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LDT4QGIS: An open-source tool to enhance landscape analysis

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ABSTRACT

Despite the variety of landscape software available, new tools keep being developed in order to improve the existing analytical capabilities. Scripts, packages, or standalone software are built to enhance performance, add features or fulfil specific needs. This paper introduces LDT4QGIS, an open-source tool built exclusively to operationalize the Landscape Dynamics Typology method. LDT4QGIS is a Python-based tool developed to assess the landscape composition and configuration and to classify different land cover / land-use changes using QGIS. By combining the metrics 'area' and 'number of patches', it is possible to define different patterns of landscape changes (types of dynamics). The tool, which uses vectorial binary landscapes, allows squares or irregular polygons to be used as analytical units. The end goal of the procedure is to assign a type of dynamic to each analytical unit. To do this, metrics and their variations are calculated and then combined through a series of queries and selections that operationalize the type of dynamic assignment. LDT4QGIS has additional functionalities that are computed at the class level; they are related to the calculation and spatially explicit representation of gained and lost areas, as well as perforations in the land cover under study. Depending on what functionalities are being used, two or three analytical moments are required as inputs. The outputs produced by LDT4QGIS can be used in landscape assessment procedures and therefore can be helpful to decision-makers, allowing them to better understand and anticipate the consequences of policies related to the use of the land. LDT4QGIS will be updated regularly and improved whenever we develop a new functionality, but the real strength of LDT4QGIS is that it is free and open-source, and it can be adapted by each user according to their own needs.

This paper describes LDT4QGIS and includes three illustrative practical examples to demonstrate the variety of scripts and outputs. The first case study concerns the dynamics of grasslands in Slovenia, and it uses two analytical moments and squares as analytical units. The second example focuses on olive groves in Portugal; it uses administrative boundaries as analytical units and three analytical moments. The last example concerns forests in Germany and showcases additional features like the detection of gained areas, lost areas, and the associated dynamics.

1. Introduction

Significant landscape changes frequently disturb ecosystem functioning and interfere with ecological processes, threatening the provision of vital ecosystem services (Millennium Ecosystem Assessment, 2005).

Habitat loss and fragmentation have been key topics in landscape ecology and conservation biology for some time (Saunders et al., 1991). They have been shown to be major causes of biodiversity loss in some regions (Jaeger et al., 2011) and are considered a significant form of land degradation by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES, 2019). Unlike 'habitat loss', 'fragmentation' is not necessarily a straightforward concept. If some amount of a given habitat existed and now there is less of that habitat, then habitat loss has occurred. However, to make such claims regarding fragmentation, one must define the term clearly. It is generally accepted that fragmentation is the process of 'breaking up of a habitat, ecosystem or land-use type into smaller parcels' (Forman, 1995), but there are different ways to carry out such a process. For instance, if area loss contributed to a larger patch splitting into two or more smaller patches, there was more happening than pure fragmentation. This brings us to the topics of landscape composition and configuration. Composition

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refers to what makes up the landscape and how much of it exists in the landscape (the types and abundance of patches), while configuration refers to the landscape's spatial arrangement (McGarigal and Marks, 1995). Variations in the amount (gain/loss) and geometry (fragmentation/aggregation) co-occur and interact in the landscape (Lindenmayer and Fischer, 2007), making the distinction between their independent effects difficult to quantify and interpret (Fahrig, 2017).

In this intrinsically complex context, one way to avoid inconsistencies between studies is to address 'fragmentation' as a process purely related to the configuration and release it from compositional aspects. In other words, whenever there is an area variation, that area loss or gain should be mentioned along with the geometric aspects reflected by fragmentation or aggregation. It is key to consider the distinction between landscape composition and configuration (Fahrig, 2003, 2002) and to be aware that some metrics may confound them to some extent (Neel et al., 2004). Despite the difficulties, recent studies have successfully addressed this issue by integrating different methods into their analytical procedures (see Arroyo-Rodríguez et al., 2020; Johnstone et al., 2014; Liu et al., 2020; Osborne and Alvares-Sanches, 2019; Plecas et al., 2014; Sauder and Rachlow, 2014; Steckel et al., 2014; Suárez-Castro et al., 2020).

The quantitative assessment of landscape patterns is performed via landscape metric calculations. Landscape metrics became popular among ecologists interested in how a landscape's structure and dynamics influence ecological processes (Turner, 1990). The technological advances in computing boosted the use and consequently the emergence of more landscape metrics. From simple and descriptive metrics to more sophisticated and harder to interpret metrics, landscape metrics have proliferated to a point where it has become challenging for investigators to choose which metrics to use (Cushman et al., 2008). The generalised advice is to use a small number of metrics and try to avoid redundancy. Still, adequate metrics should be used in accordance with the analysis being performed and the data that are available. Many metrics have been developed to assess characteristics like dominance, diversity, and contagion, among others (Haines-Young and Chopping, 1996), but few were specifically built to measure fragmentation. Processes that are hard to assess using a single metric may be better grasped using specific metric combinations that reflect actual pattern changes (spatial processes in land transformation (Bogaert et al., 2004; Forman, 1995), types of dynamics (Machado et al., 2018)).

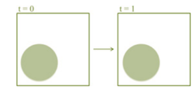
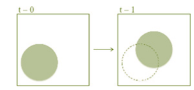
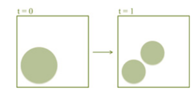
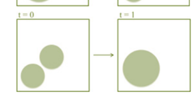
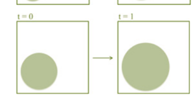
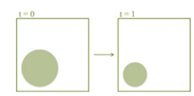
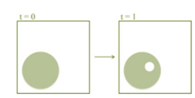
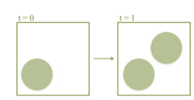
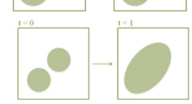
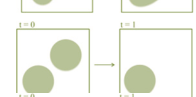
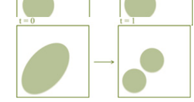
There is no shortage of software related to landscape analysis and metric calculations. There are well-known pieces of software like FRAGSTATS (McGarigal et al., 2012), Conefor Sensinode 2.2 (Saura and Torné, 2009), Land-metrics DIY (Zaragozí et al., 2012), Patch Analyst (Rempel et al., 2012), Graphab (Foltête et al., 2012), and Circuitscape (McRae et al., 2013), among others, and newer tools such as GUIDOS (Vogt et al., 2022), landscapemetrics (Hesselbarth et al., 2019), gDefrag (Mestre et al., 2019), and Motif (Nowosad, 2020). Nevertheless, new software tools will be developed to meet the demand for more analytical capabilities and the need for free and open-source software. For a comprehensive review of free and open-source software for GIS/geospatial applications, we recommend the work by Steiniger and Hay (2009). In this paper, we introduce LDT4QGIS, a tool for QGIS (QGIS.org, 2022), whose main goal is not to calculate metrics but to identify and locate distinct spatial processes in land transformation.

1.1. Background

Landscape Dynamic Typology (LDT) (Machado et al., 2018) is a method that uses landscape composition and configuration metrics to assign analytical units (AU) to a Type of Dynamic (ToD) in binary landscapes. The original version uses the area as the composition measure and the number of patches (NP) as the configuration measure. By measuring both for more than one date and combining the results, it is possible to identify several ToDs (Table 1): (A) If there is no change in an area or in the NP we assume that landscape (or the analytical unit extent) did not change; (A1) If there is no change in area and NP but the patch(es) is/are not located on the same place as before, a spatial shift has occurred (B) If the area remained the same but the NP increased, it means a fragmentation occurred; (C) If the area remained the same but NP decreased, then an aggregation took place; (D) If the area increased and the NP is equal, it represents a gain of area; (E) If the area decreased and the NP did not change, there is a loss of area; (E1) Particular case of the previous ToD in which the loss amount created a clearing; (F) If both area and NP increased, it led to new patch creation; (G) If the area increased and NP decreased, an aggregation occurred due to area gain; (H) If both area and NP decreased, a patch decrement occurred due to area loss; (I) If area decreased and the NP increased, it means that fragmentation occurred due to area loss.

