually

From Figure A 23, it is observed that the degree of dependence between the target node Interactions (Canyoning & Hiking) node and visitors on Canyoning routes is the highest (0.94), which tells us that visitors on Canyoning routes node has the strongest impact on the interactions between the two services followed by interactions (hunting and canyoning) node and seasons node. The visitors on hiking route has relatively no influence (0) on the Interactions node. This information about ESS: visitors on Canyoning routes: having most influence is similar to what the experts had described during the interviews and helps validate the CPT filled in the BBN. It is observed that this node can further be used to provide more information about the interactions node while the number of visitors on the hiking route becomes independent and does not contribute any more information for interactions node.

3. Target Node: Interactions (Canyoning & Hunting)

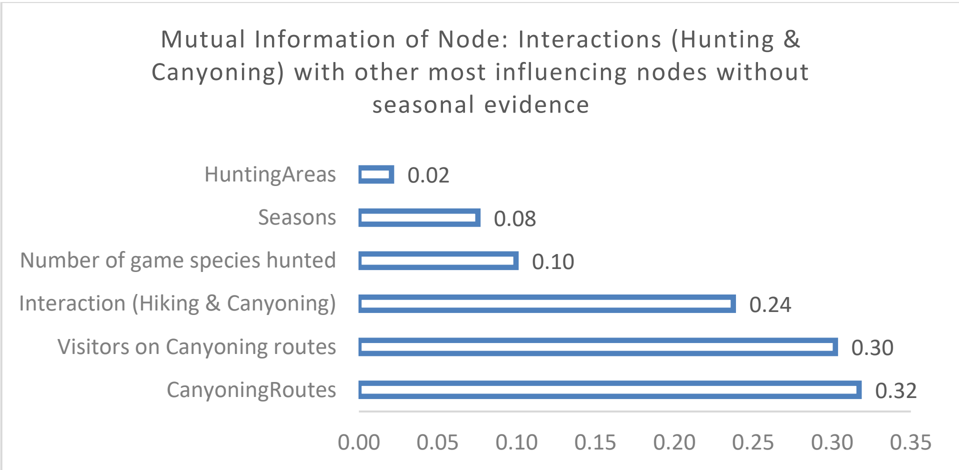


Figure A 25: The mutual information for Interactions (Canyoning & Hunting) node without seasonal evidence

