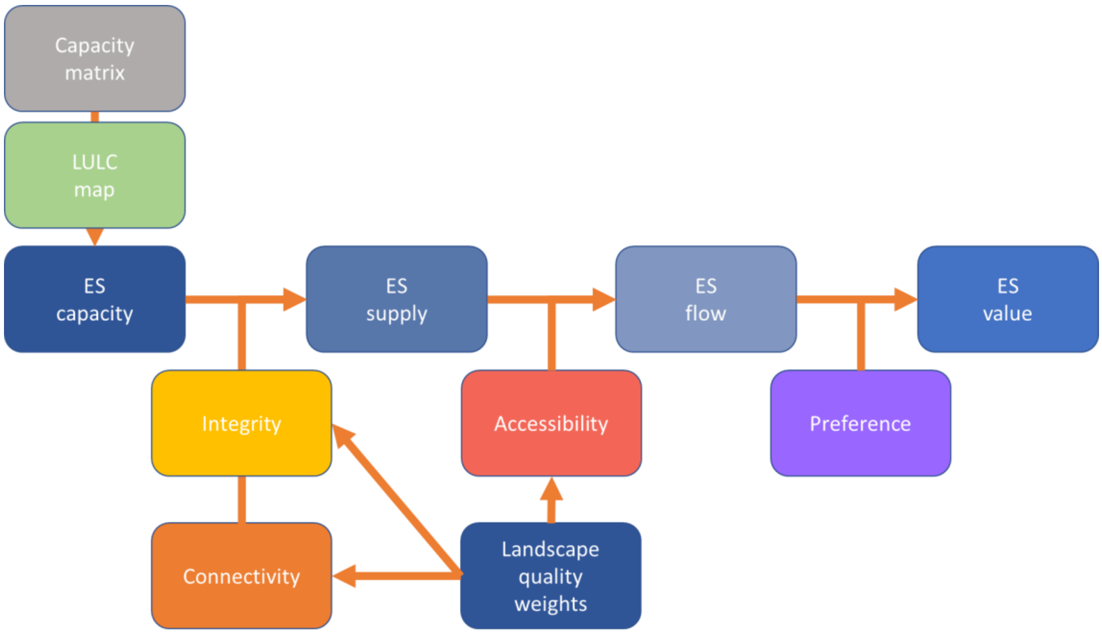
"COOKBOOK" SERIES N$^{O}$ 7

Suškevičs, M. and Roche, P.K. (Editors)

# Developing adaptive landscape planning tools for the allocation of Green Infrastructure

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## Foreword

Often the methodological side in (applied) biodiversity projects remains unelaborated as "tacit" expert knowledge, and after the project's end, is scattered across different guidelines, or is elaborated in the method's sections in respective scientific publications. This might hinder the effective use of such knowledge and experiences.

The IMAGINE "cookbooks" is a series of guidelines intended to provide guidelines and support for scientists and practitioners working on Green Infrastructure (GI) issues. Our intention with this series is to make such methodological knowledge ("how to?") more readily available for two main potential user groups:

- other scientists working on Green Infrastructure ecological or socio-political aspects;
- national, regional, or local policy-makers and GI managers, who need some advice on practical aspects of GI governance.

This series consists of nine guidelines, with the following topical focuses for:

1. Evaluating ecosystem services capacity
2. Assessing GI vulnerability to ecosystem degradation at the landscape scale
3. Assessing detailed GI habitat quality for biodiversity and ecosystem services
4. GI management for ecosystem services
5. Analysing coherence between different policies affecting GI
6. Analysing GI stakeholders, social frictions and opportunities
7. **Adaptive planning tools for the allocation of GI (this cookbook)**
8. Quantifying GI structure and connectivity in GI elements
9. Defining and evaluating ecosystem condition

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## List of Acronyms

| | |
|---|---|
| BBN | Bayesian Belief Network |
| CPT | Conditional Probability Table |
| CSS | Case Study Sites (within the IMAGINE project) |
| DAG | Directed Acyclic Graph |
| EDS | Ecosystem Disservices |
| ES | Ecosystem Services |
| GI | Green-Blue Infrastructures |
| SES | Social-Ecological System |
| SMCDA | Spatial Multi-Criteria-Decision Analyses |

# 1. Background and objective of the cookbook

The IMAGINE project studied the complex interactions of Green-Blue Infrastructures (GI), and Ecosystem Services (ES) and Disservices (EDS) dynamics across six Case Study Sites (CSS) across Europe (Etang de Thau, France; Scarpe-Escaut, France; Grote Nete, Belgium; Bornhöve, Germany; Tallinn, Estonia; Trondheim, Norway). Employing an integrated and interdisciplinary approach is essential to support the exploration of barriers, trade-offs and opportunities for GI design and management in urban and rural landscapes. The 'IMAGINE approach' identifies six key topics that address the various components of GI dynamics: (1) GI structure and connectivity; (2) GI habitat quality; (3) ecosystem (dis)service provided by GI; (4) social valuation of GI interests; (5) policy coherence related to GI; (6) integrated GI management. To aid scientists and practitioners in the application of the 'IMAGINE approach', six easy to use cookbooks have been developed to apply the methods used. **This cookbook (no. 7)** addresses the sixth key topic, "*to propose models for evaluating alternative design and management options of GI at landscape level*". The cookbook presents the development of a Bayesian Belief Network (BBN) model to combine and integrate knowledge obtained from other key topics (especially key topic 1-3) into a social-ecological systems framework to map the ecosystem (dis)service provisioning of GI. This was done for all of the case study sites across Europe as part of the so-called Core Set activities. The mapped ecosystem (dis)services are thereafter used as input to a GI design and decision-support toolbox. This toolbox, called ConSite Urban, supports the integration and management of GI in spatial planning. This toolbox was within the IMAGINE project applied to two case study sites (Scarpe-Escaut, France; Trondheim, Norway). This cookbook will therefore help produce the following:

- 1a) A Bayesian Belief Network (BBN) model linking GI management with ES and EDS outcomes (Core Set)
- 1b) A spatially explicit model where the BBN model is implemented with site-specific land cover maps (Core Set)
- 2a) An GIS interface to visualize mapped ES and EDS in the landscape, encapsulated in the ConSite Urban toolbox (optional)
- 2b) An adaptive design and decision-support toolbox (ConSite Urban) for integration and management of GI in spatial planning (optional)

Both the BBN model and the ConSite toolbox provide analytical tools with the potential to improve GI planning and management. BBN models incorporate data and knowledge from different sources within a graphical model format to help inform decision making through better understanding of functional relationships between the different variables. The Spatial Multi-Criteria Decision Analyses (SMCDA) framework of ConSite (Hanssen *et al*. 2018) allows for visualization of spatially explicit trade-offs to help inform decision makers by enabling visualizing the spatial consequences of various what-if scenarios. For the IMAGINE project, the BBN framework is used to structure and map the social-ecological system pertaining to ecosystem (dis)service provisioning of GI. The built-in functions of the ConSite toolbox aim at visualizing ecosystem (dis)services in the landscape, identifying socio-ecological bottlenecks, directing ecological restoration needs and predicting spatial effects of human impacts on GI. The first part of this cookbook describes the steps required for developing and testing the BBN model. The second part of the cookbook describes the steps for gathering inputs required for the ConSite Urban toolbox.

# 2. Main phases and steps

## 2.1. Bayesian Belief Network (BBN)

The main purpose of the BBN model in IMAGINE is to *integrate* the outputs from other key topics as part of the Core Set activities, such that stakeholders can see how their contributions regarding these various aspects of GI-ES dynamics interact within a Social-Ecological System (SES). By illustrating the synergistic value generated by connecting these different elements, allows showing how each component contributes to achieve the integrated 'IMAGINE approach'. This integration requires both *aligning* and *standardizing* the Core Set outputs from key topics in other IMAGINE work packages (see the other IMAGINE cookbooks for details). In the IMAGINE project this was done for all six CSS. The generic integrated BBN model, referred to as the Core Set BBN model, incorporates both the quantitative and qualitative findings from Core Set activities assessing ES/EDS, their linkages to GI, ecosystem quality (connectivity, integrity) and management (**Figure 1**). Many of the Core Set outputs either consist of or link to spatially explicit (georeferenced) data. This enables to use of the Core Set BBN model to generate comparable output maps for that depict ES and EDS spatial distribution for each CSS (i.e. the spatially-explicit modelling where the BBN model will be implemented with CSS-specific land cover maps). Such maps visualize the variation in the spatial distribution of a number of different GI-ES related phenomena: such as conflicts/trade-offs, management outcomes, access issues, as well as various measures of uncertainty.

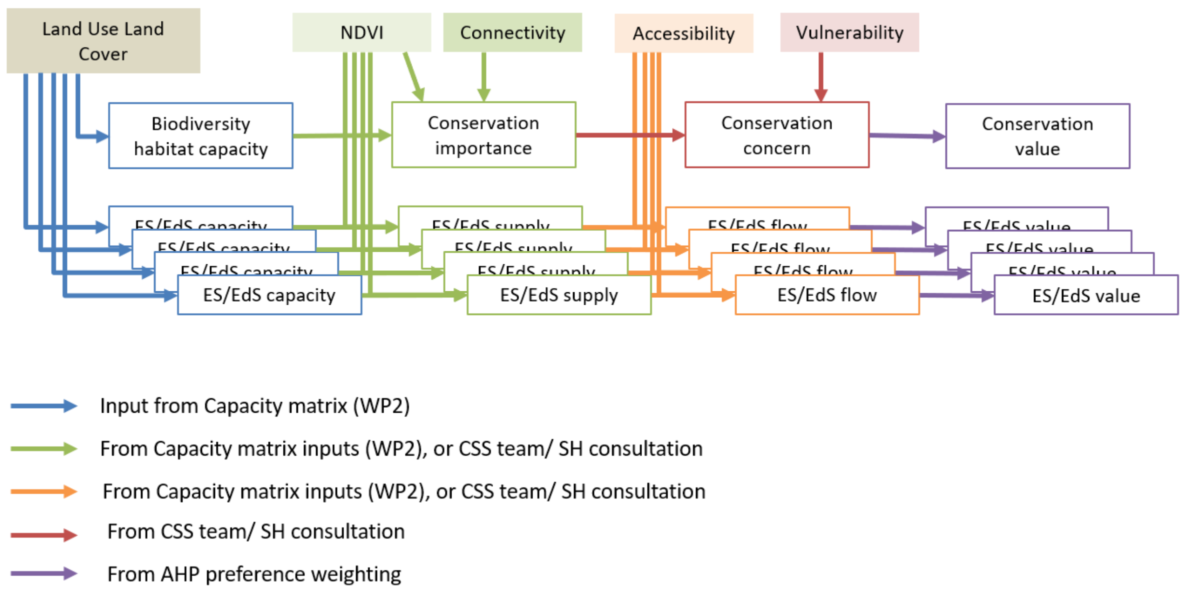



**Figure 1.** *Simplified schematic overview of the Core Set BBN model integrating outputs from other key topics presented as either input variables (boxes) or parameters for functional relationships (arrows).*

### Tailored CSS-specific BBN model – options and recommendations

Although performed generically for all CSS in IMAGINE, the Core Set BBN model framework can be adjusted and applied to help address site-specific key management challenges. The standardized inputs needed for comparison across all six CSS inherently entail restrictions that might limit a general model's usefulness for a particular management issue identified by any specific study site. However, by *tailoring* data inputs (for example by using a site-specific land cover typology or by addressing ES/EDS that are not part of the Core Set), tailored BBN model outputs can be generated (including any maps) with a higher expected level of usefulness to a site's local stakeholders. Tailored BBN models were not a Core Set activity in the IMAGINE project, but were optional for those CSS who wish to implement them. It is therefore beyond the scope of this cookbook explain how to generate site-specific BBN models from the ground up. Similarly, any data scientists and/or practitioners identify as potentially relevant for a site-specific model must be extant and readily available, or easily obtainable in combination with other Core Set activities. While methodologies for tailored BBN models and the ConSite Toolbox differ, the outputs they might generate share similar features. We anticipate that pursuing both will present an opportunity to compare their respective usefulness in spatial planning.

For those unfamiliar with BBN models, we strongly suggest reading the brief introduction to BBN in Appendix A before continuing to read the steps in this cookbook. This cookbook's BBN recipe essentially follows a general protocol for BBN modelling (Jakeman *et al*. 2006, Chen and Pollino 2012). The "BBN_Cookbook CSS_Info.xlsx" Excel file provides a form for the scientists or practitioners doing this (hereafter: CSS team) to report the steps described here. CSS teams can determine the degree of stakeholder input for each of the steps listed below. We do not anticipate that the steps for the BBN cookbook should be anywhere near as time-consuming as other activities. With very few exceptions, we expect stakeholders will mainly provide input through the other Core Set activities.

## Preparatory work

Both this key topic and other Core Set activities require that CSS teams have a clear idea of what central management issues are most interesting for their stakeholders. CSS teams should have discussed and identified the 'issues at stake' and problem-setting in their first stakeholder meetings last year (see Cookbook no. 6). If not yet in place, the CSS team can provide a handful (2-4) possibilities and let the stakeholders help decide which one to pursue.