The ArcGIS toolbox 'LDTtool' was built to facilitate the usage of this method and to automate the procedure (Machado et al., 2020). LDT4QGIS, introduced in this paper, is a free and open-source solution that makes these analytic possibilities available to QGIS users. It represents an enhanced version that brings relevant updates and functionalities, such as two more ToDs ('A1 – Spatial Shift' and 'E1 – Perforation') and two new scripts to calculate the 'perforation' and 'gained and lost patches' at the class level.

Table 1
Landscape Dynamic Types (adapted from Machado et al., 2018).

If	and	Designation	Graphic Representation	ToD
$\Delta A = 0$ ^ Symmetrical difference = 0	$\Delta NP = 0$	No change		A
$\Delta A = 0$ ^ Symmetrical difference > 0	$\Delta NP = 0$	Spatial shift		A1*
$\Delta A = 0$	$\Delta NP > 0$	Fragmentation per se		B
$\Delta A = 0$	$\Delta NP < 0$	Aggregation per se		C
$\Delta A > 0$	$\Delta NP = 0$	Gain		D
$\Delta A < 0$ ^ Symmetrical difference output **is not** completely contained in the original patch(es)	$\Delta NP = 0$	Loss		E
$\Delta A < 0$ ^ Symmetrical difference output **is** completely contained in the original patch(es)	$\Delta NP = 0$	Perforation		E1*
$\Delta A > 0$	$\Delta NP > 0$	NP increment by gain		F
$\Delta A > 0$	$\Delta NP < 0$	Aggregation by gain (NP decrement by gain)		G
$\Delta A < 0$	$\Delta NP < 0$	NP decrement by loss		H
$\Delta A < 0$	$\Delta NP > 0$	Fragmentation by loss (NP increment by loss)		I

* ToD not present in the original LDT and now added.

An important difference between LDT4QGIS and most of the existing tools is that LDT4QGIS uses vectorial format instead of raster format. The raster format is particularly useful for storing data that varies continuously (e.g., temperature, elevation, etc.), which is not the case here. For land cover maps in which each thematic class needs to be distinguished and limited by boundaries, the choice is between a discrete raster that consists of integers that are used to represent classes and a vectorial data model. However, given that LDT4QGIS uses binary landscapes (only one land cover category is geoprocessed) and considering that the typical raster advantages no longer apply, it makes sense to use a vectorial format since it may provide more geographic accuracy (it is not dependent on the pixel size) and usually performs better in terms of data storage and processing speed. Besides these operational aspects, the use of a vectorial format is also convenient since most official land cover maps are made available to the public in vectorial format.

However, the most distinctive feature of this method and the associated tools is the fact that it goes beyond metric calculations and focuses on the spatial processes in land transformation. Metrics and indices are undoubtedly useful for describing landscapes and their changes, but since certain variations in particular metrics reflect determined spatial processes, it makes sense to go one step further and provide those processes as outputs of the analysis.

2. Methods

2.1. General description

LDT4QGIS consists of three Python (www.python.org) scripts that allow the application of the LDT method in QGIS.

- I – 'LDT4QGIS.py': This is the main script that performs the LDT steps to identify the ToDs in the landscape. The analysis can be conducted using two or three analytic moments (2 M or 3 M), and the results can be spatially represented according to a regular vectorial grid built during the analysis (squares) or an irregular polygonal study area provided by the user (Districts):
  o Landscape Dynamic Types 2 M (Squares)
  o Landscape Dynamic Types 3 M (Squares)
  o Landscape Dynamic Types 2 M (Districts)
  o Landscape Dynamic Types 3 M (Districts).

There is an option to include the ToD 'E1 – Perforation' in the analysis. It is optional because when this ToD is assigned to an AU, this does mean that it occurred but does not mean that it was the only area loss that occurred, so extra caution is needed to avoid misinterpreting the results. This is not a problem when the same procedure is applied to the entire land-use / land cover (LULC) class, without AU, using the script 'perforation.py'.

- II – 'perforation.py': This is an accessory script to geoprocess, at the class scale, the spatial pattern 'perforation'. It shows where perforation happened between two analytical moments.

'Perforation, the process of making holes in an object such as a habitat or land type, is probably the most common way of beginning land transformation' (Forman, 1995). It involves a reduction in amount without NP variation, and the loss occurs inside the patch. Within the LDT framework, it is accurate to state that perforation is a particular case of ToD 'E – Loss' in which the lost amount originates a clearing.

- III – 'gained and lost patches.py': This is an accessory script to identify and locate the places where amounts of the LULC category of interest were gained and lost between two analytical moments, including new individual patches or individual patches that disappeared. It produces four output shapefiles containing all gained areas, all lost areas, gained patches, and lost patches.

The overall quality of the analysis depends on the quality of the inputs. For that reason, it is important to use adequate spatial and temporal resolutions to correctly assess the landscape changes. Additionally, to avoid possible errors or malfunctions, users are advised to use the same coordinate system for all the input elements and to delete unnecessary attribute fields.

2.1.1. Preliminary steps, inputs, and settings

The scripts are simple to use, but some details regarding data preprocessing are worth mentioning:

i) A projected (not geographic) coordinate reference system (CRS) should be used, and the coordinates should be displayed in metres. All shapefiles should be in the same CRS.
ii) LDT uses binary landscapes, and thus the input land cover shapefiles must contain only one category with the polygons of interest. Therefore, depending on the base maps available, it may be necessary to export the category under study to a new shapefile and use it in the analysis.
iii) Scripts should be stored in the QGIS script folder. The path to the folder is Processing Toolbox – Options – Processing – Scripts (Fig. 1). Exiting and restarting QGIS will ensure that the scripts are automatically loaded to the Processing Toolbox.
iv) Two symbology files (suited for two or three analytical moments) are provided and can be loaded and applied to the output files. If a symbology file is stored in the same folder as the scripts, the symbology is automatically applied.

The inputs and settings required to run the scripts are the following:
I – 'LDT4QGIS.py'

- *Moments:* Choose whether the analysis should be based on two or three moments.
- *Type of Analysis*: Choose whether the analytical units should be squares or districts. (A polygonal shapefile containing the districts' boundaries must be provided by the user.)
- *Study Area Polygon*: Provide a polygonal shapefile containing the study area boundaries.
- *Landscape Moment 1*: Provide a polygonal shapefile of the landscape in moment 1.
- *Landscape Moment 2*: Provide a polygonal shapefile of the landscape in moment 2.
- *Landscape Moment 3*: Provide a polygonal shapefile of the landscape in moment 3.
- *Keep patches equal to or larger than (square metres)*: Choose the minimum patch size to be analysed.
- *Square width and height (metres):* Choose the analytic square size (for a square-based analysis only).
- *Perforation:* Check the box to include the ToD 'E1 – Perforation' in the analysis.
- *Output Shapefile*: Provide the name and path of the output file.

