



EUROPEAN COMMISSION
DIRECTORATE-GENERAL
JOINT RESEARCH CENTRE
Directorate D – Sustainable Resources
Bio-Economy Unit

Restoration Planner

Available in the free software *GuidosToolbox*. This is a living document, please check for the latest version at: <https://forest.jrc.ec.europa.eu/en/activities/lpa/gtb/>

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1. Background

Over the past century, the human impact on the environment has resulted in a significant conversion from intact natural areas into ecosystems strongly influenced by humans. This process led to a net loss of undisturbed habitat area and a general degradation of the remaining habitat. Dedicated methods to map pattern, connectivity and fragmentation were developed to monitor and understand cause and effects of this process. To halt or combat the negative degradation effects, policy measures (EU Biodiversity Strategy¹, UN Decade of Restoration²) were designed to conserve existing habitat networks or if possible, to reverse the degradation process by trying to restore the habitat network towards a sustainable state. This document outlines a conceptual framework designed to:

- a) describe the status of a given network, termed *coherence*, and
- b) provide spatially explicit guidance on cost and efficiency of restoration scenarios.

While coherence describes the static network status, restoration can be defined as a change of the network status, composed of adding new area (i.e.: by reconnecting objects, enlarging objects or adding new objects) into the network with the aim to improve the network condition. The success of a restoration scenario can then be measured as the amount of increase in network coherence with respect to the costs involved.

¹ https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm

² <https://www.iucn.org/theme/nature-based-solutions/initiatives/decade-ecosystem-restoration>

Scope of this report:

Illustration of a map analysis methodology to measure the degree of network coherence and to provide guidance and quantitative measures for restoration planning.

The methodology outlined in this document was designed with the goal to

- a) be generic and provide quantitative measures and spatial details for planning
- b) be applicable to any kind of categorical map and at any scale
- c) provide a concise summary of key elements describing the network status
- d) provide tools to customize or simulate any restoration scenario
- e) measure cost and efficiency for a user-driven restoration scenario
- f) automatically detect the optimum restoration scenario

Spatially explicit information and quantitative, normalized indicators are key elements for efficient restoration planning and reporting. They also allow measuring progress over time and towards policy goals.

2. Methodology

The scope of the Restoration Planner is to address two different, yet strongly related topics:

- Network Coherence and
- Network Restoration.

The essential idea of restoration is to improve the current network status. The status of a network is described with the narrative *coherence*.

Definitions:

Coherence is defined as the degree of connectedness of the area of all network objects. Coherence is based on the most important network aspect, the equivalent connected area, it does not consider the shape of the objects or the distance between individual network objects. Network coherence describes the status of a network at a given point of time.

Restoration is defined as the process of adding area to an existing network aimed at increasing network coherence.

This document is focused on applications. Please consult the [GuidosToolbox manual](#) for further methodological and technical details.

2.1 Describing the status of an existing network

A network is composed of a set of objects. Here, the generic term *object* refers to a land cover parcel, species habitat, or any other homogeneous area outline. The network status is summarized with a set of four quantitative indicators designed to measure equivalent connected area (ECA), degree of coherence (COH), network coverage (RAC) and the critical new object area (CNOA) of a given network:

Acronym	Name	Description	Unit
ECA	Equivalent Connected Area	Area of a fictive single object providing the same amount of <i>reachable area</i> as the current set of objects	pixels
COH	Coherence	Degree of network coherence/connectedness	[%]
REST_POT	Restoration Potential	Network restoration potential (100% - COH)	[%]
RAC	Reference Area Coverage	Network area proportion with respect to map data area	[%]
CNOA	Critical New Object Area	Area of a single additional object resulting in the same network coherence as found in the original network.	pixels

Table 1: Summary of the network status indicators

1) SSQ (overall network connectivity): <i>Sum of Squares</i> of individual object areas	$SSQ = \sum (object_{area})^2$	[Hectare ²]
2) ECA (Equivalent Connected Area): Area of a fictive single object providing the same amount of <i>reachable area</i> as the current set of objects.	$ECA = \sqrt{SSQ}$	[Hectare]
3) ECA_{max} (maximum ECA): Area of a fictive single object having the same area as the current set of all objects (= maximum network coherence).	$ECA_{max} = \sum object_{area}$	[Hectare]
4) COH (Coherence): Normalized index of network coherence (how well is the network connected?)	$COH = \frac{ECA}{ECA_{max}} * 100$	[0, 100] %

Figure 1: Definition of the two key network status indicators ECA and COH

By attributing a higher importance to larger objects (SSQ), the equivalent connected area (ECA) is the area of a fictive single object providing the same amount of reachable area as the current set of objects. Maximum ECA is achieved if all network objects were moved together into a single object. Coherence (COH) describes the network status as the normalized degree of equivalent connected area (ECA) with respect to the ideal state of complete connectedness (ECA_{max}).

While COH measures relative network coherence (in percent) and ECA the reachable area (measured in pixels or grid cells corresponding to area units in m², or hectare, or km²), two further indicators are used to complement the network status description:

The third indicator, Reference Area Coverage (RAC) is the proportion of the network area with respect to the overall data area of the reporting unit. For example, forest network coherence and reachable area might be similar for two countries, yet it is important to know that the forest coverage (RAC) in one country is 60% while it is only 5% in the other country.

The fourth indicator, Critical New Object Area (CNOA) serves as an indicator for restoration planning, based on the idea that adding a new disjoint object will lead to an increase in fragmentation and consequently a decrease in network coherence. The Critical New Object Area corresponds to the area of a fictitious new isolated object, which is large enough to compensate the fragmentation effect it causes and will result in the same network coherence as found in the original network.