## Step 1 – Establish model purpose

<u>Objective:</u> Within the setting of the IMAGINE project the specific goals were agreed upon for generating an integrated Core Set BBN model to primarily illustrate the spatial relationships between GI, ES/EDS and biodiversity conservation. For each of the CSS (scientists as well as key stakeholders if feasible) used the reporting form to rank and describe the most relevant motivations for producing a BBN model of the GI-ES/EDS dynamics at their site. For the project as a whole, this formed the basis to generate the Core Set BBN model. CSS-specific models that focus on particular management challenges may be possible with minor modifications to this standard model.

<u>Rationale:</u> All modelling exercises begin by carefully considering the *motivation* and *goals* for the BBN model. Here, one needs to go beyond simply stating *what* we want a model to do (such as compare GI management along an urban to rural gradient), and articulate *why* we want to model a system and what we hope to gain from the endeavour. Obviously, the goals and motivations of modelling a GI and its SES context should contribute in some way to addressing a CSS's key management challenge. BBN modelling approaches have historically been a preferred method for exploring management alternatives in the face of uncertainty. In many cases, competing management alternatives imply a trade-off of some sort. In the context of the objectives of the IMAGINE project, a potential motivation

could be investigating anticipated trade-offs between non-overlapping or otherwise incompatible ES, and/or biodiversity. They could also address the trade-offs presented by ES (or bundle of similar ES) provision with associated EDS. However, BBN models also have broader utility, such as structuring discussions or predicting outcomes of management choices. Using the list of examples, CSS teams might identify a motivation that will help direct how they apply BBN model processes and outputs within their site.

## Step 2 – Specify modelling context (scope and resources)

Objective: The CSS team determines which outputs are amenable to the Core Set BBN model. While this step is an important part of any modelling exercise, the modelling context for the IMAGINE Core Set BBN models were largely determined by the structure and availability of CSS output data (see cookbooks no. 1...4 and 8...9) as well as the GI management challenge (see cookbooks no. 5 and 6).

Rationale: This step clarifies the specific problem the BBN model will address and identify the key components of the system. The defined objectives determine the modelling context for the integrative BBN Core Set model.

## Step 3 – Conceptualize the social-ecological system

Objective: The CSS team develops a common conceptual model for the Core Set BBN model through an iterative process as the outputs from other key topics become available and their context becomes clearer (i.e. adaptive approach given stakeholder and/or expert inputs). CSS teams and their key stakeholders can potentially offer suggestions for how to tailor the Core Set BBN conceptual model to address a CSS's specific central management issue.

Rationale: A Directed Acyclic Graph (DAG) (see also Appendix A for a graphical example) is the BBN's graphic representation of relevant variables (*nodes*), with arrows connecting the nodes to illustrate the direct dependence relationships (*links*) between variables (see examples in Appendix A if these terms are unfamiliar). This step involves building the conceptual structure that becomes the model's DAG, including identifying the intermediate and output nodes that can be derived from the input data. When making CSS-tailored models, the amount of changes to the general structure Core Set model's DAG can be limited by relying more on altering or modifying data supplied by the Core Set BBN model. When suggesting modifications to the Core Set BBN conceptual model, CSS teams and stakeholders should strive for parsimonious (simple) models that use as few nodes and links as necessary to capture the system's focal elements. If CSS teams are interested in pursuing modifications that would add complexity to the Core Set BBN model, they should also consider and suggest other modifications could reduce the complexity compared to the Core Set BBN model.

## Step 4 – Decide how to find parameter values

Objective: The CSS team will determine the set of states for each node and thus the conditional probability table (CPT) structure for all output nodes. The data for populating both nodes and CPTs will be standardized outputs from Core Set activities of other key topics, and other cookbooks will provide CSS teams with the appropriate methods. For parameters not derived from Core Set activities, the CSS teams can themselves generate node and CPT structures that are compatible with the Core Set BBN model.

Rationale: One characteristic of BBNs is that the data for each node must be a discrete random variable, which is a finite and exhaustive set of mutually exclusive *states* (think categorical or ordinal variables, with continuous variables converted into intervals). Independent variables, or *parentless nodes*, will have parameter values that represent marginal probability distributions. The dependent variables, *or child nodes*, will have conditional probabilities that we will allocate for each combination of states from their parent nodes, and these conditional probabilities are what constitute the conditional probability tables (CPT). The size of each CPT depends on the number of parent nodes and how many states they have. We can obtain the conditional probabilities for child nodes from datasets, process equations, input from experts and stakeholders if necessary, or a combination of several external knowledge sources. Furthermore, the GIS interface that the BBN software uses requires that all variables be expressed as intervals.

## Step 5 – Select estimation performance criteria and technique

Objective: CSS teams provides suggestions for possibilities to verify BBN model outputs for the standardized Core set BBN models. Are there independent datasets not used for model parameterization? Alternatively, would stakeholders' qualitative assessment of model outputs be sufficient given the motivations for the model? This step does not constitute an actual assessment of performance (this happens at Step 9), but rather planning for how a model might ultimately be evaluated.

Rationale: It is important to evaluate how well the desired output of the BBN model, both in terms of the motivation behind the model and the output maps, either represents reality or contributes to making better decisions regarding GI management. CSS teams will therefore need to think about ways to evaluate both Core Set and CSS-tailored BBN models' performance. Are there independent data or complimentary models that might provide model verification? In cases where the primary motivation of the BBN model is either social learning or system understanding, stakeholder opinions regarding the plausibility of the model or its realistic behaviour might be adequate. Similarly, BBN modelling software can be used to conduct a sensitivity analysis (built-in functions for this are available in both Netica and Hugin software packages; both require a user license) to determine which parameters have the greatest influence on the system. Such analyses are particularly useful if stakeholders are interested in gaining a better understanding of the role and nature of uncertainty in their system, since it can help identify the sources of uncertainty and provide suggestions for how it might be reduced.

## Step 6 – Identify model structure and parameters

Objective: The CSS team will conduct a feasibility test to verify that the model design meets the requirements for a BBN. This may include consultation with other scientists for external assistance with resolving errors, data gaps, limitations or other issues.

Rationale: This step constitutes a feasibility test of the BBN model. The CSS team evaluates whether the DAG and marginal or conditional probabilities meet the necessary criteria. Thereafter, any disagreements or unclarities can be resolved.

## Step 7 – Conditional verification and diagnostic testing

Objective: The CSS team, with possible feedback from stakeholders, assesses plausibility of the BBN model if necessary.

Rationale: The CSS team will investigate parts of the model or the whole model with various operational scenarios on input combinations to test whether the model exhibits plausible behaviour. In the likely event that help is needed from stakeholders or other scientists to assess plausibility, their feedback can be solicited at this time. Please note that in this context, modelling scenarios refer to fixing a particular input variable's state and observing the behaviour of the outputs. These operational scenarios within the modelling context might correspond with management scenarios identified by a CCS's key management challenge, but this step does not describe what one might call a proper scenario analyses.

## Step 8 – Quantify and manage uncertainty

Objective: CSS teams give their initial impressions regarding possible sources of uncertainty, on the reporting form.

Rationale: One of the strengths of the BBN approach is its ability to quantify uncertainty within the model. Uncertainty can arise from an incomplete understanding of the system and its processes, the stochastic nature of the system's drivers, data limitations, or subjective attitudes of the experts who helped generate conditional probabilities. However, the BBN itself does not have the ability to distinguish between these sources of uncertainty or error. It is therefore important to think carefully about which types of uncertainty might apply to your social-ecological system and make certain this information is a part of communicating model outcomes. A line is provided on the reporting form to enter initial impressions regarding possible sources of uncertainty. However, anticipate that a better understanding of uncertainty's role in a CSS's social-ecological system will come from working through the modelling process. This step will be revisited during Step 9.

## Step 9 – Model evaluation and testing

Objective: The CSS team evaluates the model outputs and behaviour with respect to the initial motivation of the modelling exercise together with their stakeholders, preferably at one of their final meetings.

Rationale: Once the Core Set BBN model has been built and the necessary initial diagnostic tests have been performed (Steps 6 and 7), the model can finally be run and its outputs shared with stakeholders. Here it may either be possible to perform model execution prior to stakeholder dialogue, or facilitate stakeholders' active exploration of a model's performance. Step 9 serves as a reminder that executing the model also requires evaluating the model outcomes with respect to the initial motivations of the modelling exercise. There is no input required for this step at this phase, although CSS teams need to make a mental note that they seek stakeholder opinions of the produced models to evaluate their usefulness.

## 2.2. Adaptive planning toolbox (ConSite Urban)

ConSite Urban aims to integrate, analyse and visualise GI in land use and zonal planning at local and regional scales. The toolbox is developed in desktop ArcGIS Advanced 10.7 (ESRI) and helps to quantify ecosystem services/disservices, identify socio-ecological bottlenecks, direct ecological restoration needs and predict spatial effects of human impacts within the Green Infrastructure (GI). The main purpose of the toolbox is to spatially assess the consequences of different management scenarios (i.e., What If…), and direct management actions, for the development of GI placement and design; and to provide decision-support for integration and management of GI in spatial planning. The toolbox is useful both for land use/zonal planning, ecosystem-based management, area/green accounts as well as nature conservation and restoration purposes.

The toolbox is organised into four toolsets as explained below and illustrated on **Figure 2**:

- **Inform**. Pixel and zonal statistics
- **Identify.** Identification of statistically significant clusters of high and low ES/EDS values)
- **Mitigate.** Calculate cost-connectivity between GI-patches of high ES/EDS values
- **Predict**. Prediction of spatial effects of human impacts in GI

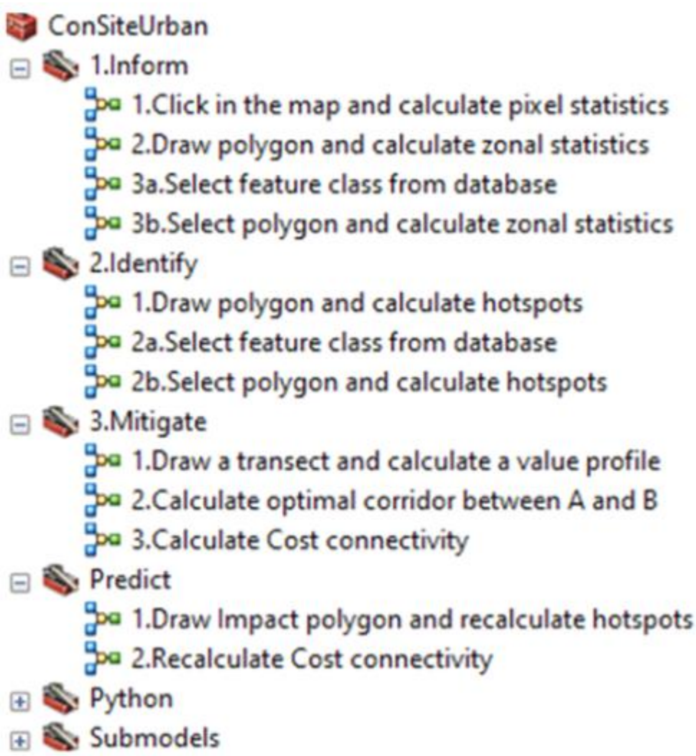



**Figure 2.** *The ConSite Urban toolbox.*

## Step 1 – Map ES/EDS capacity, supply and flow

Objective: The ConSite Urban toolbox is based on the mapped ES/EDS delivery (be that capacity, supply, flow or value). This is performed by the CSS team either as part of the ConSite routines, and directly based on the Capacity Matrices (Cookbook no. 1) or utilizing the mapped outcomes of the Core Set or tailored BBN model (see section 2.1). Routines for estimation of these maps are established both in the BBN-model and in ArcGIS (outside the ConSite Urban toolbox).

Rationale: The Capacity Matrix outcomes (Cookbook no. 1) are used to map the potential ES/EDS capacity based on the CSS land cover map. Each capacity map is then weighed by the spatial distribution of three structural quality attributes: integrity and connectivity and accessibility (Cookbook #8) into ES/EDS delivery maps as illustrated in Figure 3 below.

The mapping of Ecosystem (Dis)Service (ES/EDS) delivery (be that ES/EDS capacity, supply, flow or value) is based on a combination of the Capacity Matrix (Cookbook no. 1) to map the capacity of each land cover type to deliver a specific ES/EDS, together with a Landscape Quality Matrix (see **Table 1**) to map the importance of landscape qualities to deliver specific ES/EDS. Simultaneously with the Capacity Matrix exercise (Cookbook no. 1), expert stakeholders will also score the importance of three landscape qualities for the delivery of each ES/EDS: ecological integrity, relative connectivity and accessibility. Using the same approach as for the Capacity Matrix, stakeholder scores (0 = not relevant, 1 = of little importance … 5 = very important) are used to weigh ES/EDS capacity according to the spatial distribution of the three landscape qualities (Cookbook no. 1). For each score, stakeholders also enter a confidence index (1-3), following the same procedure as for the rest of the Capacity Matrix.

ES capacity was measured through a stakeholder-elicited capacity matrix scoring exercise (averaged over all stakeholders). The capacity matrix scores all ES for each of the LULC. ES supply was calculated by multiplying this capacity matrix by ecological integrity and potentially also connectivity where of relevance. In the IMAGINE project, species connectivity was only used for biodiversity-related ES. The same approach was also used to multiply ES supply with accessibility to obtain ES flow. Prior to this, each landscape quality is taken to the power of ES-specific quality weights (0 – 1). In cases where e.g. integrity is of no importance (weight equals 0) for obtaining a specific ES supply, the mapped integrity will 1 and ES supply would in that case equal ES capacity. Larger weights puts more importance to e.g. integrity consequently differentiating ES supply more from ES capacity.