II – 'perforation.py'

- *Landscape Before:* Provide a polygonal shapefile of the landscape in the earliest moment of analysis.
- *Landscape After:* Provide a polygonal shapefile of the landscape in the latest moment of analysis.
- *Output Shapefile:* Provide the name and path of the output file.

III – 'gained and lost patches.py'

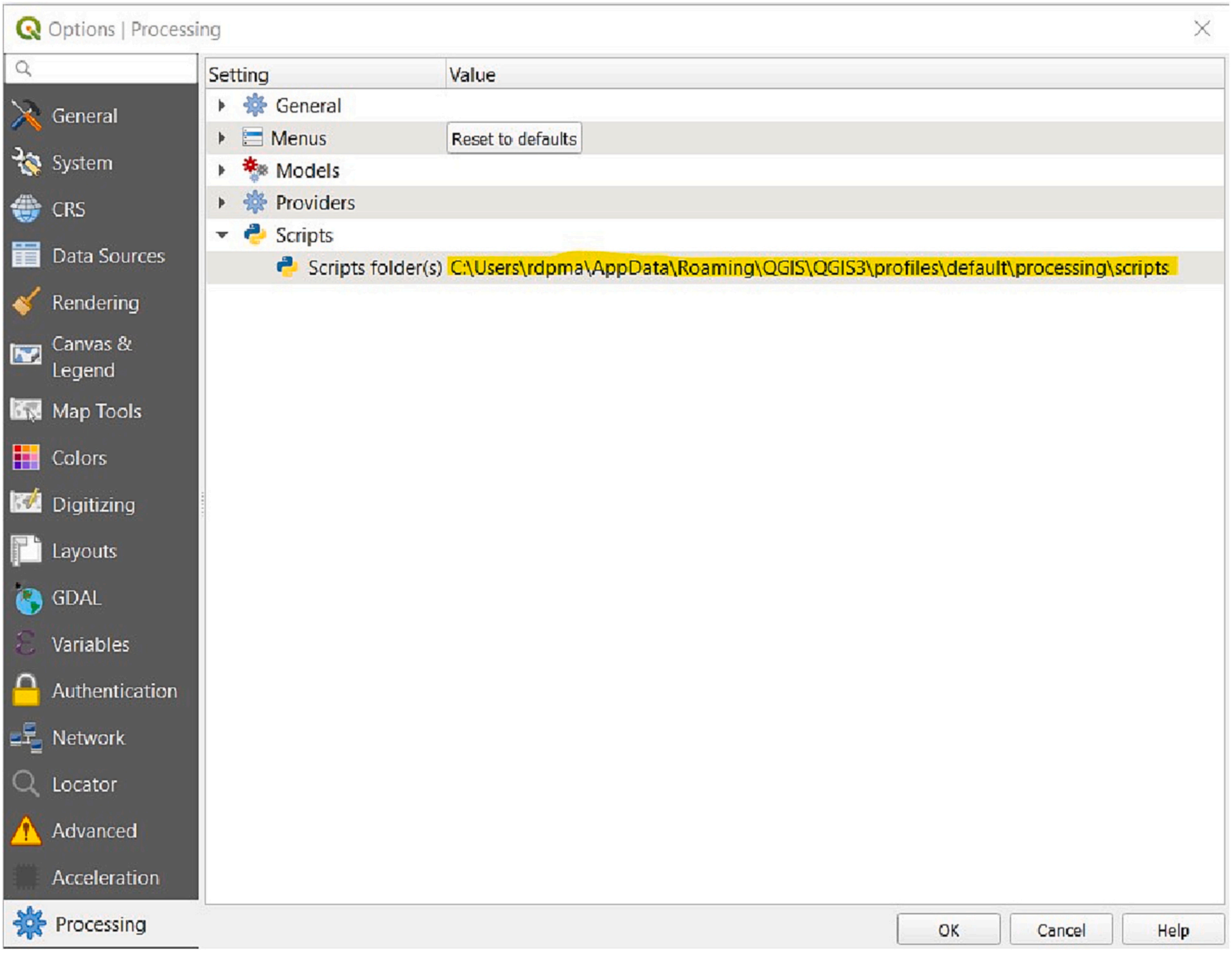


Fig. 1. - Path to the QGIS script folder (Processing Toolbox – Options – Processing – Scrips).

- *Landscape Before:* Provide a polygonal shapefile of the landscape in the earliest moment of analysis.
- *Landscape After:* Provide a polygonal shapefile of the landscape in the latest moment of analysis.
- *Output Path:* Select the folder in which the output shapefiles will be saved.
- *Output Name:* Select a prefix for the output file names. The names are, by default, 'GainedPatches', 'LostPatches', 'GainedArea', and 'LostArea'.

2.2. Demonstrations

This section includes three illustrative examples that show different approaches, features and outputs derived from LDT4QGIS application to distinct study contexts. The examples concern changes in particular LULC, in different countries: grasslands in Slovenia, olive groves in Portugal and forests in Germany (Fig. 2).

2.2.1. Grasslands in Slovenia

European semi-natural grasslands are often considered to have high conservation value due to the unique and highly diverse communities of species they harbour (Veen et al., 2009; Wilson et al., 2012). Despite their importance, species-rich grasslands have been decreasing (WallisDeVries et al., 2002) and are now one of the most endangered ecosystems in the European Union (European Environment Agency, 2020). Their existence depends on continuous sustainable and moderate use of the land, which is seldom compatible with the practices introduced by recent changes in land management. On the one hand, marginal areas are prone to be abandoned and face problems of overgrowth, and on the other hand, the best land is frequently used for more intense agriculture, which is often associated with increased fertilisation, a higher mowing frequency, and other practices associated with the deterioration of grasslands (Stoate et al., 2009; Van Vooren et al., 2018). An increase in mechanisation leads to increases in the field size, which creates coarse-grained landscapes with a lower diversity of crop types, field edges, hedgerows, ditches, and other elements that are known to promote biodiversity (Baguette and Van Dyck, 2007; Turner et al., 1989). Some polices, particularly grassland-specific agri-environmental measures, have been implemented in Slovenia, but the outcomes were far from expected (Kaligarič et al., 2019). Only effective policies can contribute to preserving these extensive grasslands and integrate them into modern and more profitable farming systems. Some grasslands are probably lost forever, and others are experiencing an accelerated pace of degradation; therefore, it is fundamental to understand the recent trends, model future LULC changes, and prioritise which grasslands are most important and worth preserving. This example consists of applying LDT4QGIS to Slovenian grasslands using 2500 ha (5 km × 5 km) squares. The base datasets are the official landscape land cover maps (http://rkg.gov.si/GERK/documents/RABA_old/index.html) for the years 2009 and 2020 (Fig. 3).