A network status assessment requires an input map where network objects are coded with 2 byte, background (non-network) with 1 byte, and optional no-data areas are assigned to 0 byte. The status summary will provide tabular statistics describing the network, showing for each reporting unit: total network area (AREA), coverage (RAC), number of network objects (NR_OBJ), area of largest object (LARG_OBJ), average object (patch) size (APS), CNOA, equivalent connected area (ECA), degree of coherence (COH) and restoration potential (REST_POT):

	A	B	C	D	E	F	G	H	I	J
1	REP_UNIT	AREA	RAC[%]	NR_OBJ	LARG_OBJ	APS	CNOA	ECA	COH[%]	REST_POT[%]
2	input.tif	428,490	42.86	2,850	214,811	150.35	311,712	221,292.76	51.64	48.36

Table 2: Example of network status assessment

The normalized indicator network coherence measures the degree of network integrity. The reporting in percent allows for easy communication, direct comparison across different assessment units as well as quantifying effective change in coherence over time.

2.2 Evaluating restoration planning

In general, any kind of restoration effort will try to enhance network coherence by adding area into an existing network. Here, the key question is: which of the following three options is most efficient?

- Reconnect existing objects
- Add area to an existing object
- Add a new isolated object

Because both, ECA and COH are driven by large object areas (Sum Of Squares – SSQ), it is evident that connecting large objects is most efficient, followed by adding area to preferably large objects. The third option, adding a new isolated object, will always trigger an increase in fragmentation, which is equivalent to a decrease in network coherence. The only exception to this rule is when the new object is larger than CNOA, which in most cases means it must be larger than the largest existing object. Since more coherence gain can be achieved by adding less area than CNOA to reconnect objects, adding new isolated objects into an existing network is an inefficient restoration scenario, at least with respect to network coherence.

If restoration benefit can be measured in coherence increase, the remaining key planning questions are:

- a) How can we measure the effort or expense for a given restoration scenario?
- b) How can we find the most efficient restoration pathway?

Both questions are addressed with the narrative *resistance*, defined as the relative difficulty to traverse land cover types (i.e. shrub land, agriculture, infrastructure, settlements) situated between the objects of the network (i.e. forest). In the case of raster data, each raster pixel belongs to a landscape type and therefore has a certain application-specific resistance. In the forest example, converting a pixel with a low resistance (shrub land) into a restoration/network pixel (forest) has a low price while the opposite is the case for a pixel with high resistance (built-up area). Because restoration implies changing existing land cover pixels into new object/habitat network pixels, the expense of a given restoration pathway is equivalent to the

accumulated resistance of the pixels forming the new pathway. And the most efficient pathway is the one with the least expense. This approach is similar to the concept of the least cost path, or a car navigator finding the shortest travel-time pathway between the start location and the destination target.

Within GuidosToolbox the following notation is used for the input resistance image:

0 byte – Missing: a pixel with infinite resistance = impossible to traverse

2 byte – Foreground (network object): pixel of interest/habitat having the lowest resistance

[3, 100] byte – Background (outside of network): a pixel having a larger resistance than foreground of at least 3 and maximum 100.

Because movement outside of the network is more difficult, the background (BG) resistance must always be higher than the foreground resistance. BG-resistance starts at 3 to maintain compatibility and input data notation with all other GuidosToolbox routines where foreground is assigned a value of 2 byte. BG-resistance values are not simply sequential but can cover the entire range from minimum to maximum resistance [3, 100].

For example, assume you are interested in woodland restoration and you have five land cover classes with different perceived resistances for woodland species: woodland, natural grassland, intensive grassland, cropland, and water. Woodland is equivalent to the target habitat (Resistance=2), natural grassland is favorable to woodland species (Resistance=5), intensive grassland is 3 times more resistant compared to natural grassland (Resistance=15), cropland is 10 times more resistant than natural grassland (Resistance=50) and water bodies cannot be traversed by the woodland species (Resistance = 0).

Note that assigning different relative resistance values to one, two or all four land cover classes other than woodland will inevitably result in different restoration pathways and expenses.

The narrative *resistance* is the single, key element driving the entire restoration planning process. Setting the BG-resistance values is crucial, requiring a good deal of thought and rationale.

GuidosToolbox provides interactive methods and guided help to setup an application-specific resistance map. Options include assigning a fixed or land cover-specific BG-resistance, resistance proportional to distance away from the existing network, pixel- or region-specific resistance, or inserting line-shaped features with custom width and custom resistance into the image (see section 4.1). Once the resistance map and a given restoration scenario is defined, cost and benefit are summarized with the following four restoration planning indicators:

Acronym	Name	Description	Unit
RP	Restore Pixels	Number of restoration pixels	[-]
EXP	Expense	Expense of restoration pixels ($\sum(RP_{RESIST})$)	[-]
EFFIC	Efficiency	Proportion: ECA gained / Expense	pixels
AVDIST	Remoteness	Average distance of RP away from existing network	pixels

Table 3: Summary of the restoration planning indicators

RP: RP is the total number of pixels that will be converted from background into foreground (network object) pixels.

EXP: EXP is a proxy for the overall expense of the restoration scenario, equivalent to the sum of resistances of all restoration pixels, where RP_{RESIST} is the resistance of a restore pixel.

EFFIC: The newly added restoration pixels are now part of the network objects and will lead to a larger equivalent connected area (ECA) of the network. The ratio of the increase in ECA to the expense ($\Delta ECA/EXP$) is a measure for the efficiency (EFFIC) of the restoration scenario. EFFIC allows comparing and measuring the efficiency of restoration scenarios by quantifying how much ΔECA is gained per unit of expense.

AVDIST: Each restoration pixel is located at a certain distance away from existing FG-objects. AVDIST provides an indication of the average “remoteness” (measured in pixels) of all restoration pixels used. Low values are obtained for restoration scenarios between existing FG-objects which are close to each other or by following a chain of FG stepping stones. Higher AVDIST values indicate a restoration scenario reconnecting network objects that are far apart.

3. Network status example applications

This section illustrates examples of coherence assessments. The examples are synthetic showcases outlining conceptual ideas for potential applications. They do not imply endorsement of specific datasets, nor are they related to past, planned, or future policy requirements.

3.1 Comparing coherence of forest networks at EU-level

Assumption: An international agency requested a comparative study on forest networks at EU-level. You have been asked to provide a solution that provides a concise summary of the current and past situation, including the possibility to define binding targets and measure progress towards policy goals.