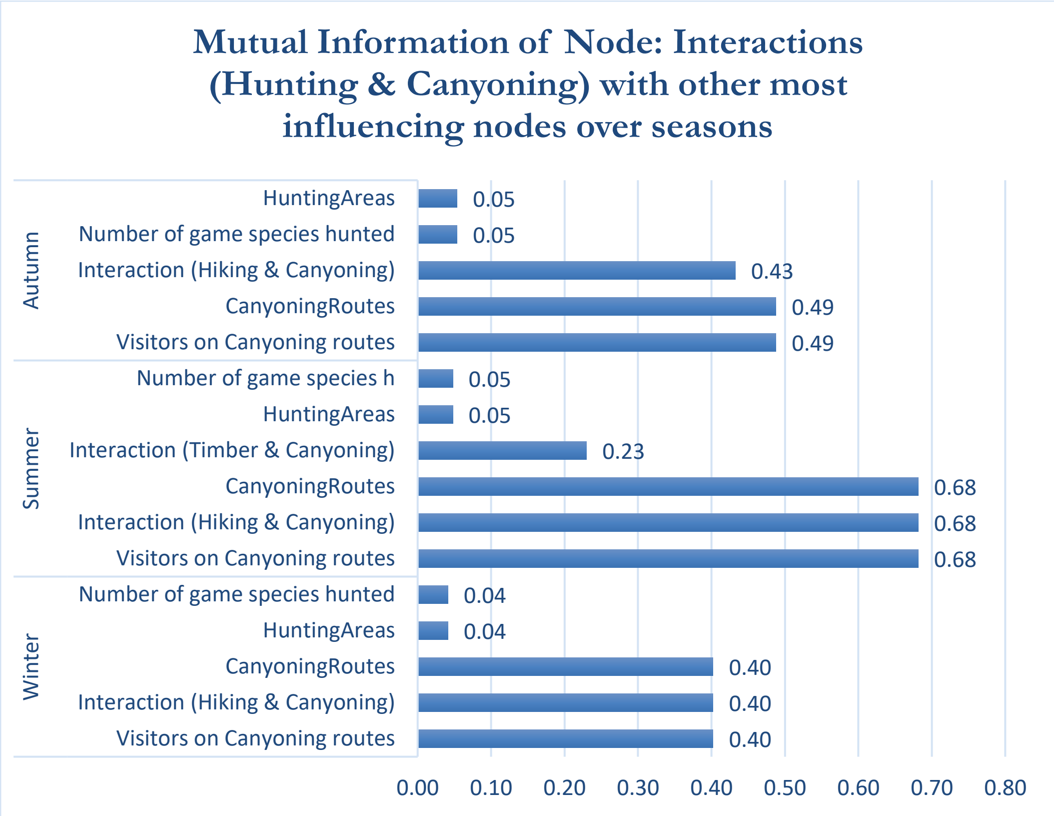


Figure A 26: The mutual information for Interactions (Canyoning & Hunting) node with season evidence of winter summer and autumn individually. No hunting during spring so no interaction

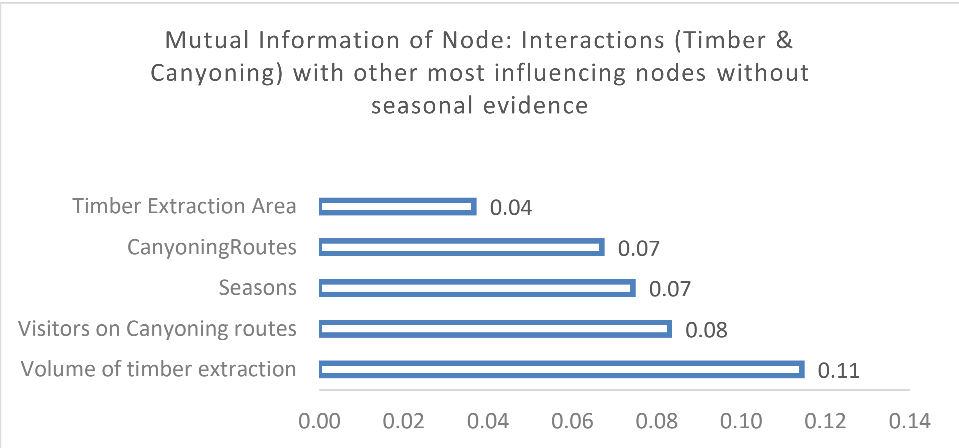


Figure A 27: The mutual information for Interactions (Canyoning & timber) node without seasonal evidence