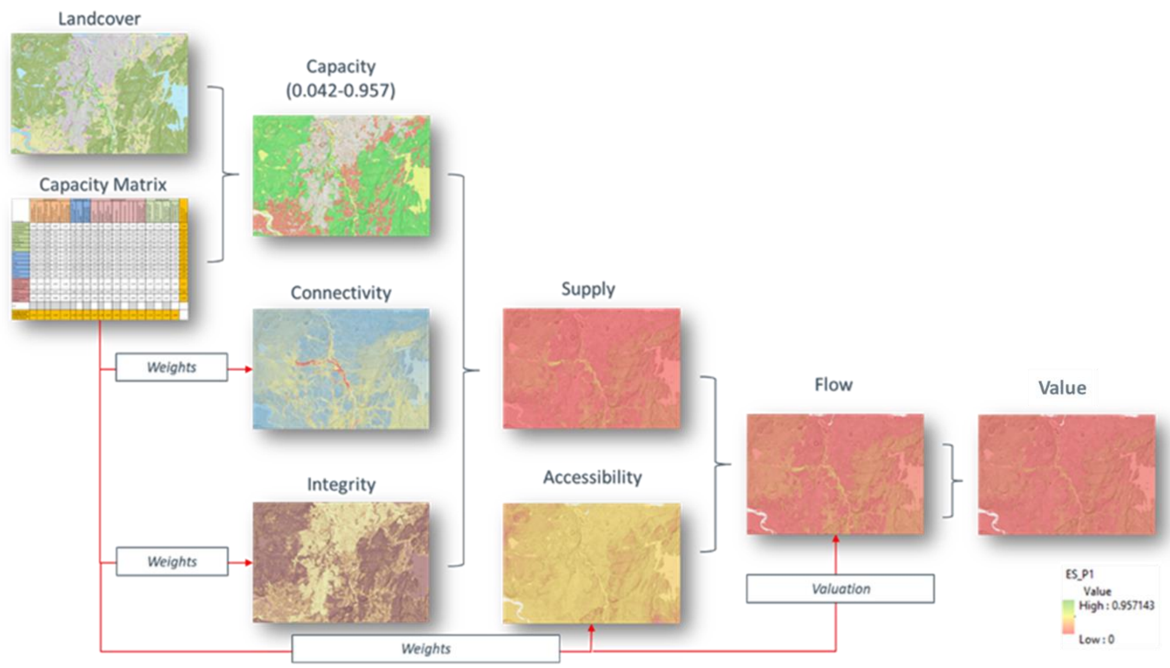



**Figure 3.** *The estimation of potential ES/EDS delivery maps.*

**Table 1.** *Landscape Quality Matrix example*.

| **How important are the following landscape quality characteristics of *relevant land cover types (those with a potential/capacity 1-5)* for the delivery of a certain ES/EDS?** | ES #1 | EDS #1 | Confidence |
|---|---|---|---|
| Ecological intact / naturalness | | | |
| Unfragmented / connected | | | |
| Accessible / Proximate to human settlements | | | |
| Confidence Index (1-3) | | | |

## Step 2 – Weigh the relative importance of ES/EDS to map ES value

Objective: The CSS team will solicit relative importance of all possible ES/EDS pairwise comparisons from their stakeholders using the Analytical Hierarchy Process (AHP) method (for background on the method, see Appendix 2). The AHP weighing of relative importance of the all ES/EDS allows the consolidated estimation of the different ES/EDS value maps, as well as aggregation of ES values into ES bundles (i.e. weighted summation).

Rationale: All the ES/EDS must be compared pairwise where the stakeholders express their judgements and transform them into a pairwise comparison matrix using a numerical scale from 1-9 (Saaty 1980) (see Appendix B, **Table 1**). Following this exercise, a consolidated understanding of the AHP weighting procedure should be reached. This can be reached by sending out a digital survey to all stakeholders to confirm their weighting scores. This allows the inclusion of stakeholders that were not able to join in the dialogue meeting and/or stakeholders who were not participating actively during the dialogue meeting. This enables assessing both the impact of the deliberative approach that may have occurred during the dialogue process, but also allows individuals to give their final scores when it still deviates from the obtained consensus (e.g., due to power structures or dominant stakeholders). Finally, ES values are mapped by multiplying ES flow maps by the (averaged) relative importance for each ES given by stakeholders. When of interest, groups of ES value maps can thereafter be summed to obtain ES bundles (e.g., provisioning, cultural, regulating ecosystem services, or ecosystem disservices).

## Step 3 – Calculate pixel and zonal statistics

Who & What: This toolset enables the CSS team to extract pixel and zonal statistics from ES/EDS capacity, supply, flow and value maps as illustrated on **Figure 4a-c**.

Rationale: This toolset is useful for area and green accounting, ecosystem-based management and spatial planning. With the zonal statistics, the CSS team can draw a region of interest or import a predefined polygon shapefile (e.g., zonal plan units). The CSS team has then the opportunity to select maps for each ES/EDS (capacity, supply, flow and value), click on a location, draw or import a polygon (e.g., a zonal plan unit) to derive ES/EDS statistics and a Shannon Diversity Index (SHDI) as a measure on ES/EDS diversity and dominance.

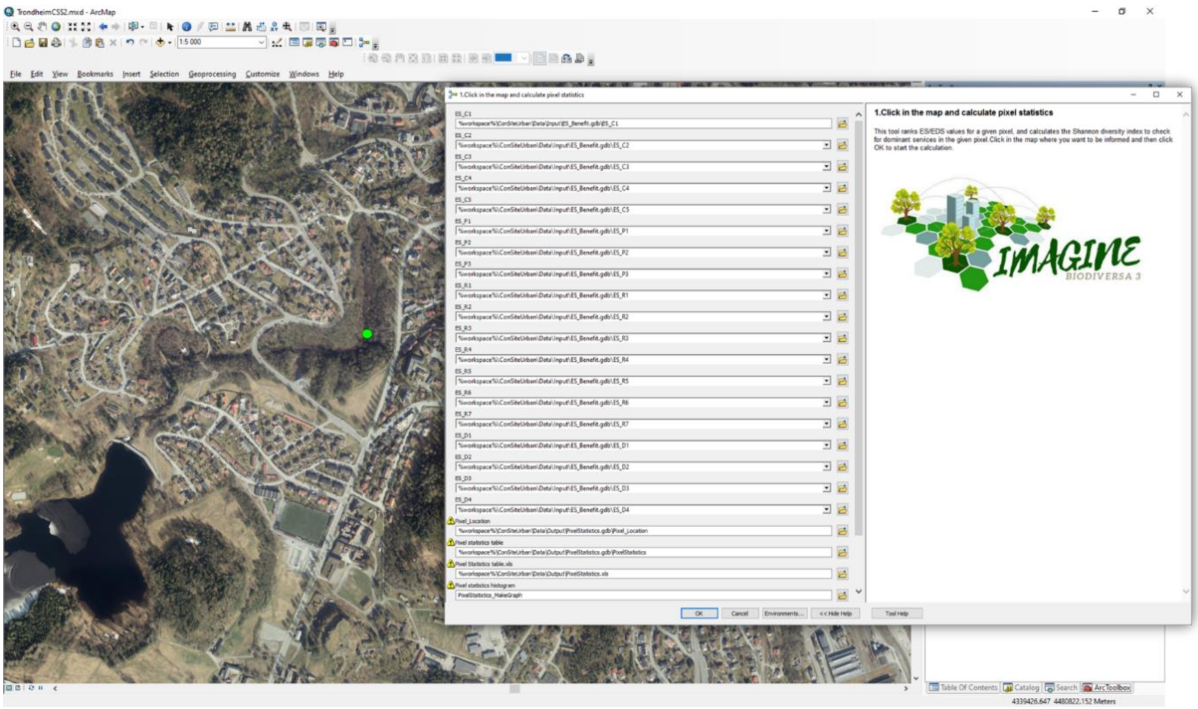
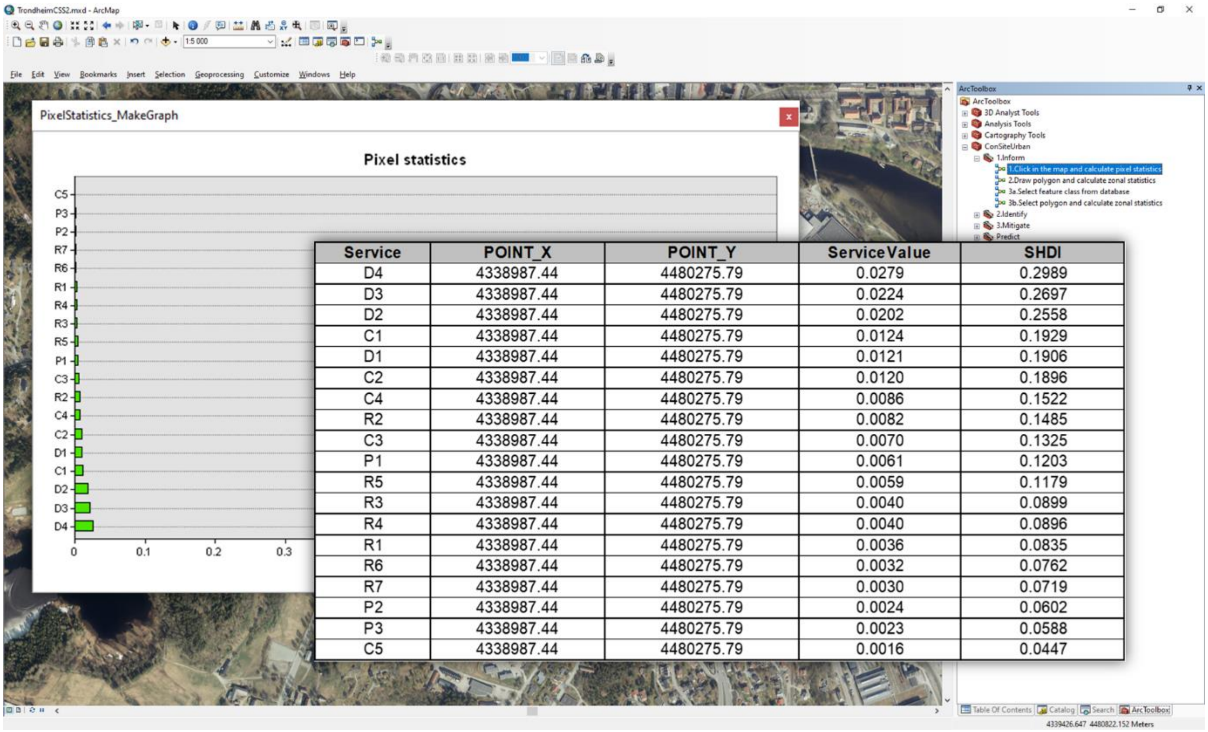
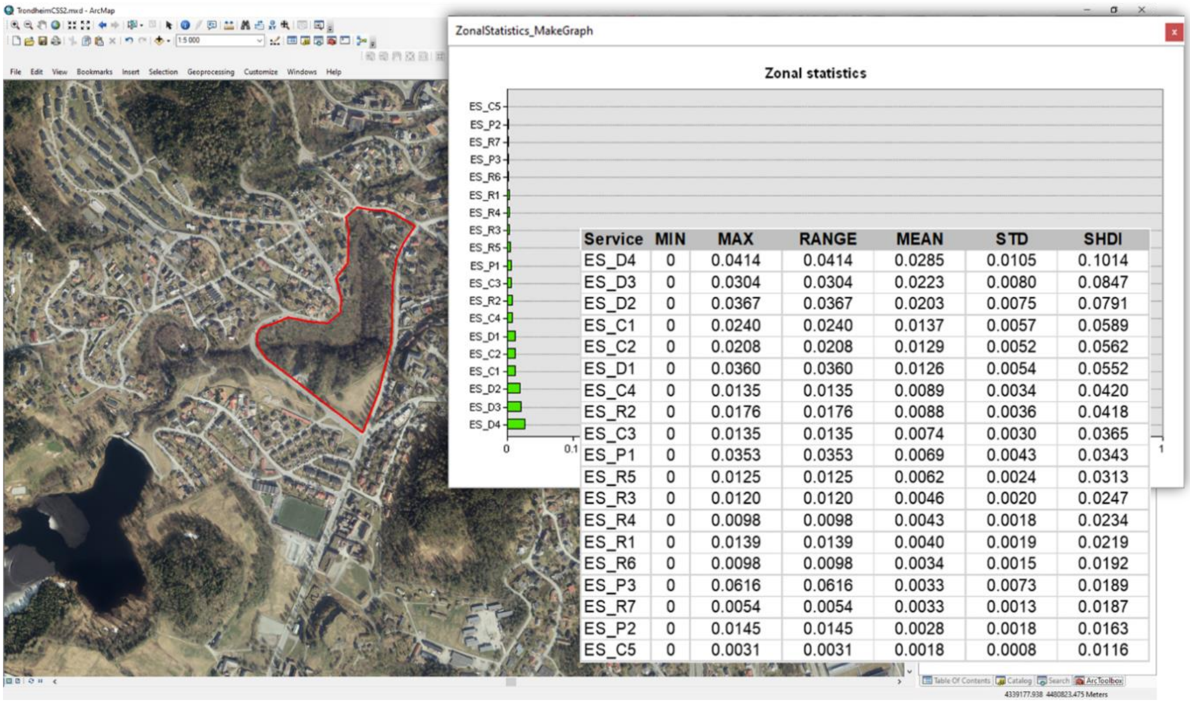