2.2.2. Olive groves in Portugal

Traditional olive groves are an historical element of Mediterranean landscapes. Besides the sense of belonging derived from the rural culture acquired by several generations, olive groves provide food and wood. The balanced management typical of the traditional groves makes them

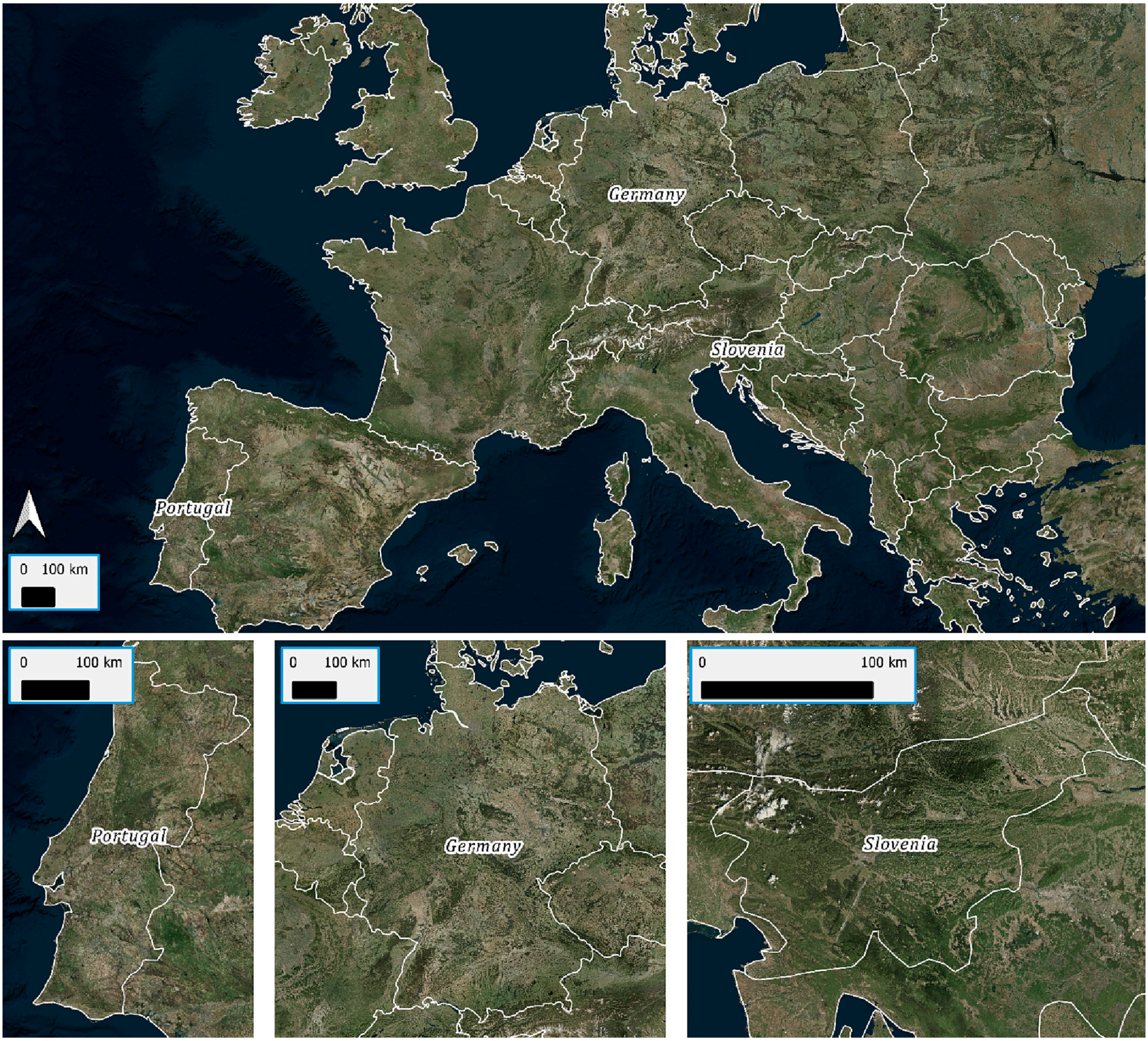


Fig. 2. Study areas.

relevant as far as biodiversity is concerned since they harbour many fauna and flora species (Fernández-Habas et al., 2018; Zaccarelli et al., 2008). In the Iberian Peninsula, the quest for higher yields has led to a noticeable landscape change over the last few decades. Yield increases are obtained via intensification and/or by increasing the agricultural area, and both can have negative impacts on local populations and the environment. In Portugal, despite the seasonal water scarcity, large new reservoirs have allowed irrigation agriculture to significantly increase its scale. A direct consequence of this is the fast expansion of high-yield olive groves that has been happening over the last few years; they often replace traditional biodiversity-rich groves and other land-use types (Morgado et al., 2022, 2020). The main challenge today is to successfully implement high-yield, more intensive, and economically more profitable production models while mitigating the negative environmental impacts of these large-scale industrial groves.

In terms of the impacts on biodiversity, besides the initial LULC change that large groves represent, with serious habitat loss for many species, there is also the risk of mass bird mortality due to nocturnal mechanical harvesting (Silva and Mata, 2019), landscape homogenisation that leads to lower specific diversity (Carpio et al., 2016), compromising biocontrol services (for instance, by bats; Costa et al., 2020), and lowering the spatial resilience of olive landscapes (Ortega et al., 2020).

To address this topic, it is fundamental to assess olive groves changes, monitor their expansion patterns, and determine how these dynamics are contributing to landscape homogenisation. In this example, to differ from the previous example and demonstrate a different LDT4QGIS feature, the analysis is conducted based on administrative boundaries, using the smallest Portuguese administrative unit (the *freguesia*, or parish). The data used are the Portuguese official land-use maps for the years 1990, 2010, and 2018 (Direção-Geral do Território, 2019) (Fig. 4).

2.2.3. *Forests in Germany*

Forests provide several ecosystem services, such as water regulation, carbon sequestration, biodiversity conservation, recreation, etc. (Ninan

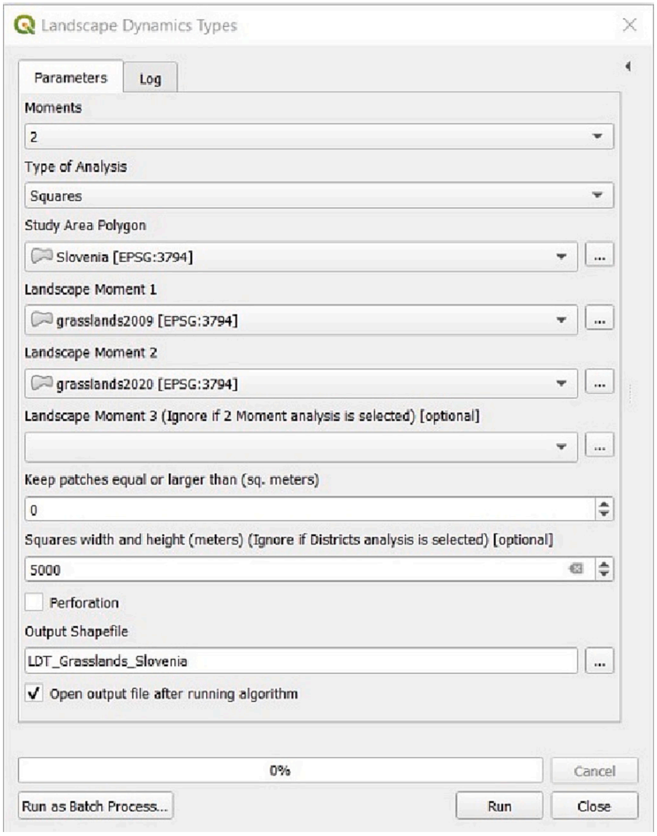


Fig. 3. Example of inputs and settings for the tool "Landscape Dynamic Types 2M (Squares)".