Implementation: Using the 100m resolution CORINE 2018³ land cover map, we build a forest map using the CLC classes 311, 312, 313 (broad-leaved, coniferous, mixed forest) and mask the area of individual national territories having forest coverage. The 43 forest maps are then used as input maps to summarize the forest network status of each territory:

	A	B	C	D	E	F	G	H	I	J	K
1	Sorting	REP_UNIT	AREA [ha]	RAC [%]	NR_OBJ [#]	LARG_OBJ [ha]	APS [ha]	CNOA [ha]	ECA [ha]	COH [%]	REST_POT [%]
2	1	CLC_2018_AL-fmap.tif	711,124	24.71	1,596	56,135	445.57	29,235	100,922	14.19	85.81
3	2	CLC_2018_AT-fmap.tif	3,662,419	43.63	5,034	1,195,891	727.54	1,311,526	1,427,220	38.97	61.03
4	3	CLC_2018_BA-fmap.tif	2,373,283	46.35	2,763	1,726,400	858.95	5,367,404	1,728,904	72.85	27.15
5	4	CLC_2018_BE-fmap.tif	609,947	19.92	1,819	258,950	335.32	276,156	262,057	42.96	57.04
6	5	CLC_2018_BG-fmap.tif	3,475,462	31.31	4,887	1,675,395	711.16	2,173,126	1,696,138	48.80	51.20
7	6	CLC_2018_CH-fmap.tif	1,179,192	28.56	2,305	140,874	511.58	83,254	217,744	18.47	81.53
8	7	CLC_2018_CV-fmap.tif	146,909	15.90	99	72,162	1,483.93	104,287	75,191	51.18	48.82
9	8	CLC_2018_CZ-fmap.tif	2,592,992	32.88	5,493	110,610	472.05	61,225	280,092	10.80	89.20
10	9	CLC_2018_DE-fmap.tif	10,814,995	30.27	24,678	556,235	438.24	224,792	1,096,838	10.14	89.86
11	10	CLC_2018_DK-fmap.tif	390,324	9.08	2,409	9,996	162.03	2,413	21,664	5.55	94.45
12	11	CLC_2018_EE-fmap.tif	2,125,395	46.92	2,231	567,820	952.66	564,905	727,943	34.25	65.75
13	12	CLC_2018_EL-fmap.tif	2,634,025	20.01	4,140	276,631	636.24	153,078	442,620	16.80	83.20
14	13	CLC_2018_ES-fmap.tif	10,916,140	21.58	42,354	1,140,238	257.74	518,147	1,662,083	15.23	84.77
15	14	CLC_2018_FI-fmap.tif	21,487,467	63.70	9,594	18,618,005	2,239.68	130,115,309	18,630,012	86.70	13.30
16	15	CLC_2018_FR-fmap.tif	14,358,209	26.16	39,950	557,010	359.40	268,544	1,382,041	9.63	90.37

Figure 2: Extract of a forest network status assessment

³ <https://land.copernicus.eu/pan-europe/corine-land-cover/clc2018>

The full table can then serve to setup bar charts or dashboards showing forest network statistics. By filtering the table, one can find which reporting unit has the highest coherence (COH), most forest coverage (RAC) or compare the restoration potential of reporting units having a similar amount of forest coverage, etc. Applying the same procedure, but using the CORINE 2012 dataset instead, would provide the respective 2012 table. Compare the two tables to find where forest coherence, or any other parameter, has decreased, is stable or has increased.

Policy goals could be defined by setting adequate thresholds in network coherence, for example suggesting reporting units with a high value of restoration potential ($= 100\% - \text{Coherence}$), to conduct restoration measures aimed at increasing network coherence by a given percentile in a given time.

Someone may argue that the FG-definition should include the CLC-class Transitional Woodland Shrub. The impact of using this extended definition of forest could be easily assessed by running the same assessment again with the amended definition of forest.

Remarks: Please note that the same procedure could be produced by any other reporting unit (administrative level such as [NUTS/CENSUS](#) or biogeographical region). You could equally conduct a network status assessment for any other thematic layer of interest (agriculture, grassland, protected natural sites, state-owned land, high nature value farmland, species habitat, etc.).

3.2 Environmental impact assessment

Assumption: The Department of Transport has decided to build a new motorway. There are three alternative build options of similar expense and each of the three options cuts through the existing network of natural land at different locations. You are working in the Environment Agency and have been asked by the Department of Transport to evaluate the three build options and find out, which of the three has the least impact on the network of natural land.

Implementation: Using the existing GIS data of the Agency, we create a mask where natural land is assigned with 2 byte (foreground). We run a network status assessment to establish the status of the existing network of natural land, including measuring its coherence (like Table 2). Next, we use the Restoration Planner Setup Tools in GuidosToolbox (see section 4.1) to prepare three new maps by interactively inserting one of the three motorway tracks into each map of natural land. Each build option will cut the existing objects of natural land at different locations or reduce their size, which will result in three degrees of reduced network coherence, one for each motorway build option. Finally, we run the network status assessment on each of the three simulated maps to retrieve network coherence statistics for each build option. The results of the three build options are communicated to the Department of Transport with the suggestion to implement the option resulting in the least coherence decrease, which is the one having the least impact on the network of natural land.

4. Network restoration planning example applications

This section illustrates examples of restoration planning assessments. The examples are synthetic showcases outlining conceptual ideas for potential applications. They do not imply endorsement of specific datasets, nor are they related to past, planned, or future policy requirements.

4.1 Setting the scene...

Assumption: As a landscape architect, you conduct environmental assessments of planned major infrastructure developments such as roads, wind farms and other commercial or industrial complexes. Environmental policy compliance requires quantifiable indicators to forecast the impact and to monitor the implementation progress of a given development plan.