**Figure 4a.** *Select location and ES/EDS Maps.*




| Service | POINT_X | POINT_Y | ServiceValue | SHDI |
|---|---|---|---|---|
| D4 | 4338987.44 | 4480275.79 | 0.0279 | 0.2989 |
| D3 | 4338987.44 | 4480275.79 | 0.0224 | 0.2697 |
| D2 | 4338987.44 | 4480275.79 | 0.0202 | 0.2558 |
| C1 | 4338987.44 | 4480275.79 | 0.0124 | 0.1929 |
| D1 | 4338987.44 | 4480275.79 | 0.0121 | 0.1906 |
| C2 | 4338987.44 | 4480275.79 | 0.0120 | 0.1896 |
| C4 | 4338987.44 | 4480275.79 | 0.0086 | 0.1522 |
| R2 | 4338987.44 | 4480275.79 | 0.0082 | 0.1485 |
| C3 | 4338987.44 | 4480275.79 | 0.0070 | 0.1325 |
| P1 | 4338987.44 | 4480275.79 | 0.0061 | 0.1203 |
| R5 | 4338987.44 | 4480275.79 | 0.0059 | 0.1179 |
| R3 | 4338987.44 | 4480275.79 | 0.0040 | 0.0899 |
| R4 | 4338987.44 | 4480275.79 | 0.0040 | 0.0896 |
| R1 | 4338987.44 | 4480275.79 | 0.0036 | 0.0835 |
| R6 | 4338987.44 | 4480275.79 | 0.0032 | 0.0762 |
| R7 | 4338987.44 | 4480275.79 | 0.0030 | 0.0719 |
| P2 | 4338987.44 | 4480275.79 | 0.0024 | 0.0602 |
| P3 | 4338987.44 | 4480275.79 | 0.0023 | 0.0588 |
| C5 | 4338987.44 | 4480275.79 | 0.0016 | 0.0447 |

**Figure 4b.** *Pixel statistics for selected ES/EDS maps for the chosen location.*




| Service | MIN | MAX | RANGE | MEAN | STD | SHDI |
|---|---|---|---|---|---|---|
| ES_D4 | 0 | 0.0414 | 0.0414 | 0.0285 | 0.0105 | 0.1014 |
| ES_D3 | 0 | 0.0304 | 0.0304 | 0.0223 | 0.0080 | 0.0847 |
| ES_D2 | 0 | 0.0367 | 0.0367 | 0.0203 | 0.0075 | 0.0791 |
| ES_C1 | 0 | 0.0240 | 0.0240 | 0.0137 | 0.0057 | 0.0589 |
| ES_C2 | 0 | 0.0208 | 0.0208 | 0.0129 | 0.0052 | 0.0562 |
| ES_D1 | 0 | 0.0360 | 0.0360 | 0.0126 | 0.0054 | 0.0552 |
| ES_C4 | 0 | 0.0135 | 0.0135 | 0.0089 | 0.0034 | 0.0420 |
| ES_R2 | 0 | 0.0176 | 0.0176 | 0.0088 | 0.0036 | 0.0418 |
| ES_C3 | 0 | 0.0135 | 0.0135 | 0.0074 | 0.0030 | 0.0365 |
| ES_P1 | 0 | 0.0353 | 0.0353 | 0.0069 | 0.0043 | 0.0343 |
| ES_R5 | 0 | 0.0125 | 0.0125 | 0.0062 | 0.0024 | 0.0313 |
| ES_R3 | 0 | 0.0120 | 0.0120 | 0.0046 | 0.0020 | 0.0247 |
| ES_R4 | 0 | 0.0098 | 0.0098 | 0.0043 | 0.0018 | 0.0234 |
| ES_R1 | 0 | 0.0139 | 0.0139 | 0.0040 | 0.0019 | 0.0219 |
| ES_R6 | 0 | 0.0098 | 0.0098 | 0.0034 | 0.0015 | 0.0192 |
| ES_P3 | 0 | 0.0616 | 0.0616 | 0.0033 | 0.0073 | 0.0189 |
| ES_R7 | 0 | 0.0054 | 0.0054 | 0.0033 | 0.0013 | 0.0187 |
| ES_P2 | 0 | 0.0145 | 0.0145 | 0.0028 | 0.0018 | 0.0163 |
| ES_C5 | 0 | 0.0031 | 0.0031 | 0.0018 | 0.0008 | 0.0116 |

**Figure 4c.** *Zonal statistics for selected ES/EDS maps for the chosen area.*

## Step 4 – Identify statistically significant clusters of ES/EDS values

Objective: For a given polygon, this toolset enables the CSS team to identify and delimit areas with statistically significant clusters of high and low ES/EDS values for a given ES/EDS map or a collection of many ES/EDS maps based on standard overlay statistical functions (**Figure 5a-b**).

Rationale: This tool is useful for area and green accounting, ecosystem-based management, restoration purposes and spatial planning. The purpose of this tool is to calculate and identify statistically significant clusters of ES/EDS values in a given polygon unit. In order to do this, the user initially has to draw or import a polygon (for example a zonal plan unit) and select a service or a service bundle. The default settings for overlay statistics, conceptualisation of spatial relationships and distance/threshold band are choosed to optimize the geoprocessing time.

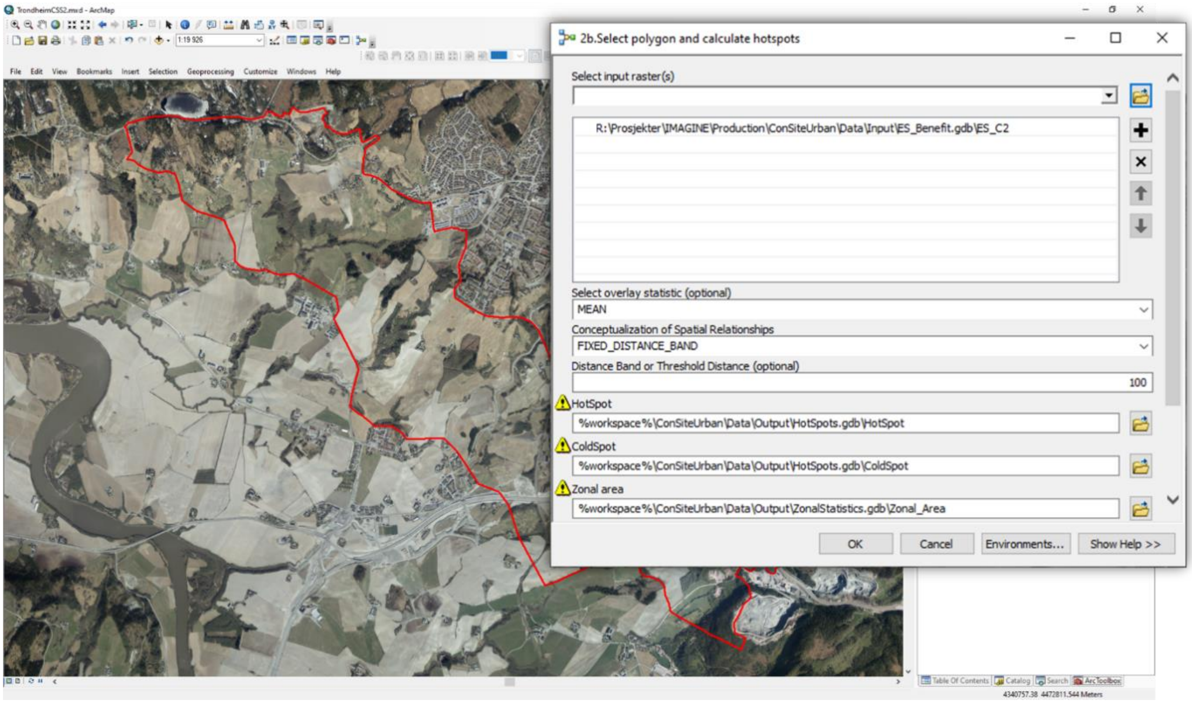



**Figure 5a.** *Select area of interest.*

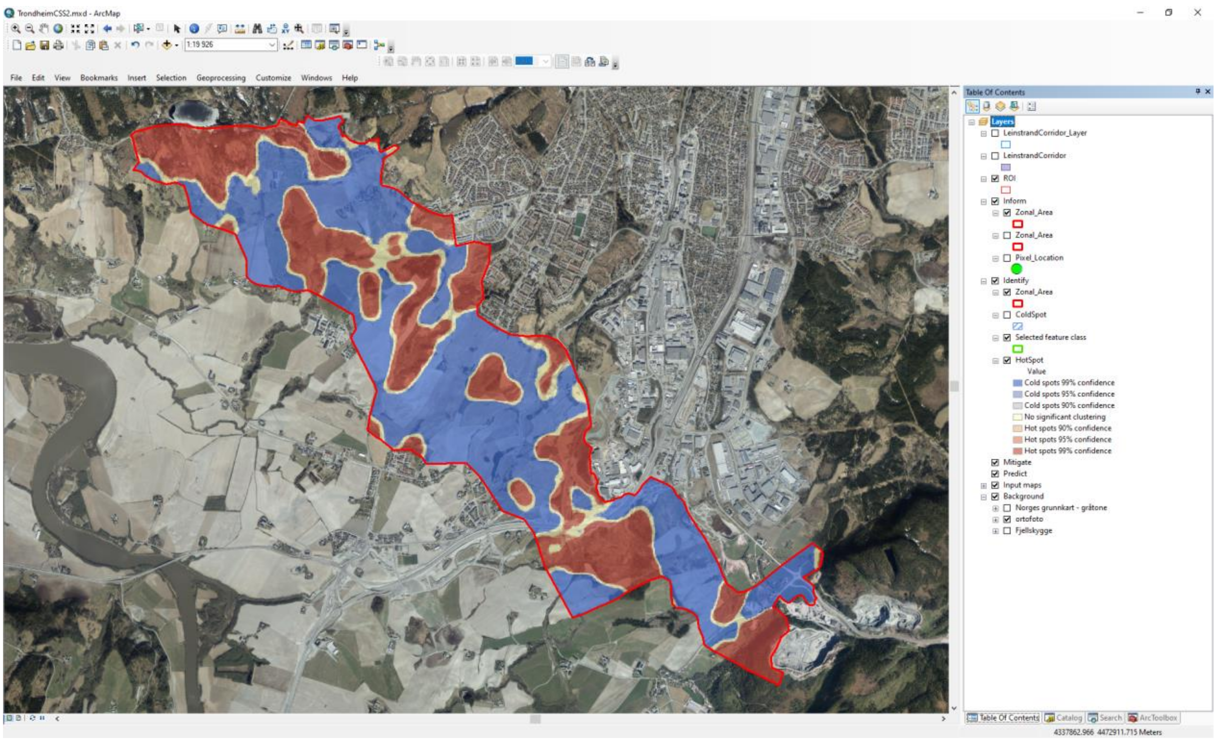


**Figure 5b.** *Statistically significant clusters of high and low ES/EDS values for a given ES/EDS map.*

## Step 5 – Calculate connectedness between GI-patches of high ES/EDS values

Objective: This tool enables the CSS team to calculate both **simple** and **advanced cost-connectivity measures** between GI-patches of high ES/EDS-values. This measure can be used to assess level of connectedness of GI and identify locations where GI should be strengthened.

Rationale: The simple cost-connectivity refers to the least-cost network of paths necessary to connect each of the input regions, whereas the complex cost-connectivity refers to the least-cost network of all paths originating from each region to each of their closest-cost neighbours. The term "cost" here refer to the "resistance" of moving between areas over a friction surface (in this context an inverted ES/EDS map). The algorithm is a function of accumulated distance and friction value, and calculates the road of least resistance (low cost representing high ES/EDS values) between two or more areas (**Figure 6a-b**). This way it will be more costly to traverse an area of low ES/EDS values than high ES/EDS values. The tool also enables the CSS team to calculate ES/EDS transect profiles between patches (**Figure 6c**), and to calculate an optimal restoration corridor (least cost corridor) based on the spatial distribution of local ES/EDS values (Figure 6d). This tool is useful for area and green accounting, ecosystem-based management, restoration purposes and spatial planning. To do the calculation the user has to tag a start and a stop location for calculation of connectedness between GI-patches of high ES/EDS values within the given region of interest.