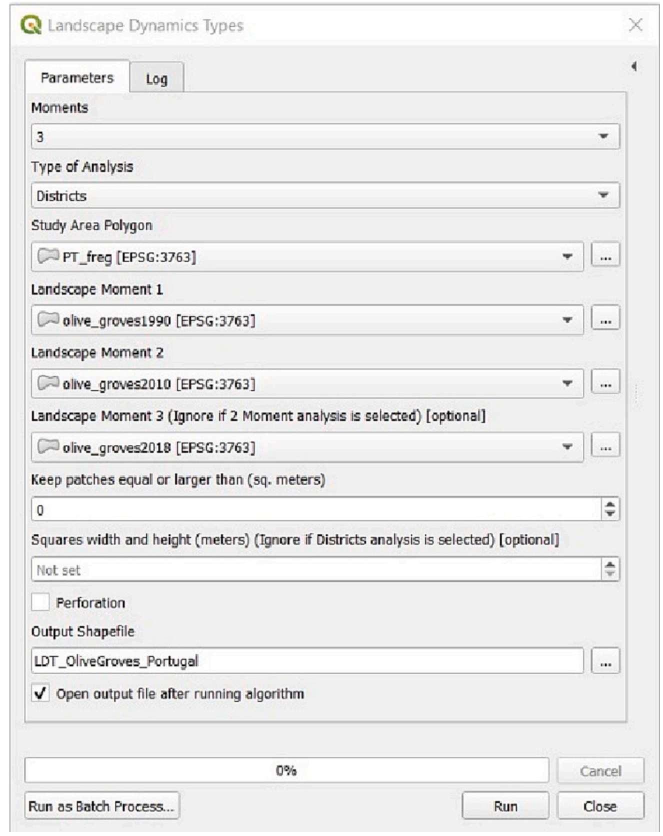


Fig. 4. Example of inputs and settings for the tool "Landscape Dynamic Types 3M (Districts)".

and Inoue, 2013). Timber and fuelwood, the most relevant products, can, in some countries, account for less than a third of the total economic value of forests, when activities like hunting and ecosystem services like watershed protection and carbon sequestration are considered (Millennium Ecosystem Assessment, 2005). Despite their importance, forests are not immune to disturbances, and transformational drivers that can put them at risk. Wildfires, diseases, or simple decisions on how much and where to harvest are obvious drivers for changes in forests. In a landscape management framework, it is useful to assess local changes, including purely amount-related features (how many hectares lost or gained) and also geometric features (e.g., changes affecting patches entirely or partially). For instance, the spatial process known as 'perforation', which involves removing (losing) a given amount inside a patch and originating a clearing, is a common way to trigger land transformations (Forman, 1995); these changes can be small at first but can escalate and evolve into more severe processes of landscape dynamics. The conceptualisation of perforation depends in the first place on the focus of the study. For instance, the gap formed by the falling of a tree may be relevant for someone tracking the canopy cover (Salvador-Van Eysenrode et al., 2000), while for other topics, only clearcut areas larger than several hectares may be worth considering. In this example, we run scripts II ('perforation.py') and III ('gained and lost patches.py') with CORINE Land Cover maps to identify all the gains and losses, gained and lost patches, and perforations that occurred in German forests between 2000 and 2018 (Fig. 5).

3. Results and discussion

3.1. Grasslands in Slovenia

The results reveal the dominance of squares related to loss (ToDs E, H, and I) compared to those related to gains (ToDs D, F, and G) (Fig. 6). Squares identified as ToD I represent areas where one or more grassland patches lost area in a way that caused patches to be divided, increasing the total number of patches. This happened nationwide but mainly occurred in the centre of Slovenia, where the capital, Ljubljana, is located. Squares identified as ToD H reflect areas where one or more grassland patches disappeared; ToD H can be interpreted as the phase that follows ToD I. In Forman's framework, this would equate to fragmentation followed by attrition, possibly with shrinkage as an intermediary phase (Forman, 1995). Whichever model and nomenclature are used, the process initiated with an area loss that caused the division of large patches, and then some smaller patches began to disappear. Given that ToD I is the precursor of ToD H, if the declining trend continues, it is expected that some (or many) squares now identified as ToD I will later be identified as ToD H.

Focusing the discussion on biodiversity, the impacts are different for species that depend on (specialists) or facultatively use (generalists) grasslands. For specialists, grasslands may represent a high proportion or the totality of their habitat; generalists may benefit from grasslands, but they are just one of many biotopes that constitute a generalist's habitat. Assuming that habitat loss is always negative for species, specialists are particularly affected by the current trend. The main spatial pattern in which the area loss occurs (ToD 'I – Fragmentation by loss') is also likely to be especially detrimental for specialists because it promotes the breaking up of patches into smaller patches and thus increases the edge length. This brings more landscape heterogeneity, more edge effect, higher levels of disturbance, and an increased probability of encounters with generalists. Meanwhile, generalists may thrive in intermediate levels of landscape heterogeneity, and therefore benefit from the phase of the land transformation related to ToD I. However, if the area loss of the grasslands continues and triggers ToD H, it represents landscape homogenisation, fewer edge effect and potentially a less suitable habitat for at least some generalists. This would depend on

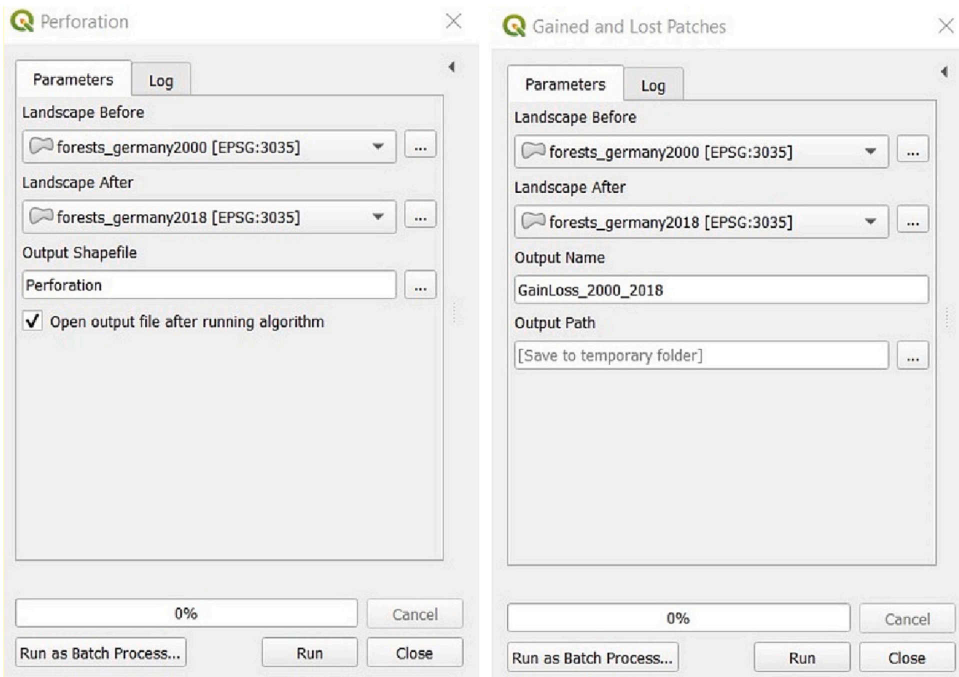


Fig. 5. Example of inputs and settings for the tools “Perforation” and “Gained and Lost Patches”.

several factors, namely the magnitude of the changes, the species mobility, and the degree of dependency on grasslands.

Ultimately, conservation efforts are a function of which biodiversity values are the most important according to experts' opinions, and the results derived from LDT4QGIS can be combined with other sectorial and thematic data to produce more explanatory information. Future projections based on current trends provide fundamental insights that can be used to design better land-use policies and concrete measures to ensure a balanced coexistence of agricultural practices and biodiversity conservation in Slovenian grasslands.

