Development of custom ArcGIS tools for Landscape Ecology: A multi-scale and multi-resolution approach

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Abstract

This study addresses the need for tools within ArcGIS Pro to calculate landscape metrics. Landscape metrics, which quantify the structure, composition, and spatial configuration of landscapes, are vital for ecological analysis. Traditional tools like 'FRAGSTATS' and 'landscapemetrics' require additional learning and operating of new software, data transposition as well as programming skills thus, limiting ease and accessibility. This study develops custom ArcGIS tools to calculate class-level metrics such as Class Area, Percentage of Landscape and Mean Patch Area directly within ArcGIS Pro, making landscape ecology more accessible to a wide range of users. The tools were tested across various datasets and resolutions to ensure accuracy and reliability and validated against the 'landscapemetrics' package in R. Results show high consistency between the ArcGIS tools and 'landscapemetrics,' confirming the validity of the custom tools. The study additionally underscores the importance of considering spatial resolution and scale in landscape metric analysis and provides a foundation for more accessible and efficient landscape ecology research within ArcGIS Pro. Future work should focus on expanding this toolbox for further computations of different metrics and expanding their applicability across diverse environmental contexts.

1.0 Introduction

Remote sensing has been transformative in the understanding of environmental dynamics; rapidly evolving and developing ecological research. particularly in the field of spatial ecology. Remotely sensed data provides easily accessible and quantifiable spatio-temporal perspectives on the patterns and processes affecting ecological systems (Jackson et al., 2020). Understanding this spatial structure and arrangement of landscapes is essential to address various ecological and environmental challenges, such as habitat fragmentation, biodiversity conservation, and land management (Anderson and Gaston, 2013).

Landscape metrics are quantitative measures used to describe the structure, composition, and spatial configuration of landscapes (Fan and Myint 2014) providing critical insights into habitat quality, biodiversity, and ecological processes. The study of landscape ecology through spatial indices can be traced back to Patton's diversity index for quantifying habitat 'edge' (Patton, 1975). Since then, the development of new landscape metrics along with software packages to aid in calculation has been a productive stream of research, yet to subside.

'FRAGSTATS' (McGarigal et al., 2023), a software initially released in 2002 with numerous iterations since then has been at the forefront of landscape analysis. 'Landscapemetrics' re-implements landscape metrics as they are mostly described in the 'FRAGSTATS' software in R, a widely used statistical software in ecological research. This removes the necessity of learning and operating a new software thus, increasing efficiency in analysis. In correlation testing between the two methods, Hesselbarth (2024) found a correlation of $p >= 0.975$ between patch level metrics, and few differences between class level and landscape level metrics. This package offers a standardised approach to computing a wide range of metrics, making it a valuable tool for researchers in landscape ecology.

However, utilising the ‘landscapemetrics’ package still requires users to transpose data from one spatial analysis software, such as ArcGIS Pro, into R for analysis. This process also demands programming knowledge, decreasing accessibility for a wide range of users. While ArcGIS Pro is a powerful and extensive platform for spatial analysis, it lacks direct tools for calculating these landscape metrics. Users often have to employ multiple tools to compute a single metric, which can be time consuming and can easily result in errors.

Given the increasing use of ArcGIS Pro in ecological and environmental studies, there is a need for custom tools that streamline the calculation of landscape metrics within this platform. This project aims to develop such tools using ArcPy, the Python site package that provides access to ArcGIS geoprocessing tools (Dong and Weiling, 2021). Thus, replicating landscape metrics as they are mostly described in the ‘landscapemetrics’ package in ArcGIS Pro to enhance the accessibility and efficiency of landscape metric analysis in the software.

The tools chosen to replicate in ArcGIS Pro were all class-level metrics: class area, mean patch area, and percentage of landscape. These metrics were selected due to their fundamental importance in understanding landscape structure and their widespread use in ecological research.

2. Methodology

2.1 Data Acquisition and Pre-processing.

To begin developing the tools, three datasets were selected to provide a range of environmental contexts. This selection allows for a comprehensive assessment of how scale (difference in size of the analysis area) or location (difference in coordinate reference system) influence the results, thereby testing the accuracy of the custom tools.

‘The Forest Cover Map 2006’ map is 25m spatial resolution raster derived from LISS III and SPOT 4/5 imagery and Corine Land Cover 2006 data. This data covering the United Kingdom was acquired from the European Commission (2006). The Tree Cover 2000 map is a 30 m spatial resolution raster derived from Landsat 7 imagery (Hansen et al., 2013). Data is available to download in tiles and the tiles covering both Rome and Trinidad were downloaded. Using ArcGIS Pro, the datasets were clipped to Leeds, Rome and Trinidad using shapefiles and reprojected to the appropriate projected Coordinate Reference Systems (CRS) listed in table 1 below.