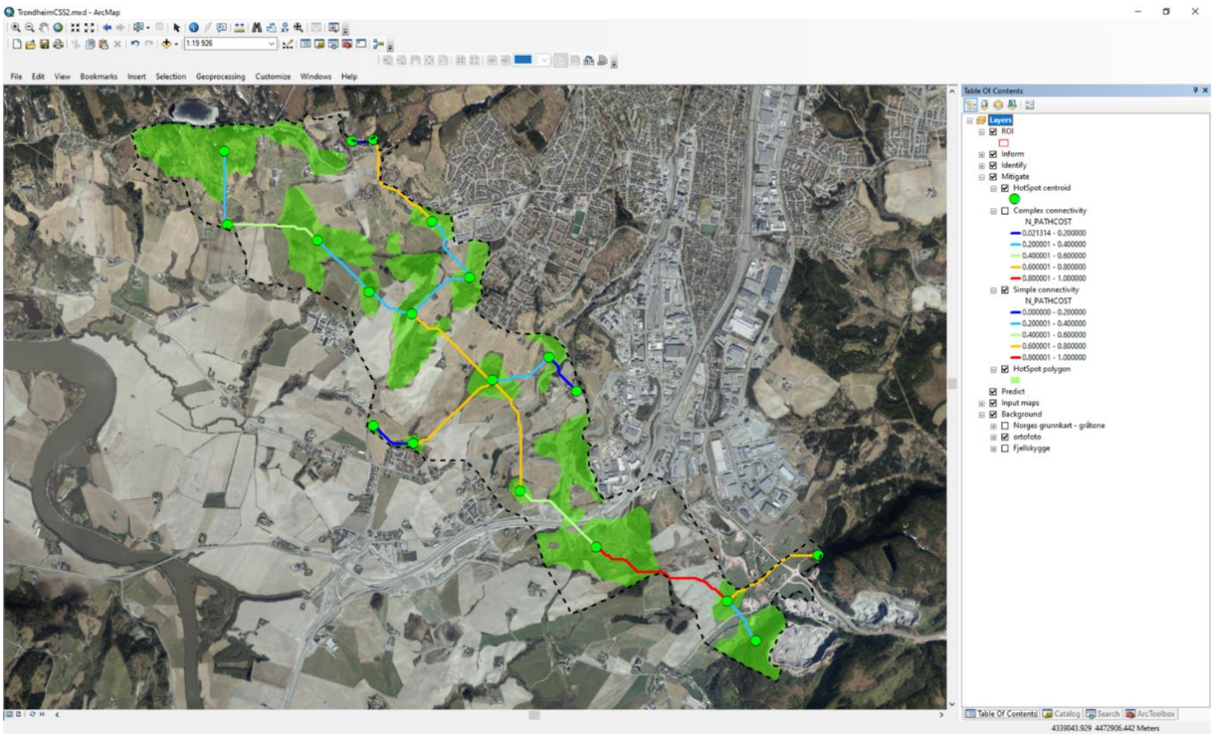


**Figure 6a.** *Simple connectivity between statistically significant clusters of high ES/EDS values. Cost values ranging from 0 (blue) to 1 (red).*

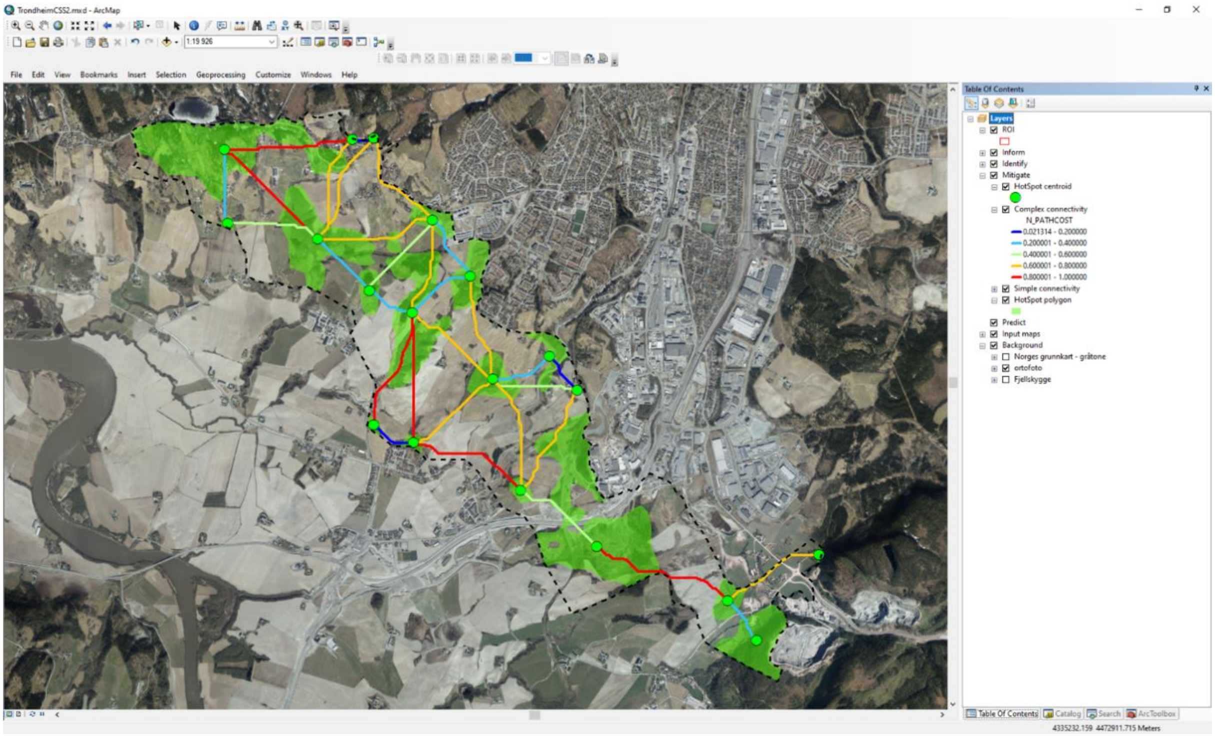


**Figure 6b.** *Complex connectivity between statistically significant clusters of high ES/EDS values. Cost values ranging from 0 (blue) to 1 (red).*

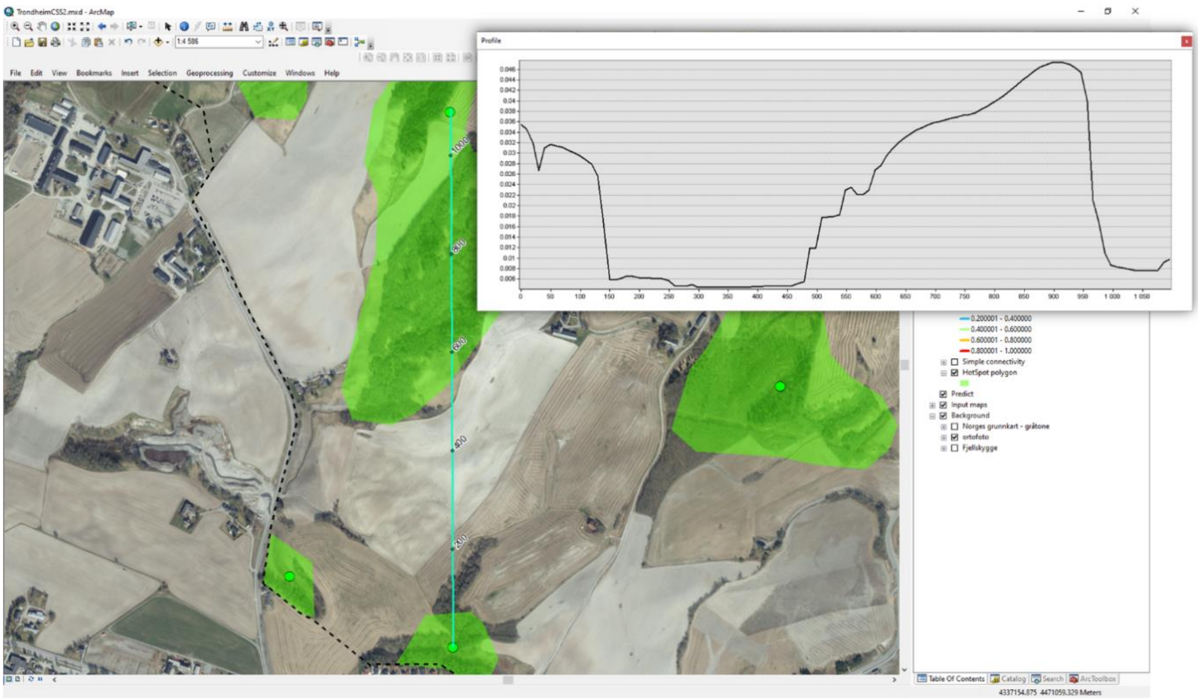


**Figure 6c.** *Transect profiles between patches over a given ES/EDS.*

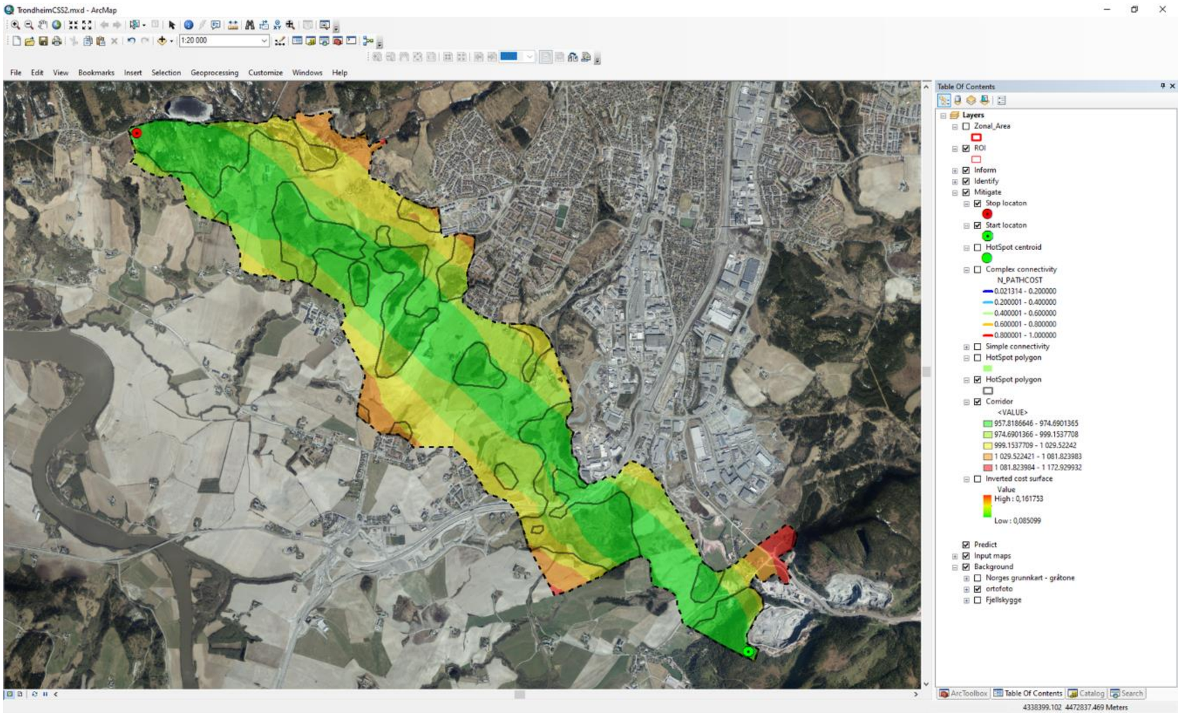



**Figure 6d.** *Optimal restoration corridor from between two locations (green and red dots). The suitability is ranging from low (red) to high (green).*

## Step 6 – Predict spatial effects of human impacts in GI

Objective: This toolset enables the CSS team to study how infrastructural development (e.g., the development of an industrial area) can influence both clusters of ES/EDS values and their inherent cost-connectivity within a GI.

Rationale: The CSS team can draw a polygon mask (e.g. an industrial area, as illustrated in **Figure 7a**) which is then used to reclassify original ES/EDS values to zero in the actual ES/EDS map or collection of ES/EDS maps within this mask. Based on this alteration, Step 5 and Step 6 are rerun to produce the new statistically significant clusters of ES/EDS values (**Figure 7b**) and their associated cost-connectivity networks (**Figure 7c**). This tool is useful for area and green accounting, ecosystem-based management, restoration purposes and spatial planning. The purpose of this tool is to investigate how a human impact (e.g., a construction site) can influence the connectedness between GI-patches of high ES/EDS values within the given region of interest.