3.2. Olive groves in Portugal

The map shows the data aggregated in irregular areas provided by the user instead of showing a software-generated sampling grid like the map in the previous example. This analysis involved three moments, so three maps were produced: one with the dynamics between 1990 and 2000, one with the dynamics between 2000 and 2018, and the map displayed in Fig. 7, which shows the overall changes between 1990 and 2018. We can see that olive groves are not present in most mainland Portugal parishes. There are 383 parishes with ToDs related to gain and 376 with ToDs related to loss, but the magnitude of the transitions is quite different, with an overall gain of 69,493 ha. Focusing on the gain side, 275 parishes were assigned to ToD ‘F – NP increment by gain’, which reflects the emergence of new groves isolated from the existing groves. ToD ‘D – Gain’, which identifies areas where existing groves increased their size, was assigned to 77 parishes. This suggests that, at the parish scale, the increase in area is mostly obtained via new plantations rather than through the expansion of existing groves. Finally, 31 parishes increased the total area covered by olive groves while losing patches (ToD ‘G – Aggregation by gain’). Although olive groves have been increasing significantly, they still represent a small percentage of agricultural land, and thus the identification of 31 parishes as ToD G seems reasonable, but further area gains will increase the probability of the occurrence of ToD G. It is important to highlight that the increase in the area covered by olive groves does not itself imply landscape homogenisation. For instance, in a region dominated by other LULC types, the establishment of olive groves may contribute to landscape diversification. Concerns arise when a single species or similar species that share a production model and produce similar transformations in the landscape cover vast areas continuously. The figures may be insignificant at the national level but problematic at the local and regional levels due to these massive and quick transformations and the associated disturbances that they bring. Some large-scale olive groves are being contested by local communities and compromising the ecosystem's balanced functioning, but investment in this type of agribusiness does not seem to be slowing down. In fact, more irrigated groves are being added successfully and achieving good yields, making them more important in the Portuguese agricultural scene. The area covered by olive groves and other intensive perennial crops is expected to increase in the future, pushed by the increasing popularity of Mediterranean products (Esgalhado et al., 2021), and although further investment may be desired due to the positive impacts on production, the extension and spatial context of such plantations should be carefully examined.

Outputs such as those obtained through LDT4QGIS are useful for diagnosing the current situation, as well as for simulating what different land transformation alternatives could represent in terms of spatial patterns and the associated environmental impacts. Such elements, combined with measurable indicators or decisive criteria, can help policymakers to predict the effects of agricultural policies in a given territory. Some examples of these policies could be ‘preferentially place olive groves in areas highly dominated by other LULC’, ‘do not promote patch fusion (ToD G) if olive groves cover more than 40% of the parish, square, or defined proximity neighbourhood’, ‘establish a maximum plantation/patch size, unless the perimeter-area ratio is ≥ …’, and ‘preserve or restore x ha of different LULC for each ha of irrigated cultures above the x ha threshold’.

3.3. Forests in Germany

Between 2000 and 2018, German forests had a net gain of 420,999 ha (10,383,107 ha in 2000 and 10,804,106 ha in 2018). The partial balances are 1,161,929 ha of new forest and 740,930 ha of lost forest. These numbers show that the area covered by forest has been increasing, and the areas converted from and to forest (the sum of the partial balances = 1,902,859 ha) represent 18% of the average forest area (average

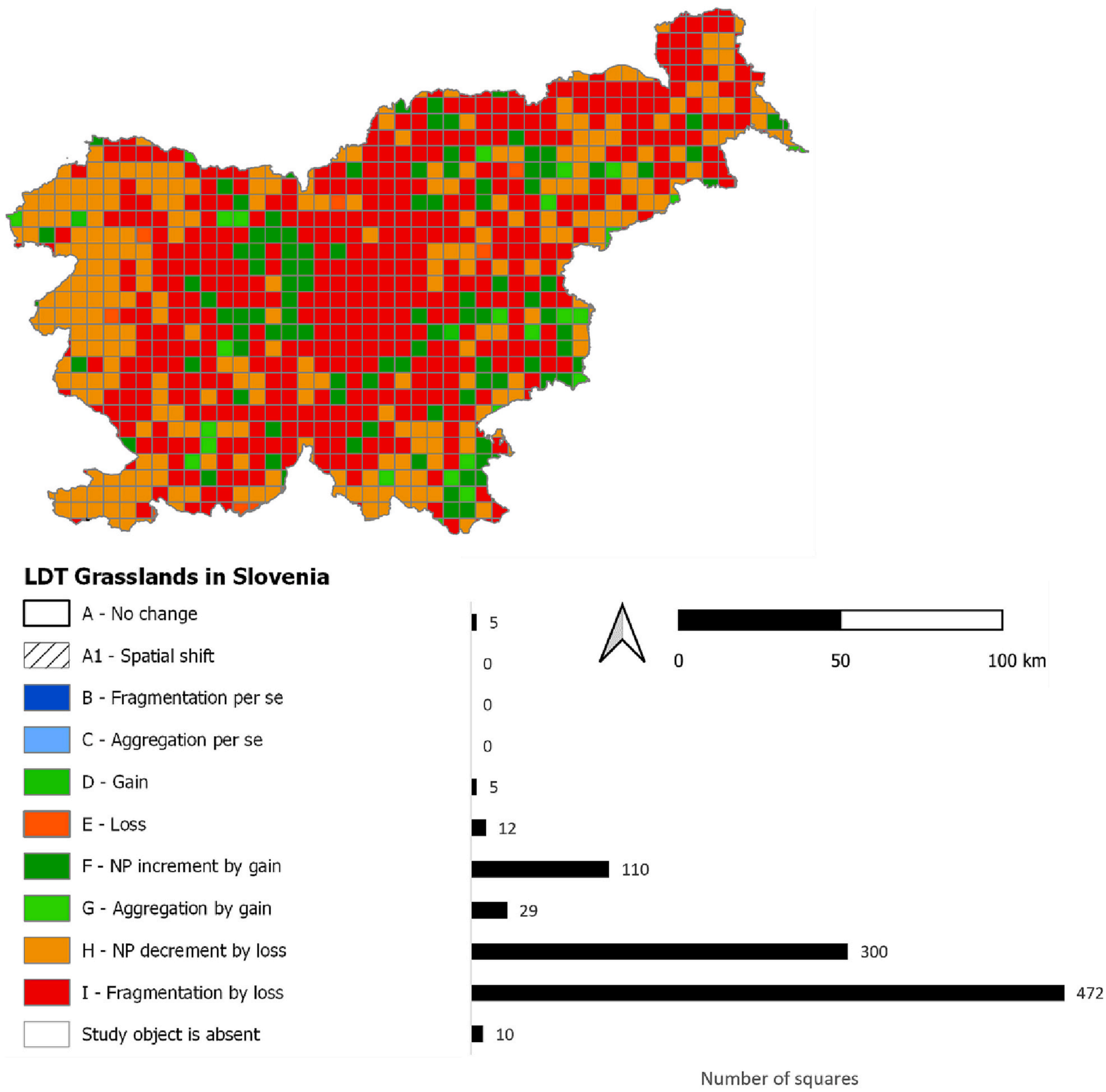


Fig. 6. Map of the case study regarding the grasslands in Slovenia with associated legend to identify the Types of Dynamics (spatial processes) and chart showing the number of squares assigned to each type.

of the total areas in 2000 and 2018 = 10,593,607 ha), which suggests that the system is fairly stable. Going beyond a strictly numerical approach and using the spatially explicit information provided by LDT4QGIS, we can see where these changes occurred throughout the study area. Identifying the gained and lost individual patches is important because the spatial patterns created by forest gains (natural afforestation or planting) or losses (burnt by wildfire or cut) may have major ecological consequences (Franklin and Forman, 1987). Considering only new patches and completely lost patches (not variations in the amount like ToD 'D – Gain' or ToD 'E – Loss'), we found 22,312 gained patches and 9066 lost patches. The analysis also showed 936 perforations with a total area of 37,172 ha. Fig. 8 shows an overall view of German forests in 2000 on the left-hand side, and an example of perforation on the right-hand side. The light green colour, representing the forests in 2000, can be seen behind the darker green colour that represents the forests in 2018. Although more of the areas shown in the image were lost, only one area that was initially completely contained by the forest in 2000 and is now lost, forming a clearing, is classified as a perforation (hashed red).