Implementation: Your task requires to simulate planned land cover change within the land cover datasets you have. The impact of a project is quantified by building the difference between the current status and the planned, new status of the network. The previous example illustrated this idea for a motorway. While a network status assessment only requires to analyze the network itself, restoration planning is more complex because of the need to assign existing background to an appropriate resistance.

Resistance is key, driving the expense of a given restoration pathway or ultimately, the geographic location of cost-efficient restoration pathways, which will follow the path of least resistance. Moreover, the resistance, which is serving as a proxy to define the relative difficulty to traverse a given pixel, strongly depends on the application.

The restoration planner submenu *Setup Tools* provides the following methods to define suitable input maps for specific restoration planning analysis:

- **Fixed BG-Resistance:** This option may be useful as a quick guess or if no further knowledge on the background is available, a fixed average background resistance can be assigned.
- **Land Cover → Resistance:** If resistance is land cover specific (for example, land cover specific movement probability for a mammal in a biodiversity study), a lookup table is used to reclassify land cover to appropriate resistance values. Note, this option can also be used to simulate land cover change, for example recode existing specific background land cover to foreground (Resistance=2), or a blocking land cover class (i.e. water) that cannot be traversed (Resistance=0).
- **Distance → Resistance:** In case of flying insects or birds, resistance can be set to be proportional to the distance away from habitat, independent of the existing land cover.
- **Pixel → Resistance:** Assign a specific location with a specific resistance. This option may be useful to adequately represent local conditions, for example to amend
- **Line → Resistance:** Interactively insert a line of specific shape, width and with specific resistance into the image (see Figure 3). This option can be used to simulate the pathway, width and resistance of planned roads (small country roads with relatively low resistance versus wide motorways with high resistance, or other custom line-shaped features, such as ditches, hedgerows, lines of trees and field margins, that provide important habitats and ecosystem services and function as ecological infrastructure for species within agricultural landscapes.

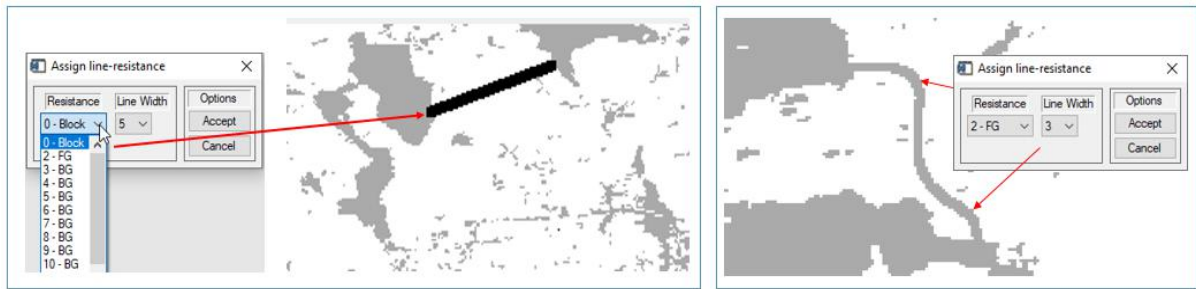


Figure 3: Example of Line → Resistance interface: insert a straight line of width 5 pixels, i.e. a motorway (blocking – resistance = 0) (left panel); insert a freehand line of width 3 pixels, i.e. a hedge row into natural land habitat (right panel).

- Region Of Interest → Resistance:** The *Region Of Interest* (ROI) interface can be used to define any custom-shaped ROI and resistance or select an existing ROI to redefine its resistance. The top panel of Figure 4 shows an example of four custom regions, outlined in cyan and red color. After the definition of the ROI perimeter, the resistance to be assigned to the newly defined ROI area is selected from the final dropdown menu (Figure 4, bottom right panel). Selecting a resistance of 0 is equivalent to a blocking object, 2 for foreground and a resistance within the range of [3, 100] is used to characterize the relative difficulty to traverse a background object.