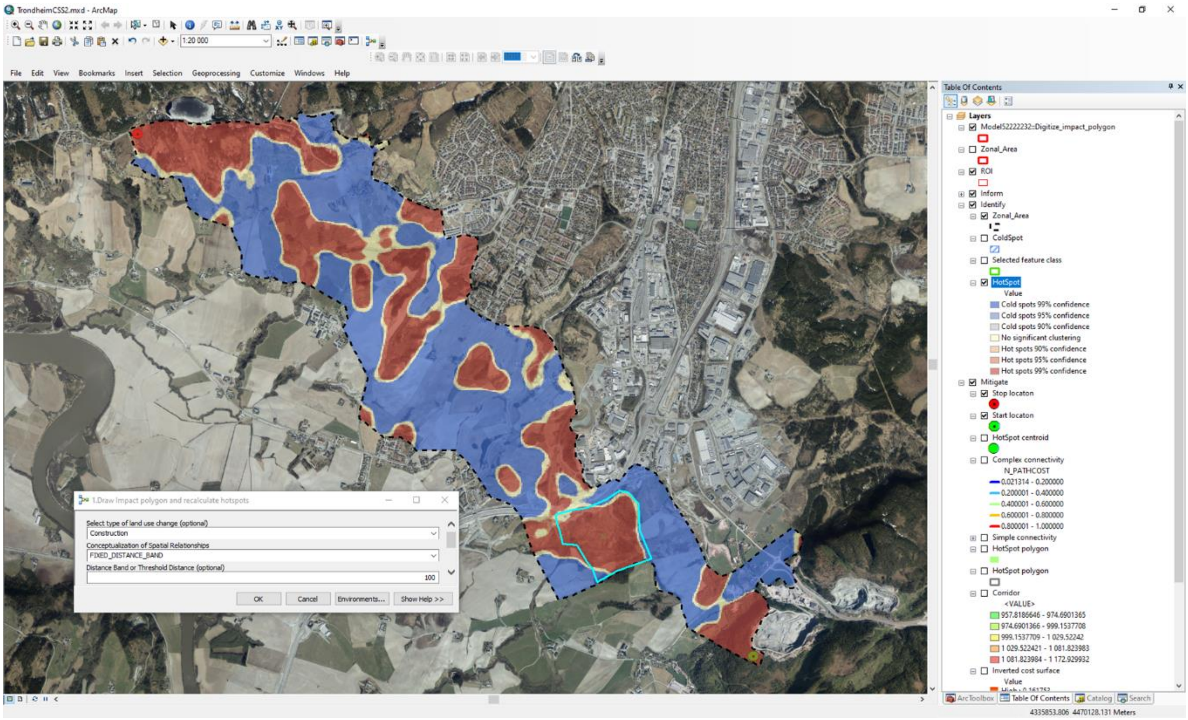


**Figure 7a.** *Draw a polygon mask (outlined in magenta) to reclassify the original values to zero in the actual ES/EDS map or collection of ES/EDS, and rerun the calculation of statistically significant clusters of high and low ES/EDS values).*

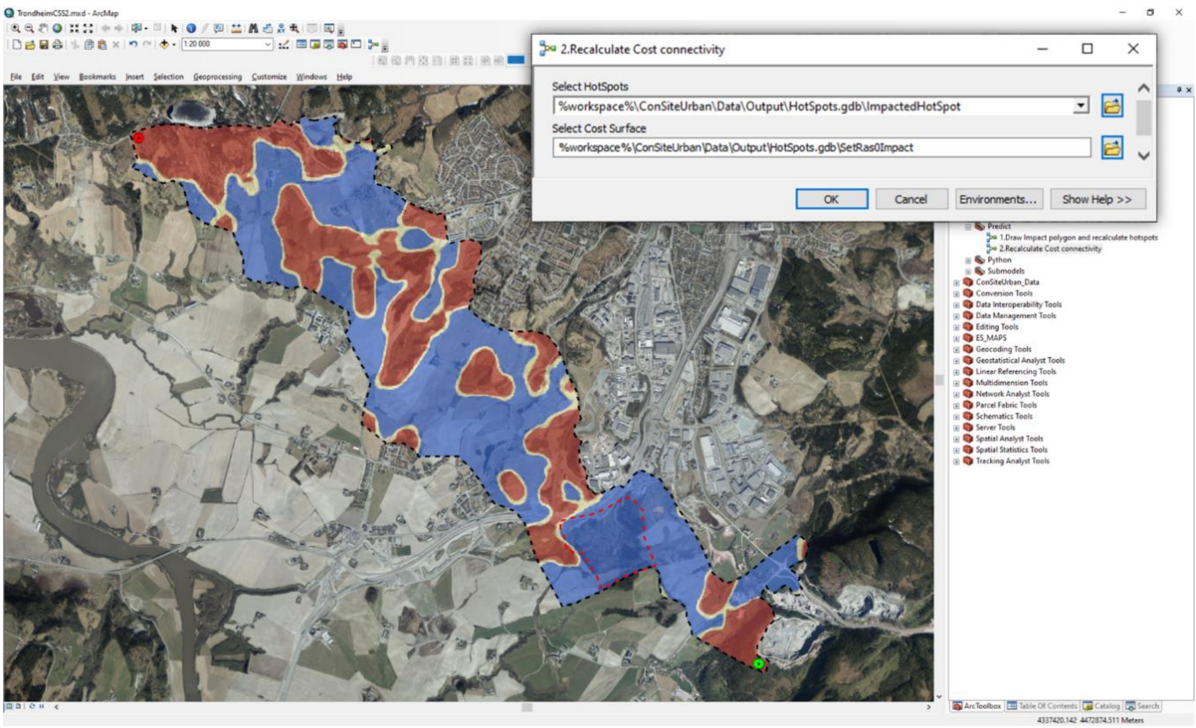



**Figure 7b.** *Re-calculated map of significant clusters of high and low ES/EDS values.*

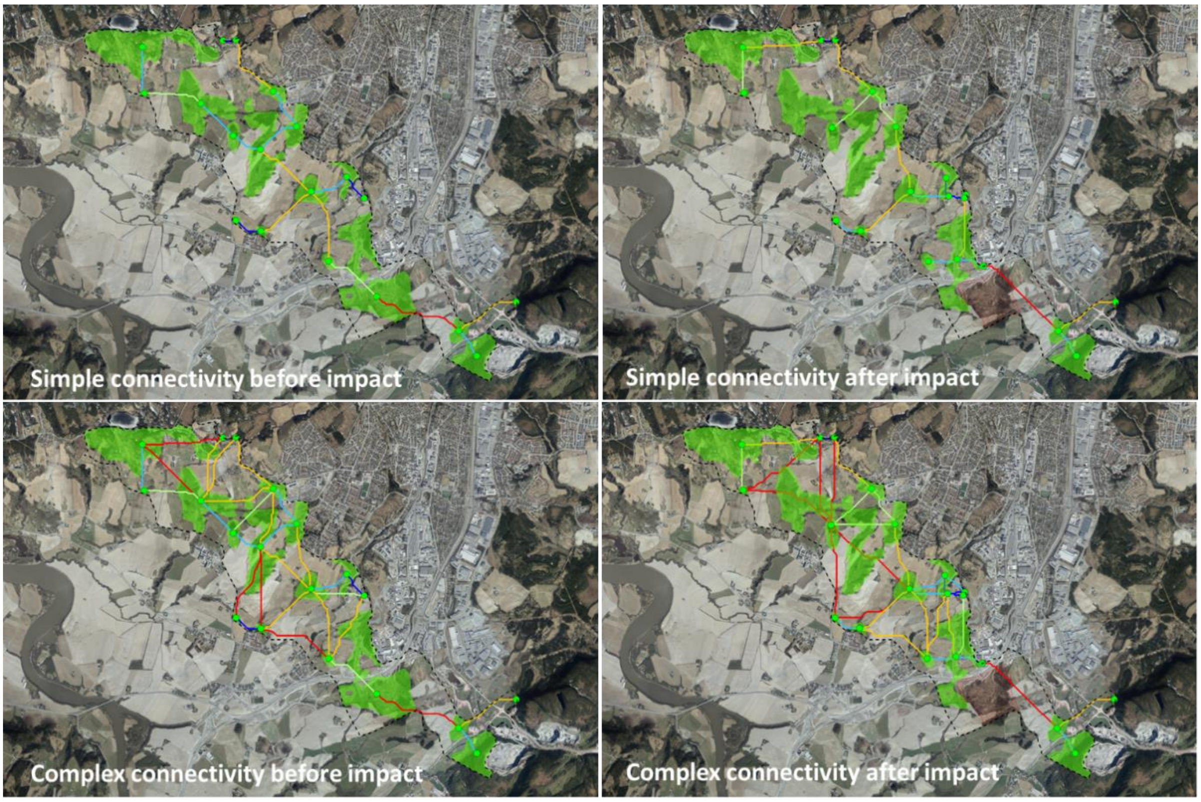



**Figure 7c.** *Prediction of the simple and complex connectivity networks before and after the imaginary development of an industrial area within a GI. Cost values ranging from 0 (blue) to 1 (red).*

## 3. Intended outputs and outcomes

This cookbook presents the development of two connected tools to visualize the delivery of Ecosystem Services in rural-urban landscapes. First, a Bayesian Belief Network (BBN) model combines and integrates knowledge obtained from other key topics (especially key topic 1-3) into a social-ecological systems framework to map the ecosystem (dis)service provisioning of GI. The mapped ecosystem (dis)services are thereafter used as input to the ConSite Urban toolbox for GI design and decision-support. The ConSite Urban toolbox supports the integration and management of GI in spatial planning. Both the BBN model and the ConSite toolbox provide analytical tools with the potential to improve GI planning and management. The purpose of the ConSite Urban toolbox is to:

- Inform planners on Ecosystem (dis)Service delivery,
- Identify bundles of Ecosystem (dis)Services,
- Calculate cost-connectivity between valued Green Infrastructure patches, and
- Predict spatial effects of human activities in Green Infrastructure.

These tools are intended to support rural and urban planners in balancing biodiversity and societal interests of Green-Blue Infrastructure.

# Appendices

## APPENDIX A: Introduction to Bayesian Belief Network (BBN) modelling

Bayesian Belief Networks (BBN) are a knowledge representation tool with tremendous potential for addressing ecosystem management issues with their typically complex and imperfectly understood biophysical, social and economic interactions. BBNs were originally developed to account for the impact of uncertainty on management decisions, so that decision makers could balance the desirability of an outcome against the chance that a given management option might fail. Specifically, BBNs have particular utility for 1) clarifying objectives 2) identifying and articulating alternatives, 3) synthesizing available knowledge 4) quantifying uncertainty 5) pinpointing critical assumptions (Chee *et al*. 2016).

BBNs differ from other model frameworks by representing a system in terms of a set of conditional probabilities to express the relationships between relevant variables, which we can think of as our "belief" regarding the strength of the relationships. BBNs are apt at utilizing data and knowledge from different sources (including physical, social, ecological, and economic components), as well as handling missing data and uncertainty. Because BBNs are based on a relatively simple causal graphical structure that does not demand highly technical modelling skills, non-technical users and stakeholders (SH) generally have an easier time comprehending the modelling process and outcomes.

A BBN has two parts. The first is a Directed Acyclic Graph (DAG), which is the graphic representation of relevant variables (**nodes**) with arrows (**links,** also referred to as **edges**) depicting the direct dependence relationships between variables. All nodes must consist of variables that are either perceptible (i.e., they can be observed), manageable (i.e., the result of an individual or group's decisions), or predictable. The DAG name also conveys that the model is directional and does not account for feedback from child nodes to parent nodes. Links depict the causal chain, or the relationships between a **parent** node and its **child** node. Child nodes depend only on their direct parent nodes, so we can treat nodes that are not directly connected as independent of each other.

Figure A1 provides an illustration of a BBN describing habitat suitability for grazing deer and elk in the Interior Columbia Basin Ecosystem Management Project of Northwestern USA. The figure illustrates how data for both input node (gray boxes) and output nodes (light boxes) in a BBN are expressed as a set of *exhaustive* and *mutually exclusive* states. In this example, all variables are ordinal (i.e., they are a sequential list from none or low to high). BBN models can also use continuous variables, however such data must be "discretized" into a finite set of states (e.g., <50, 50-85,>85). This approach provides clear advantages for dealing with non-linear relationships and complex data distributions. The parent nodes for a child node can either be data input nodes or output nodes (the descendants) of other input nodes. Note that two or more parents can generate a child node, and that a single parent node can have a relationship with more than one child (see "B30: Cover area" in **Figure 1**). The example in Figure 1 specified all input nodes as a single state. However, we can also account for uncertainty by using a distribution of probabilities across the set of states for any given input node. Both intermediate and final output nodes provide both the expected outcome value derived from a given combination of specified input values, and the probability distribution for all states within that node.