Landscape planning is a complex issue that involves many variables. Although, for simplicity, because the aim of the study does not require further detail, we can classify the forest as a single land-cover class, it is a varied system that can be divided into different sub-classes. In addition to species, age is an evident distinctive criterion that has direct repercussions on subsequent forest functions, like harbouring fauna. The loss of mature forest not only is understood as more detrimental than the loss of younger forest but also has a larger effect than fragmentation on bird abundances (St-Laurent et al., 2009). Forest segmentation by species, age, density, function, or physiological condition would make sense for more detailed approaches, and LDT4QGIS would be able to deliver potentially relevant outputs (e.g., distinct ToDs for primary forests and managed forests in the same analytical unit) concerning the spatial pattern dynamics and their consequences.

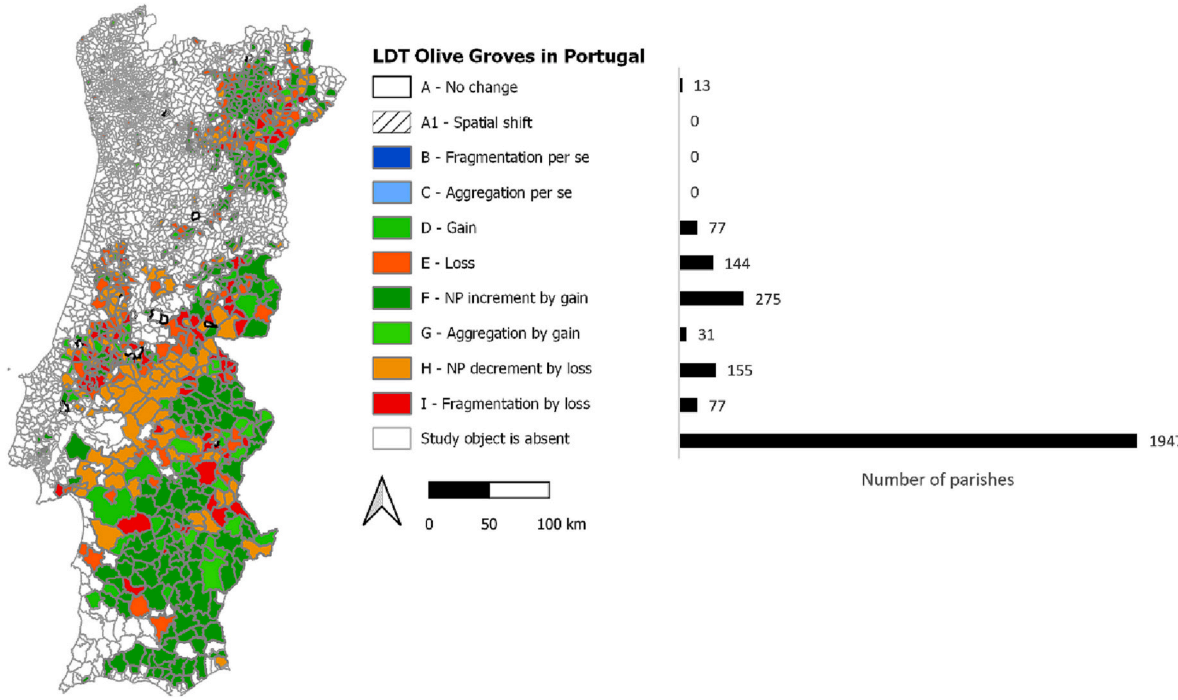


Fig. 7. Map of the case study regarding the olive groves in Portugal with associated legend to identify the Types of Dynamics (spatial processes) and chart showing the number of parishes assigned to each type.

3.4. LDT4QGIS

The previous demonstrations show how LDT4GQIS works and the type of outputs it produces. These are illustrative examples and not exhaustive approaches to each of the topics. They are supported by brief background descriptions and use real data, and the results are valid, although deeper studies on each topic could render these results incomplete. Depending on the depth of the analysis, LDT4QGIS outputs can be sufficient, or can integrate wider procedures as inputs or variables. For instance, since many official statistics are aggregated according to administrative units, the ToD values of an output shapefile with districts can be exported to such a database and used for statistical analysis together with other relevant and related variables, such as economic or social indicators. Another example would be to use the final LDT4QGIS squares shapefile as a sampling grid in other specialised software tools for landscape metrics, like FRAGSTATS. Simply put, this would require one to convert the vectorial grid into a raster format, edit the attribute values accordingly, and select the new file to be used as a provided tile. A multiplicity of metrics could be computed, and after a few value extraction and table management steps, we would end up with a table containing all the values of the metrics, as well as the ToD.

The main goal of LDT4GQIS is to facilitate the identification and geopositioning of ToDs that have occurred between analytical moments. Complementary functionalities achieve similar results for the detection and mapping of LULC area changes. By calculating the area and NP of the LULC category of interest, LDT4GQIS can provide information concerning how much land this category covers and how it is distributed. Additionally, LDT4GQIS goes beyond summaries and statistics and provides spatially explicit information. The geographic data that support map production are vital to finding spatial variability and therefore to identifying local trends.

3.4.1. Strengths and limitations

The outputs are highly dependent on the characteristics and overall quality of the inputs. Better spatial, temporal, and thematic resolutions are essential to producing more valuable results. For instance, using base maps with a minimum map unit of 1 ha for three analytical moments for primary forests only (Sabatini et al., 2021) produces more detailed outputs than using base maps with a minimum map unit of 10 ha for two analytical moments for the forest as a whole. Nevertheless, the software itself has strengths and limitations of its own that should be acknowledged by the users.

The evident strength of LDT4QGIS is its simplicity and how easy it is to use. It is designed to be a prompt and versatile solution, delivered as a ready-to-use set of scripts for QGIS. The inputs do not generally require much pre-processing or preliminary work, and the outputs are very straightforward, as they are provided in the form of value variations and maps (Machado et al., 2018). The versatility of LDT4QGIS comes from the possibility of fine-tuning parameters such as the AU and the minimum patch size, and the user can customise the code to match the analysis being performed. We emphasise that although LDT4QGIS operates based on metric calculations, it does not provide metric values or indices as final outputs, like most software tools for landscape analysis. Instead, these calculations are instrumental to the end goal of identifying ToDs / spatial patterns, which are real-world recognised combinations of landscape metrics.

The use of user-provided districts or automatically generated squares as AU has advantages and disadvantages. On the one hand, it can help one to understand the data by aggregating it at proper spatial resolutions, but on the other hand, this introduces the uncertainty and bias of the modifiable areal unit problem (MAUP) (Gehlke and Biehl, 1934; Openshaw, 1984). This and other associated topics were extensively discussed from the LDT point of view in Machado et al. (2020). A limitation related to the effect of the MAUP is, for instance, what happens with perforation, which is correctly computed at the class scale but requires interpretative caution when it is assigned to a square or district. An AU that displays other losses in addition to perforation will automatically be identified as ‘E1 – Perforation’, which means that an AU classified as ToD ‘E – Loss’ surely did not experience perforation, but an AU classified as ToD ‘E1 – Perforation’ may also have experienced other losses (e.g., along the edges). For this reason, this ToD is not computed by default and it is up to the user to decide whether it makes sense to use it or not.