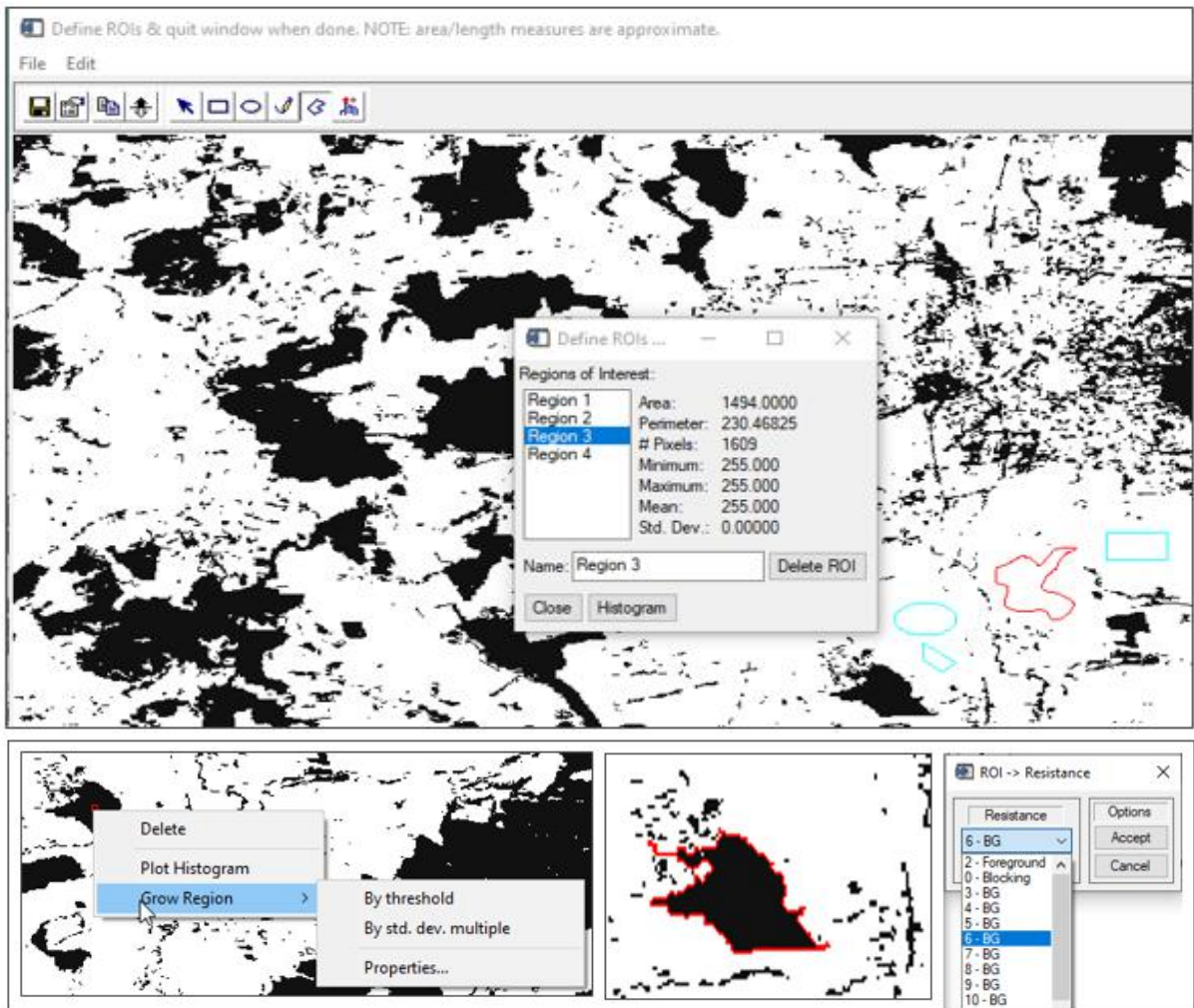


Figure 4: Example to interactively define custom regions (top), or select irregular shaped objects (bottom left and center), and final resistance assignment for the selected object highlighted in red color (bottom right).

Remarks: The various Setup Tools provide full flexibility to simulate any kind of land cover change or to model any suitable resistance assignment. The tools allow to define the shape (point, line, area) and the resistance type (blocking, foreground, background). This feature is of critical importance to appropriately match an application specific resistance map for restoration planning.

4.2 Evaluating restoration scenarios

Assumption: A car manufacturer has planned a new production plant. The site would remove a substantial area of forest, resulting in a 3% decrease in coherence of forest land. National legislation requires to compensate any negative impact with an adequate restoration measure, which must be validated by the Environment Agency. You are working as an environmental officer for the car manufacturer and are in charge to define an appropriate restoration scenario to be provided to the Environment Agency.

Implementation: Because forest restoration implies converting existing non-forest land cover into forest we need to setup a resistance map, serving as a proxy for the restoration expense. Precondition: For best compatibility we use the same GIS data as is used by the Agency.

1. We start with setting up a mask where forest land is assigned with 2 (foreground).
2. Land cover elements that cannot be changed or used for restoration will be coded with 0 (blocking); this includes roads, rivers, urban environments, commercial sites and protected areas.
3. The remaining area, which is potentially viable for restoration measures, is then assigned with either an average resistance value or dedicated resistance values corresponding to the conversion feasibility and expense. For example:
 - a) Public grassland is relatively easy and hence more cost effective to convert to forest and could be assigned with a resistance of 5.
 - b) Private grassland may cost more, assign a resistance of 10.
 - c) Bio-fuel farming land may cost even more, assign a resistance of 20.
 - d) Agricultural land may cost even more, assign a resistance of 40, etc.

The Restoration Planner **Setup Tools** in GuidosToolbox can be used to easily assign appropriate resistance values to land cover classes, or polygons, pixels, lines or any custom area. Once defined, we use this resistance map in GuidosToolbox.

4. Now we use the **Add Custom Path** option of the Restoration Planner to interactively insert restoration pathways between existing forest objects and instantly retrieve key information on restoration expense and efficiency. Figure 5 shows an example of an interactively drawn restoration path (red pixels) reconnecting and traversing previously disjoint forest objects (beige color) in a subsection of the forest network.

Here, a constant background resistance of 30 was assumed, leading to a restoration expense (EXP_30) of 6000 units = 200 (restoration pixels) * 30 (resistance). With respect to the entire network, this simulated restoration path would result in a coherence increase of 0.07% (too little to fulfill the requirement of 3%), a gain in ECA of 416 pixels, and an efficiency of 0.069 ($\Delta ECA / \text{expense} = \text{how much do I get for my investment}$).
5. Returning to our initial requirement of finding a restoration path providing 3% gain in coherence, we would now try to establish different reconnecting pathways, preferably

between large forest objects, because this will provide a higher gain in coherence. When new pathways have been defined, the change in coherence and all other restoration planning indicators are displayed and can be checked immediately.

- Once a restoration pathway with the required gain of 3% has been found by the environmental officer of the car manufacturer, it can be suggested to the Environment Agency.