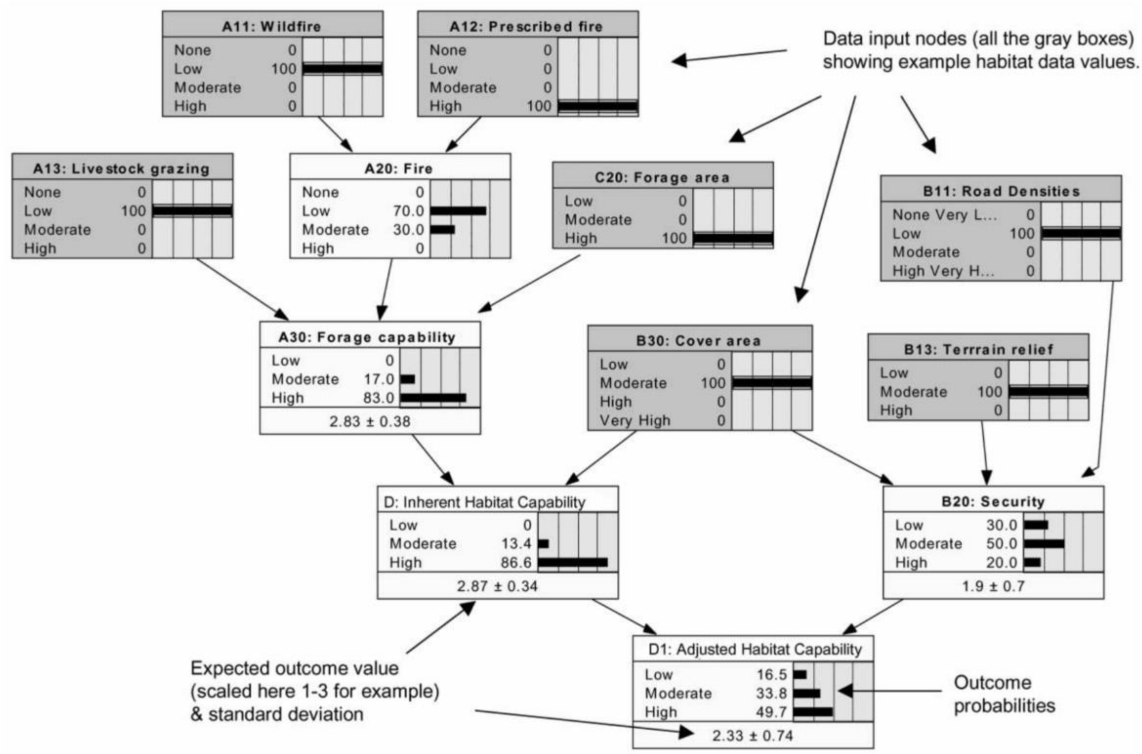
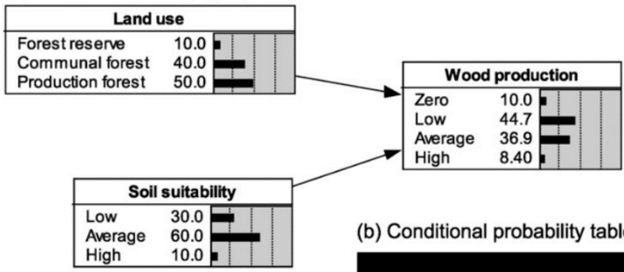



**Figure A1.** *Example of a BBN describing deer and elk habitat in USA (from Lehmkuhl et al. 2001). Grey boxes illustrate data input nodes with example data values fixed for one state. Light boxes illustrate output nodes with calculated expected outcome values (scaled) and probability distributions for those values.*

The second part of a BBN is the conditional probability tables (CPT) that quantify the relationships between variables. A CPT defines the probability that a specific child node's state will occur, given all possible combinations of parent node states. Lemkuhl *et al*. (2001) provide the following as an example for a subset of a CPT for the Security node: If road density is high, terrain is flat, and cover is low, then elk security, expressed as the likely probability of each outcome category, is: low = 0.90, moderate = 0.10, and high 0.00. The authors then defined similar probabilities of for all other combinations of road density, terrain, and cover categories. The full CPT for the "security" node would have 36 columns to include all possible combinations of inputs nodes' states (4 x 3 x 3), with a row for each possible state for the output node itself (3: low, medium and high). This simple example should help convey the importance of striving for parsimony when designing a BBN. CPTs can rapidly become difficult to manage when nodes have many states or if a child node has more than a handful of parents.

**Figure A2** provides another way of seeing how CPTs are constructed. **Figure A2** illustrates a simplistic DAG with the CPT for its output node describing wood production based on two input nodes for land use and soil suitability (Landuyt *et al*. 2016). The probabilities for Land use and soil suitability nodes can represent the distribution of values over a specified area (i.e., 50 % of a given area is covered by production forest) or likelihoods of a state at a particular site that account for uncertainty due to various categories of error or chance outcomes. Landuyt *et al*. (2016) do not specify how they determined the probability values for the CPT in **Figure A2**. However, probability parameters could have been generated from either data on wood production, expert opinions or consensus reached from interactions with several stakeholders.

(a) Directed acyclic graph (DAG)




(b) Conditional probability table (CPT)

| Land use | Soil suitability | Wood production | | | |
|---|---|---|---|---|---|
| | | Zero | Low | Average | High |
| Forest reserve | Low | 1 | 0 | 0 | 0 |
| Forest reserve | Average | 1 | 0 | 0 | 0 |
| Forest reserve | High | 1 | 0 | 0 | 0 |
| Communal forest | Low | 0 | 1 | 0 | 0 |
| Communal forest | Average | 0 | 0.8 | 0.2 | 0 |
| Communal forest | High | 0 | 0 | 0.9 | 0.1 |
| Production forest | Low | 0 | 0.7 | 0.3 | 0 |
| Production forest | Average | 0 | 0.1 | 0.8 | 0.1 |
| Production forest | High | 0 | 0 | 0 | 1 |

**Figure A2.** *Directed acyclic graph or DAG (a) and conditional probability table (b) for a BBN predicting wood production based on land use and soil suitability (Landuyt et al. 2016).*

## Recommended reading

Chen, S.H., Pollino, C. A. 2012. Good practice in Bayesian network modelling. Environmental Modelling & Software 37:134–145.

Gonzalez-Redin, J., Luque, S., Poggio, L., Smith, R., Gimona, A. 2016. Spatial Bayesian belief networks as a planning decision tool for mapping ecosystem services trade-offs on forested landscapes. Environmental Research 144:15–26.

Hamilton, S.H., Pollino, C.A., Jakeman, A. J. 2015. Habitat suitability modelling of rare species using Bayesian networks: Model evaluation under limited data. Ecological Modelling 299:64–78.

Landuyt, D., Broekx, S., D'Hondt, R., Engelen, G., Aertsens, J., Goethals, P.L.M. 2013. A review of Bayesian belief networks in ecosystem service modelling. Environmental Modelling & Software 46:1–11.

Landuyt, D., Broekx, S., Engelen, G., Uljee, I., van der Meulen, M., Goethals, P.L.M. 2016. The importance of uncertainties in scenario analyses - A study on future ecosystem service delivery in Flanders. Science of the Total Environment 553:504–518.

Lehmkuhl, J.F., Kie, J.G., Bender, L.C., Servheen, G., Nyberg, H. 2001. Evaluating the effects of ecosystem management alternatives on elk, mule deer, and white-tailed deer in the interior Columbia River basin, USA. Forest Ecology and Management 153:89–104.

Smith, R.I., Barton, D.N., Dick, J., Haines-Young, R., Madsen, A.L., Rusch, G.M., Termansen, M., Woods, H., Carvalho, L., Giucă, R.C., Luque, S., Odee, D., Rusch, V., Saarikoski, H., Adamescu, C.M., Dunford, R., Ochieng, J., Gonzalez-Redin, J., Stange, E., Vădineanu, A., Verweij, P., Vikström, S. 2018. Operationalising ecosystem service assessment in Bayesian Belief Networks: Experiences within the OpenNESS project. Ecosystem Services 29:452–464.

## APPENDIX B: Introduction to Analytical Hierarchy Processing

### Analytical Hierarchy Processing (AHP)

AHP is a multi-criteria decision-making method (MCDM) that helps to mathematically structure the findings from the social valuation into consolidated criteria weights. All criteria must be compared pairwise (based on legal requirements and best practices) where the stakeholder express their judgements and transform them into a pairwise comparison matrix using a numerical scale from 1-9 (Saaty 1980) (see **Table B1**).

**Table B1.** *Pairwise comparison scale (from: Saaty 1980).*

| Assigned value | Interpretation |
|---|---|
| **1** | $C_1$ and $C_2$ are of equal importance |
| **3** | $C_1$ is weakly more important than $C_2$ |
| **5** | $C_1$ is strongly more important than $C_2$ |
| **7** | $C_1$ is very strongly or demonstrably more important than $C_2$ |
| **9** | $C_1$ is absolutely more important than $C_2$ |
| **2,4,6,8** | Intermediate values, e.g. a value of 8 means that $C_1$ is midway between strongly and absolutely more important than $C_2$ |

For implementation of AHP in the stakeholder meetings, we will implement an AHP excel workbook developed by Goepel (2013) [1 2] (see exemplification in **Figure B2** below). This workbook is very suitable for group decisions, such as the dialogue stakeholder meetings. The limitation of the workbook is that it only supports at maximum 10 criteria and 20 participants.

[1] http://bpmsg.com/academic/ahp.php
[2] http://bpmsg.com/ahp-introduction/

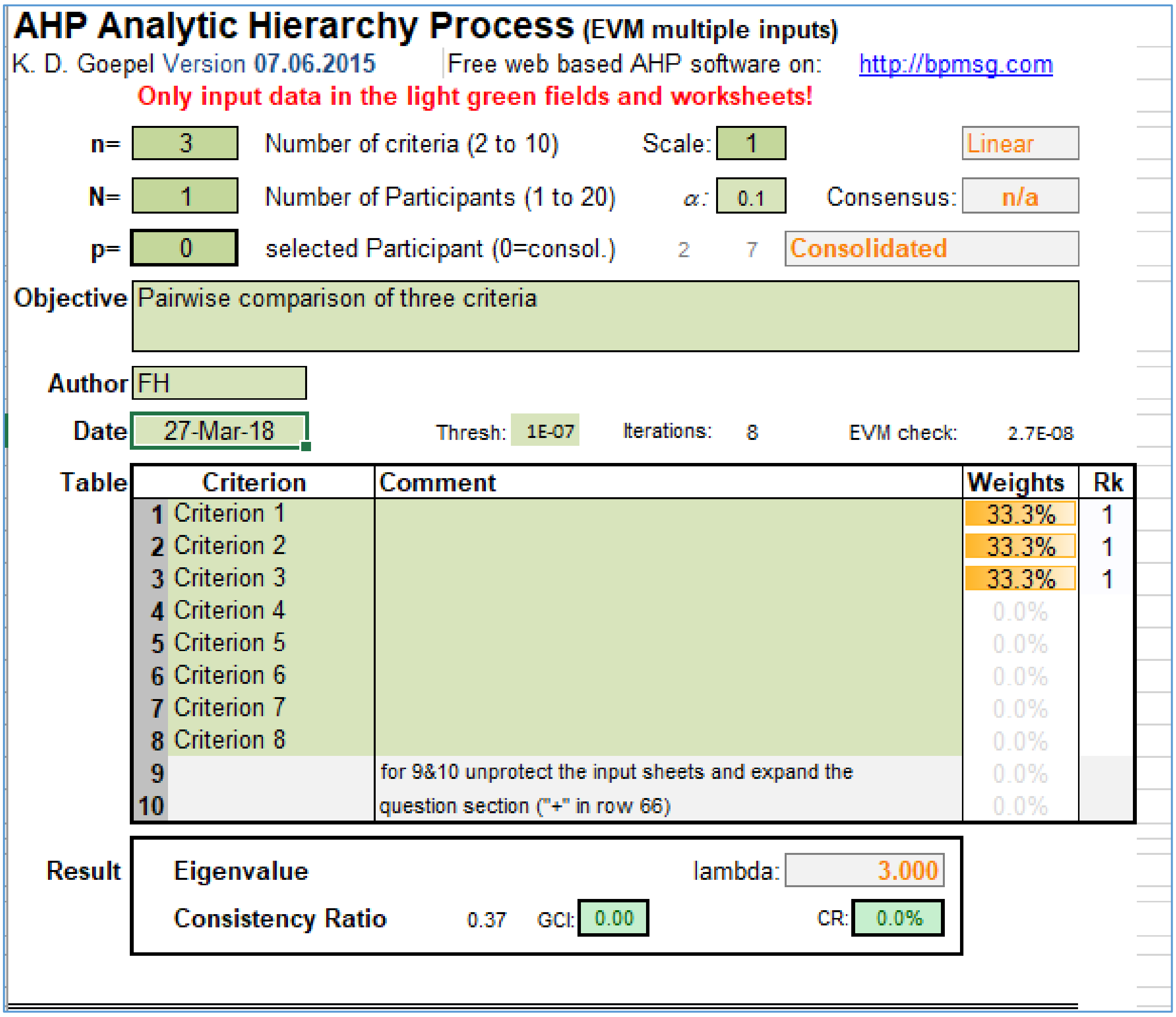



**Figure B2.** *AHP excel template summary page (prior to the pairwise comparison).*

The AHP workbook consists of 20 input worksheets for pairwise comparisons, a sheet for the consolidation of all judgments, a summary sheet to display the result, a sheet with reference tables (random index, limits for geometric consistency index GCI, judgment scales) and a sheet for solving the eigenvalue problem when using the eigenvector method (EVM). First the number of criteria and participants must be registered. Second, an appropriate AHP scale must be chosen. The default is scale 1, which is the standard linear 1 to 9 AHP scale (described in Table 1 above). Additional scales supported in the AHP excel template are Logarithmic (2), Square root (3), Invers linear (4), Balanced (5), Power (6) and Geometric (7).

The Alpha (α) value field represent a threshold for acceptance of inconsistency. The recommended threshold value range between 0.1 and 0.2. The consensus field is an output field showing the AHP consensus index, if you have more than one decision maker/participant. The consensus indicator ranges from 0% (no consensus) to 100% (full consensus). For more than one participant you can select whose participant's result to be displayed. Participants are numbered from 1 to 20 according the input sheets for pair-wise comparisons. When selecting 0, the consolidated result for all participants will be shown, using the geometric mean of all decision matrices.

For example, when doing a pairwise comparison of three criteria the first comparison is criteria 1 versus criteria 2. In the second last column the participant must select either A (criteria 1 is more important than 2), or B (criteria 2 is more important than 1). In the last column of the table the participant specifies the intensity – how much more important is criteria 1 compared to criteria. Valid inputs are integers from 1 to 9 (when using the standard linear AHP scale described in **Table B1**). Each workbook will show the resulting priorities calculated from the pairwise comparisons based on the row geometric mean method (RGMM). The final calculation using the Eigen vector method (EVM) will only be shown in the summary sheet (see **Figure B3**).