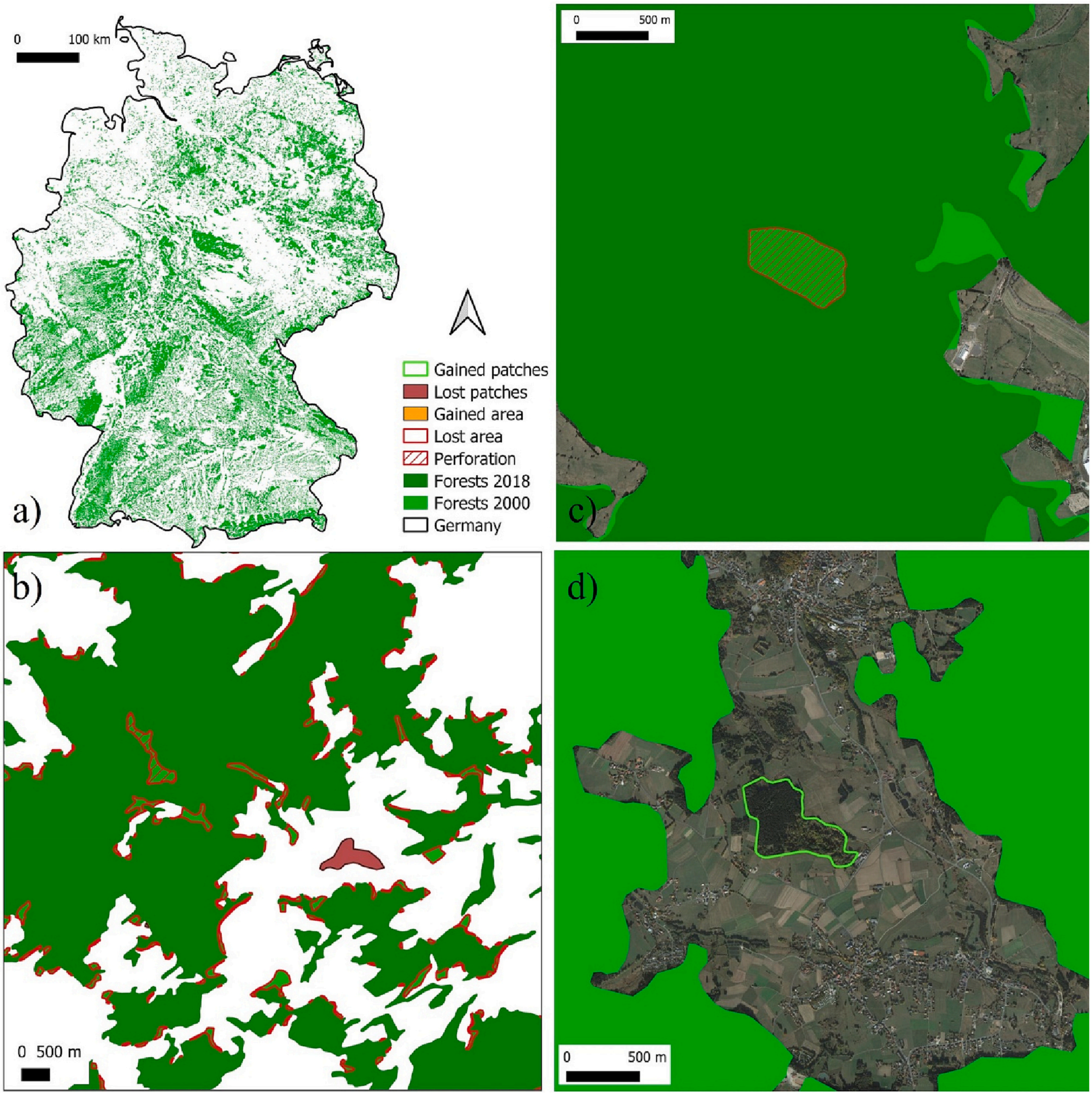


Fig. 8. Map of the German forests in 2000 (a); snapshot showing, lost areas a lost patch and a perforation (b); close view of a perforation (c); and close view of a gained patch.

4. Conclusions

LDT4QGIS adds value to landscape assessments related to LULC changes. These assessments may encompass topics as varied as biodiversity conservation, ecosystem services, game management, or invasive species control. Quantitative measurements, together with spatially explicit maps, are essential for landscape status assessments and ultimately for an informed policy design. In this paper, three case studies were used to showcase the multiple functionalities of LDT4QGIS. In the first two case studies, the script 'LDT4QGIS.py' was used to analyse changes in the Slovenian grasslands that occurred between two moments using 2500 ha squares and to assess the dynamics in Portuguese olive groves, aggregating data from three dates according to the administrative boundaries. In the third example, the scripts 'gained and lost patches.py' and 'perforation.py' were used to detect changes, in particular, the perforation spatial pattern, that occurred in German forests between two dates.

Compared to the previous LDTtool, LDT4QGIS represents an advance regarding accessibility since it was developed for non-proprietary software, thus fitting a geospatial free and open-source software philosophy.

Concerning the analytical capabilities of LDT4QGIS, the novelties introduced are the following:

- The Type of Dynamic 'A1 – Spatial Shift';
- The Type of Dynamic 'E1 – Perforation';
- The script 'perforation.py';
- The script 'gained and lost patches.py'.

We expect the development and updating of LDT4QGIS to be ongoing work. Some future improvements currently being considered are the following:

- Integrating more spatial patterns / ToDs (e.g., dissection);
- Allowing the selection of the LULC category even if the input shapefile is not originally binary (to further avoid the need for preliminary tasks such as selecting the correct LULC according to its attributes and exporting the polygons to a new shapefile);
- Exporting a text file containing relevant elements regarding the results (e.g., a summary of ToD counts).
- Adding the tool "Forecast" already functional in LDTtool, which computes hypothetical trajectories for the LULC of interest, based on the existing trends.

The objective of this paper is to introduce LDT4QGIS and hopefully motivate user interest. The fundamental geoprocessing steps that compose LDT can be operationalised sequentially without a formal conceptual model or script. However, the numerous geoprocessing steps/functions and occasional complexity make this a difficult task with a high probability of errors. LDT4QGIS is a solution that can be used to ease this workload and automate the procedure. In addition to improving the current QGIS tool, we aim to extend these analytical capabilities to other platforms. The growing popularity of R (www.r-project.org) as an open-source computing environment has made it our highest priority regarding the expansion of LDT4QGIS.

Software availability

Name of software: LDT4QGIS.

Availability and cost: LDT4QGIS can be requested from the authors or downloaded from https://gitlab.com/lgplgp/ldt4qgis. (Includes a README file with description and instructions).

License: GNU GPLv3.

Developers: Luis Paixão and Rui Machado.

Contact address: Departamento de Paisagem, Ambiente e Ordenamento, Universidade de Évora, Rua Romão Ramalho, n° 59, 7000–671 Évora, Portugal (Rui Machado).

E-mail: luispaixao@agroinsider.com; rdpm@uevora.pt

Year first available : 2022.

Software required: QGIS.

Program language: Python.

Program size: 165 kB.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

There is a link to access the code in the manuscript.

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