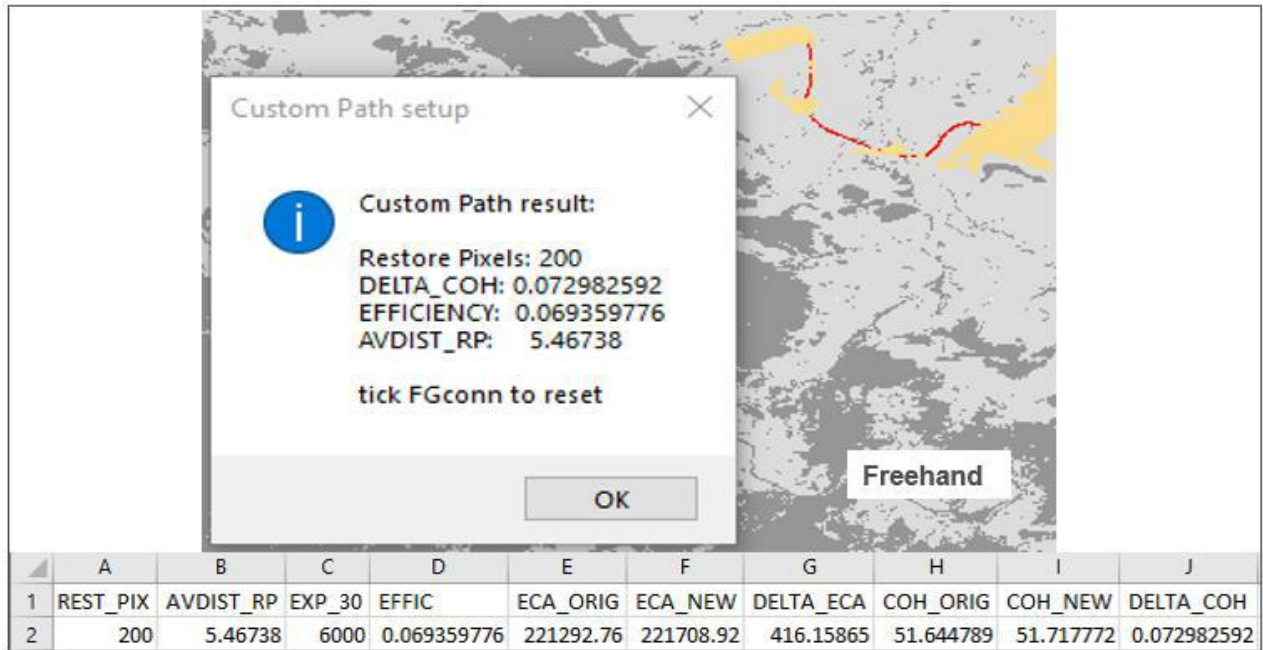


Figure 5: Example of restoration statistics for a freehand drawn restoration path within a subsection of the forest network

Remarks: You may find several suitable restoration pathways. If two pathways provide a similar gain you would choose the one with a higher efficiency, equivalent to less investment for the same gain. Or instead of a single pathway you may suggest to add two or more restoration pathways to achieve the overall goal of 3% coherence increase.

The option *Add Custom Path* is ideal to quickly assess any custom restoration path of your choice or to evaluate the efficiency of restoration pathways suggested by a third party. The beneficial effect of reconnecting intermediate objects is even more pronounced when detecting the *optimum* reconnecting pathway as described in the next example.

4.3 Finding the optimum restoration pathway

Assumption: The same scenario as outlined in the previous example 4.2 but now with the option to optimize restoration efficiency between start and target object.

Implementation: If the restoration path is not pre-defined, an optimization routine can be applied. This routine (GGEO, Soille 1994) is implemented in the processing option **Find**

Optimum Path, which tries to take advantage of intermediate objects (stepping stones) to minimize restoration expense and to maximize restoration benefit.

Figure 6 shows the result of the optimization process for the same start- and target objects as selected in Figure 5. The optimum path includes larger intermediate objects (beige color) to increase coherence and connected area gained. Compared with the statistics from Figure 5 we find that to establish the optimum path, only 65 restore pixels (red color) are needed with an expense of $65 \cdot 30 = 1950$, while coherence will increase by 11 %. The combination of fewer restore pixels and increased gain of equivalent connected area (ECA) leads to a higher increase of the parameter efficiency (EFFIC).

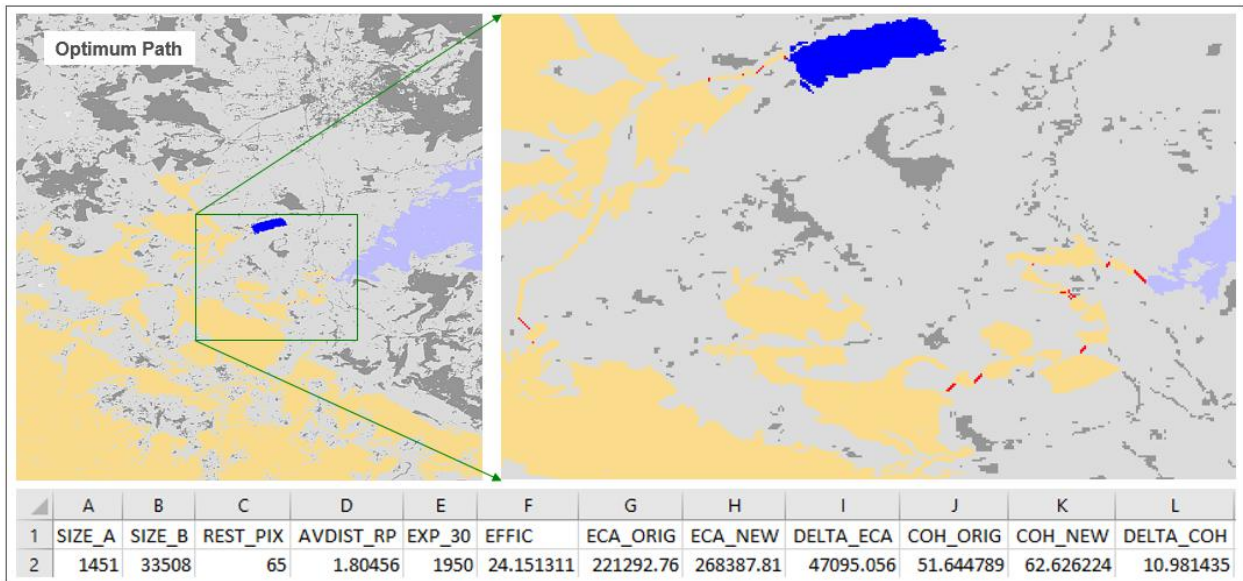


Figure 6: Example of restoration pathway and statistics for the optimum restoration pathway (red) between a start object (dark blue) and target object (light blue).

Remarks: The optimization is most efficient if very large objects are found near the start and target object. The optimum path also strongly depends on the resistance in the background. A very low resistance will result in a direct line between start and target object. Using a high background resistance enforces strong optimization by avoiding high resistance background pixels and favoring low resistance foreground objects. This travel time optimization is analogous to a car navigator avoiding traffic jam congested roads and preferring faster travel on alternative roads.