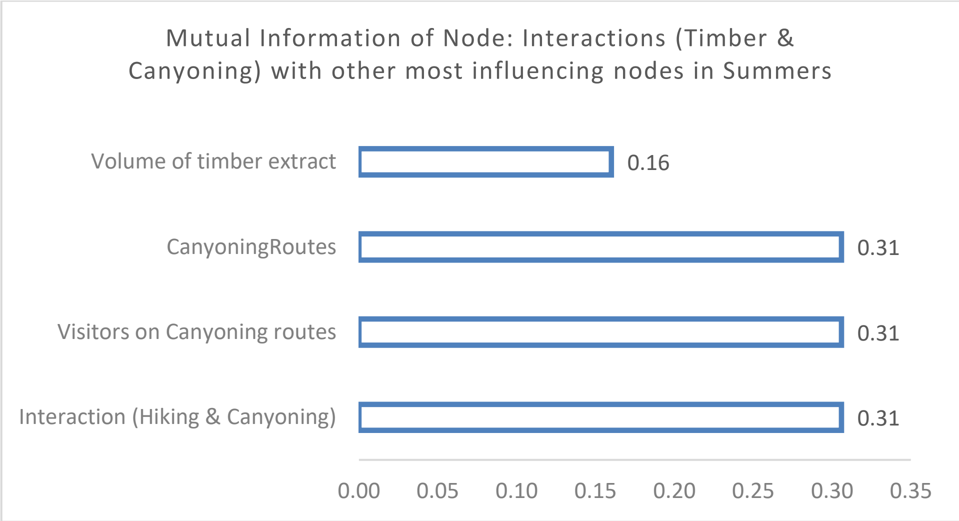


Figure A 28: The mutual information for Interactions (Canyoning & Hiking) node with season evidence of summer as no interaction during other months as timber extraction does not occur

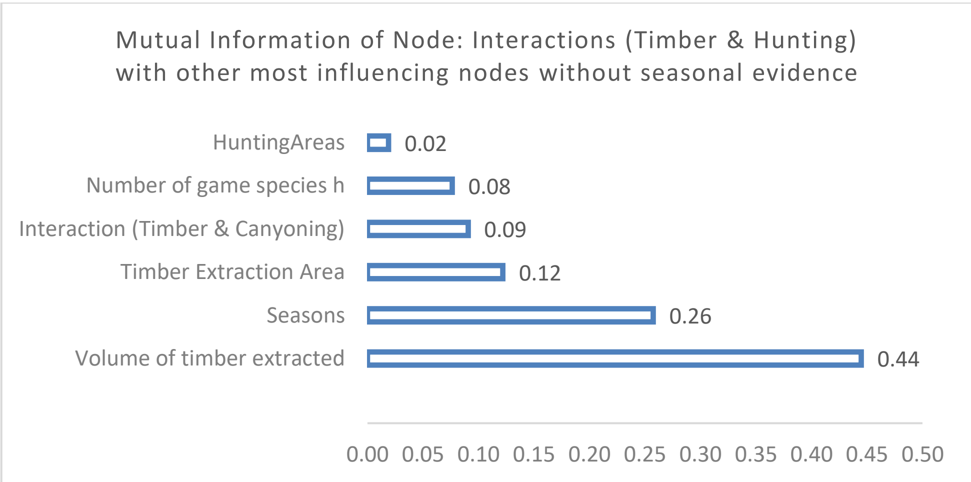


Figure A 29: The mutual information for Interactions (Timber & Hunting) node without seasonal evidence

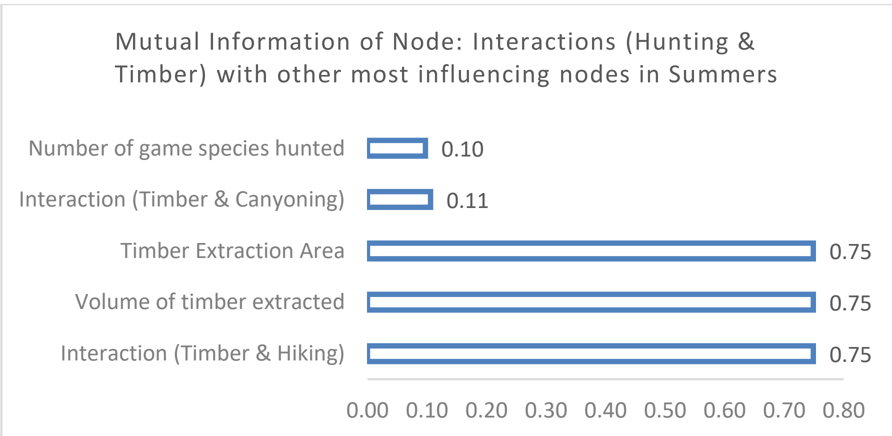


Figure A 30: The mutual information for Interactions (Canyoning & Hiking) node with season evidence of summer as no timber is extracted in other seasons so no interaction