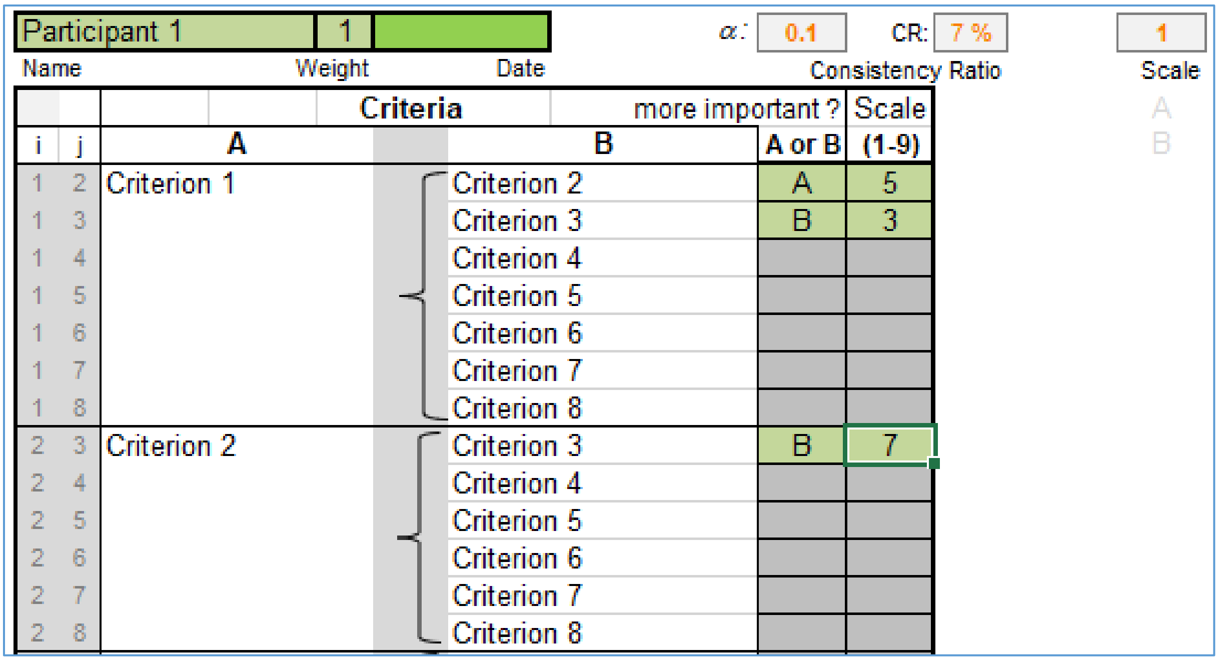



**Figure B3.** *Pairwise comparison matrix.*

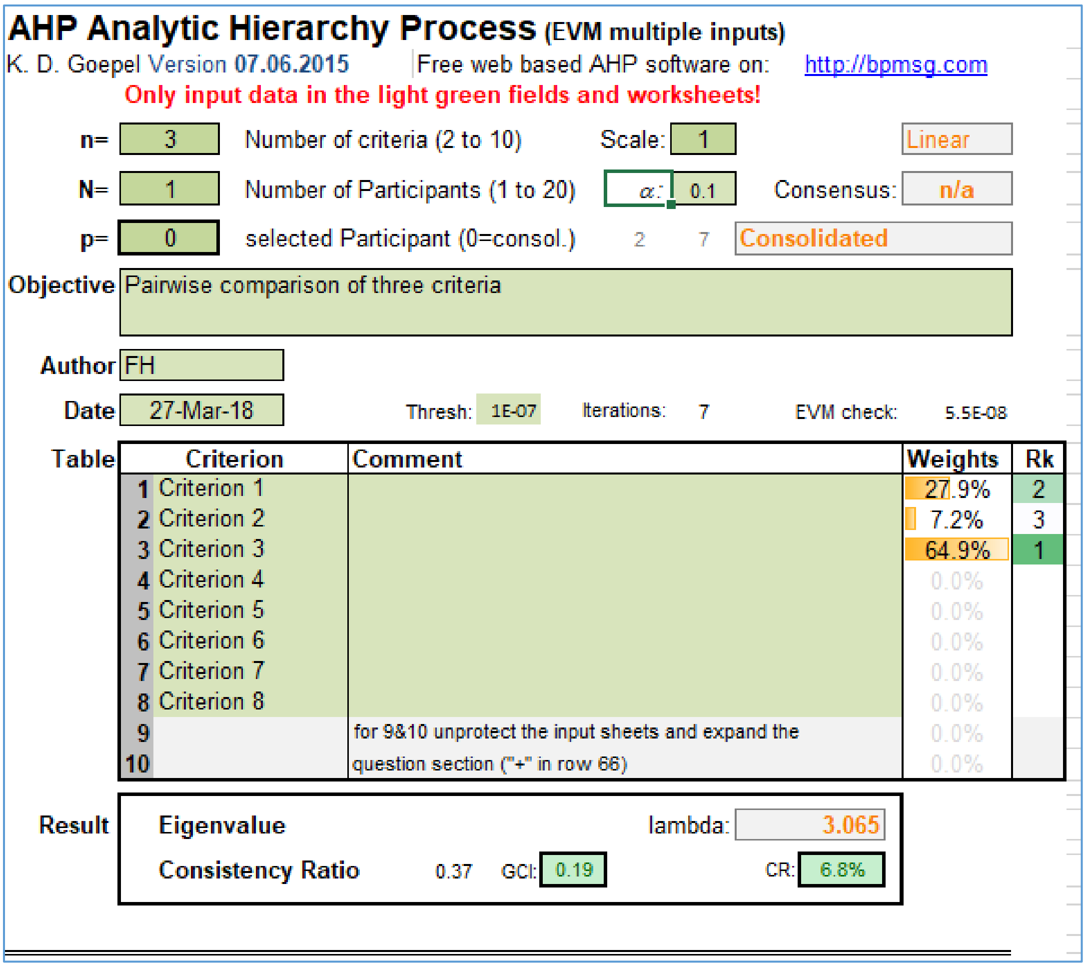



**Figure B4.** *Estimated weights, the recommended threshold inconsistency value and the Eigen Value Method (EVM) check which should be close to zero.*

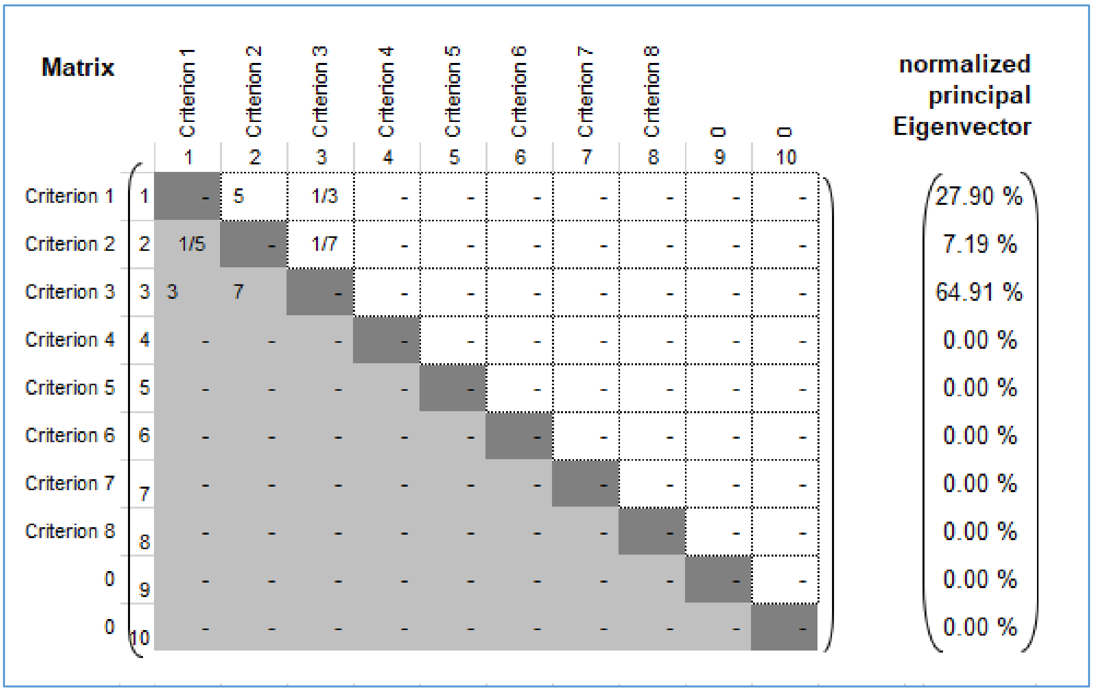



**Figure B5.** *The comparison matrix.*

Finally, the AHP-weights should be evaluated (**Figure B4**). The power of AHP is that it is relatively easy to use, and that it is especially suitable for complex decisions handling vague criteria. AHP is based on the assumption that when faced with a complex decision, the natural human response is to cluster the criteria according to their common characteristics (**Figure B5**). The inherent uncertainty of prioritizing the different criteria in fixed values (through pairwise comparison) is however not addressed in traditional AHP.  One way to bypass this uncertainty is to utilize fuzzy ranges instead of fixed values (Mateo 2015). In practice, fixed criteria values are often inadequate in MCA since human judgments often are vague. Adding fuzzy theory to AHP (often called Fuzzy AHP or FAHP) will therefore overcome the classical AHP shortcomings (Hanine *et al*. 2016). FAHP utilize linguistic ratings in the calculations of criteria weights by giving them a certain range. Further on it has been observed that stakeholders often are more willing to give interval judgments than fixed-value judgments (Büyüközkan and Ruan 2008). Balli and Korukoglu (2009) recognize that FAHP is effective in handling vague and ambiguity information. There are many procedures for calculating criteria weights using FAHP in the literature. Brief information about many of these procedures and a concise comparison of them can be found in Bozbura *et al*. (2007) and Mateo (2015). In addition, other methods like Monte Carlo Simulation (MCS) and variance-based Global Sensitivity Analysis (GSA) have been applied to compute the inherent uncertainty and perform sensitivity analysis in decision-making based on FAHP (Feizizadeh 2015).

## Recommended reading

Balli, S., Korukoğlu S. 2009. Operating system selection using fuzzy AHP and TOPSIS methods. Mathematical and Computational Applications 14(2):119–130.

Bozbura, F., Beskese A, Kahraman C. 2007. Prioritization of human capital measurement indicators using fuzzy AHP. Expert Systems with Applications 32(4): 1100–1112.

Büyüközkan, G., Ruan, D. 2008. Evaluation of software development projects using a fuzzy multi-criteria decision approach. Mathematics and Computers in Simulation 77(5–6):464–475.

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Goepel, K.D. 2013. Implementing the analytic hierarchy process as a standard method for multi-criteria decision making in corporate enterprises – a new AHP excel template with multiple in-puts. Proceedings of the international symposium on the analytic hierarchy process, Kuala Lumpur, Malaysia.

Hanine, M., Boutkhoum, O., Tikniouine, A., Agouti, T. 2016. Comparison of fuzzy AHP and fuzzy TODIM methods for landfill location selection. SpringerPlus. 5: 501.

Mateo, J.R.S.C. 2015. Multi-Criteria Analysis in the Renewable Energy Industry. Green Energy and Technology, Springer-Verlag London.

Saaty, T.L. 1980. The analytic hierarchy process: planning, priority setting, resources allocation. McGraw-Hill.

## IMAGINE project summary

The IMAGINE project ran between 2017–2020, between five countries and 6 partner institutions:

- INRAE (FR);
- Institute for Social-Ecological Research (ISOE, DE);
- Kiel University (UniKiel, DE);
- Norwegian Institute for Nature Research (NINA, NO);
- Estonian University of Life Sciences (EMU, EE), and
- Research Institute for Nature & Forest (INBO, BE).

The project aimed at quantifying the multiple functions, ecosystem services, and benefits provided by Green Infrastructures (GI) in different contexts from rural to urban. It used a multidisciplinary approach across six case study territories spanning a European north-south gradient from the Boreal zone to the Mediterranean.

IMAGINE aimed to demonstrate an integrative assessment of GI multifunctionality and biocapacity to deliver ES and to propose options to manage and design GI from patch to landscape. The project contributed to developing an innovative approach to support ecosystem resilience, sustainable essential ecosystem services flow, and contributing to human wellbeing to meet EU policy targets.

Project Coordinator: Philip Roche (INRAE) philip.roche@inrae.fr

Website: https://imagine.inrae.fr/

This project was selected and supported by

biodiversa

BiodivERsA COFUND Call (2015-2016)
« Understanding and managing biodiversity dynamics to improve ecosystem functioning and delivery of ecosystem services in a global change context: the cases of soils and sediments, and land- river and sea-scapes »

IMAGINE was funded by: the French National Research Agency, the German federal Ministry for Research and Education, the Belgian Science Policy Office and the Research Council of Norway.

AGENCE NATIONALE DE LA RECHERCHE ANR

Bundesministerium für Bildung und Forschung

Belgian Science Policy Office belspo

Forskningsrådet The Research Council of Norway

ALTER-Net

IMAGINE is an Alternet Project. The idea of proposing this project and the initial consortium members was initiated during the Alternet Conference session on Biodiversa Calls.