The option **Find Optimum Path** is ideal to detect the most efficient restoration pathway between two user-selected objects. The increase in coherence (COH) is most pronounced when reconnecting very large objects, triggered by a strong increase of SSQ, see Figure 1.

4.4 Finding most efficient restoration pathways

Assumption: The same scenario as outlined in the previous example 4.2 but now with the option to automatically show most efficient restoration pathways.

Implementation: The option **Show Optimum Big 5** will automatically calculate the pairwise optimum restoration pathway between the five largest objects. The result is a map showing the

location of the ten pathways (Figure 7) as well as a tabular summary (Table 4) listing the size of the objects and the related restoration planning indicators.

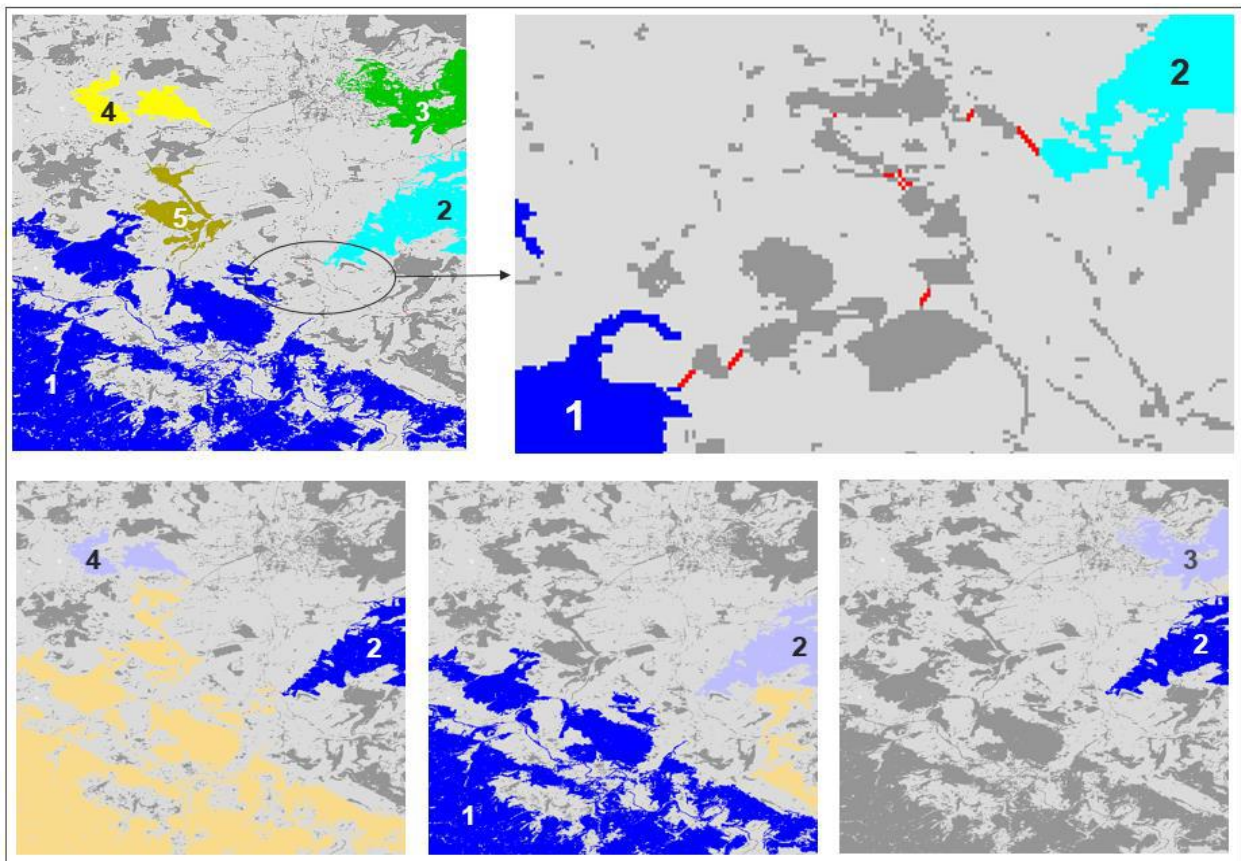


Figure 7: Example showing the automatic detection of restoration pathways between the five largest objects, summary (top left) and example of individual pairs (bottom panel).

The top left panel in Figure 7 shows the summary of all ten restoration pathways between the five largest objects, color-coded in decreasing size from the largest object in blue to cyan, green, yellow and brown. The top right panel shows an enlarged subsection with restore pixels in red color.

The bottom panel shows examples of individual optimum restoration pathways between the second- and fourth-largest object ($2 \leftrightarrow 4$, left), largest- and second-largest object ($1 \leftrightarrow 2$, center), or second- and third-largest object ($2 \leftrightarrow 3$, right). In each of the ten individual assessments, the start object is marked in dark-blue, the target object in pale-blue and intermediate objects (if encountered) in beige color.

Remark: The optimum path may include alternative, parallel pathways and/or bifurcations of equal expense (see top right panel in Figure 7). While alternative pathways are important information for planning restoration pathways, these features may lead to an increased number of restore pixels and expense resulting in a decrease in efficiency. This implies, that the actual efficiency will be higher, if alternative pathways are neglected.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	RESTORE	SIZE_A	SIZE_B	REST_PIX	AVDIST_RP	EXP_30	EFFIC	ECA_ORIG	ECA_NEW	DELTA_ECA	COH_ORIG	COH_NEW	DELTA_COH
2	1 <-> 2	214811	33508	18	2.14992	540	90.476013	221292.76	270149.8	48857.047	51.644789	63.044285	11.3995
3	1 <-> 3	214811	26366	43	1.24715	1290	34.731307	221292.76	266096.14	44803.386	51.644789	62.094668	10.4499
4	1 <-> 4	214811	14983	8	1.20711	240	131.13431	221292.76	252764.99	31472.233	51.644789	58.988605	7.34382
5	1 <-> 5	214811	13850	2	1.41421	60	217.68263	221292.76	234353.72	13060.958	51.644789	54.69267	3.04788
6	2 <-> 3	33508	26366	23	4.66506	690	5.8013699	221292.76	225295.7	4002.9452	51.644789	52.576165	0.931376
7	2 <-> 4	33508	14983	61	1.79058	1830	35.133502	221292.76	285587.07	64294.309	51.644789	66.640159	14.9954
8	2 <-> 5	33508	13850	56	1.85377	1680	27.135228	221292.76	266879.94	45587.183	51.644789	62.275681	10.6309
9	3 <-> 4	26366	14983	41	1.239	1230	2.6203955	221292.76	224515.84	3223.0865	51.644789	52.391973	0.747183
10	3 <-> 5	26366	13850	40	1.23462	1200	2.5434958	221292.76	224344.95	3052.195	51.644789	52.352216	0.707427
11	4 <-> 5	14983	13850	5	1.08284	150	9.9899756	221292.76	222791.25	1498.4963	51.644789	51.993898	0.349109

Table 4: Tabular summary result of the automatic detection of restoration pathways between the five largest objects (Show Optimum Big 5).

Table 4 shows the tabular summary of the ten pairwise optimum restoration pathways between the five largest objects. This table can be sorted for the indicator of interest, for example, the most efficient restoration pathway (EFFIC = 217) is found for connecting the largest object with the fifth-largest object (1↔5), requiring 2 restore pixels only to achieve the highest efficiency (ratio of ΔECA/EXPENSE).

If the focus is on coherence increase, then the connection between the second and fourth biggest component (2↔4) should be considered (ΔCOH = 14.9954). The respective downscaled screenshot (2↔4, Figure 7, bottom-left) shows this restoration pathway with intermediate stepping stones highlighted in beige color: The restoration pathway (2↔4) starts from the second-largest object No. 2 and includes smaller foreground objects on its way to the largest object No. 1 (2↔1, Figure 7, top-right), then traverses through the fifth-largest object No. 5 and a few smaller ones south of object No. 4.

The exact geographic pathway location is marked with red pixels and can be easily followed when looking at the corresponding full-resolution map product (2↔4).

5. Discussion

This document describes a methodology to measure the status of network coherence as well as to plan restoration options and assess their impact. Key features of the methodology are intuitive and quantitative indicators tailored for status reporting, planning alternatives and a quantifiable change assessment. This generic methodology is applicable to any thematic area of interest and at any geographic scale.

The network status is assessed via the narrative *coherence*. The two principle properties driving the network status are ECA (the amount of reachable habitat) and COH (the network coherence). From the definition of network coherence, it is evident that reconnecting large objects via a restoration pathway is the most cost-efficient restoration process. Reporting the equivalent connected area, the overall extent and the degree of network coherence provides a concise and comprehensive summary of the network status.

Please note that coherence is a relative measure describing the consistency of a given network. In principle, the degree of network coherence could be increased by simply removing small objects. For this reason, a valid restoration scenario must always imply to add area into an existing network.

Restoration planning is assessed via the narrative *resistance*, allowing the user to simulate application-specific restoration conditions, for example the landscape can be assigned to have:

- a typical, fixed resistance,
- a variable land cover-specific resistance,
- a resistance that is proportional to the distance away from network objects (i.e. for birds or flying insects),
- local, custom resistance to assign country roads a lower resistance than motorways, or privately-owned farmland a higher resistance than public farmland, etc.
- Finally, areas can be blocked from being traversed by assigning them a resistance value of zero.

Assigning a low resistance value to certain regions will favor restoration in these areas. In addition, the interactive *Setup Tools* allow to insert and configure any shape of choice, thus providing full flexibility to simulate any restoration scenario.

Once the background resistance is defined, the restoration impact result provides details on effort and benefit of the planned or simulated scenario.

Two dedicated tools, *Add Custom Path* and *Find Optimum Path* address two typical restoration planning tasks:

- a) evaluating pre-defined restoration pathways and
- b) detecting the most cost-efficient, optimum pathway.

In summary, when adding new restoration area into the network:

- ECA will *always* increase regardless of the amount or location of added area.
- ECA will increase more when a given area is attached to a large object.
- ECA will increase even more if a given area is invested into a reconnecting path.
- ECA will increase most when reconnecting large objects.

The effect of coherence increase is:

- Negative, when adding a disjoint object smaller than the Critical New Object Area (CNOA).
- Positive, when adding a restoration path between different medium/large network objects.
- Very positive, when adding a restoration path between the largest network objects.
- Maximum, when reconnecting all objects.

6. Conclusions

The Restoration Planner provides a set of tools to tackle two topics, network status assessment and evaluating restoration scenarios. Each topic applies a single, generic narrative, *coherence* and *resistance*. Both topics can be applied for the assessment of any thematic layer and at any geographic scale.

The resulting maps are essential products, providing guidance in the spatial planning phase of the restoration scenario. Here, the final restoration pathway depends on the application-specific resistance setup of the landscape, which is under full control of the user.

The quantitative indicator values and their change (before/after) serve as strong arguments to define and defend the most cost-efficient restoration scenario. Moreover, they are critical to quantify temporal progress towards policy goals and the final overall success of the restoration project.

References:

Vogt P., Riitters, K., 2017. GuidosToolbox: universal digital image object analysis. *European Journal of Remote Sensing* 50:1, 352-361, DOI: [10.1080/22797254.2017.1330650](https://doi.org/10.1080/22797254.2017.1330650).

Soille, P. (1994). Generalized geodesy via geodesic time. *Pattern Recognition Letters* 15(12), pp. 1235-1240. DOI: [10.1016/0167-8655\(94\)90113-9](https://doi.org/10.1016/0167-8655(94)90113-9)

In addition to the outlined Restoration Planner module, GuidosToolbox provides dedicated routines for spatial mapping and quantification of fragmentation, distance, naturalness, landscape parcellation and other aspects derived from land cover maps. Further information is available in related product sheets available on the GuidosToolbox homepage.