The datasets were then resampled from its original resolution to 10 M, 20 M and 50 M to additionally test the tools' performance across different resolutions.

Table 1. Data sources and information

Information	Leeds	Rome	Trinidad
Coordinate System	British National Grid	RDN2008 UTM zone 33N	WGS 1984 Complex UTM Zone 20N
Data Source	European Commission, 2006	Hansen et al., 2013	Hansen et al., 2013
Size	552 km²	1,285 km²	4,768 km2

2.2 Tool Development

The landscape metrics chosen for this study are among the most widely used class level metrics in landscape ecology research (Wei et al., 2016; Plexida et al., 2014; Lausch, 2002; Cardille and Turner, 2017). These metrics provide insights into the structure and composition of landscapes, making them invaluable for a variety of ecological and environmental applications.

1) Class Area (CA): CA measures the total area covered by each land cover class within the landscape; it provides a straightforward quantification of the extent of different habitat types (Liu and Yang, 2015).

2) Percentage of Landscape (PLAND): PLAND calculates the percentage of the landscape occupied by each land cover class. It is a normalised measure that allows for easy comparison across different landscapes and scales (Wei et al., 2016).

3) Mean Patch Area (MPA): MPA assesses the average size of patches for each land cover class, giving insights into landscape connectivity (Plexida et al., 2014).

The ESRI Python Toolbox template was used as a base to create the toolbox for each metric (ESRI, n.d.). The script was then written using ArcPy, an ESRI Python site package allowing users to perform a range of geographic data analysis and automation (Dong and Weiling, 2021).

Similar to the 'landscapemetrics' replication of 'FRAGSTATS,' the ArcGIS tools were created based on the equations for each metric provided in the 'landscapemetrics' documentation by Hesselbarth et al. (2024). The following section provides the equations for each metric, followed by the corresponding Python code that relates to the computation of the metrics:

Class Area

$$CA = \mathrm{sum}(AREA[patch_{ij}]) ,$$

Where $AREA[patch_{ij}]$ is the area of each patch in hectares.

```
# Convert binary raster to polygons
arcpy.RasterToPolygon_conversion(binary_raster, "in_memory/polygons", "NO_SIMPLIFY")

# Add field to store patch area
arcpy.AddField_management("in_memory/polygons", "AREA_HECTARES", "DOUBLE")

# Calculate area in hectares
arcpy.CalculateField_management("in_memory/polygons", "AREA_HECTARES", "!shape.area@hectares!", "PYTHON_9.3")

# Calculate total area of patches with specified class value
class_area = 0
with arcpy.da.SearchCursor("in_memory/polygons", ["AREA_HECTARES"], '"GRIDCODE" = {}'.format(class_value)) as cursor:
    for row in cursor:
        class_area += row[0]

# Set output value
parameters[2].value = class_area
```

Figure 1. Snippet of ArcGIS toolbox python code to compute class area

Percentage of Landscape

$$\mathrm{PLAND} = (\sum_{j=1}^{n} a_{aj} \div A) * 100 ,$$

where a_{ij} is the area of each patch and A is the total landscape area.

```
# Calculate area in hectares
arcpy.CalculateField_management("in_memory/polygons", "AREA_HECTARES", "!shape.area@hectares!", "PYTHON_9.3")

# Calculate total area of all patches
total_area = 0
with arcpy.da.SearchCursor("in_memory/polygons", ["AREA_HECTARES"]) as cursor:
    for row in cursor:
        total_area += row[0]

# Calculate total area of patches with specified class value
class_area = 0
with arcpy.da.SearchCursor("in_memory/polygons", ["AREA_HECTARES"], '"GRIDCODE" = {}'.format(class_value)) as cursor:
    for row in cursor:
        class_area += row[0]

# Calculate percentage
if total_area != 0:  # Avoid division by zero
    percentage = (class_area / total_area) * 100
else:
    percentage = 0
```

Figure 2. Snippet of ArcGIS toolbox python code to compute percentage of landscape

Mean Patch Area

$$MPA = \mathrm{mean}(AREA[patch_{ij}]) ,$$

where $AREA[patch_{ij}]$ is the area of each patch in hectares

```python
# Calculate area in hectares
arcpy.CalculateField_management("in_memory/polygons", "AREA_HECTARES", "!shape.area@hectares!", "PYTHON_9.3")

# Calculate total area of patches with specified class value
class_area = 0
with arcpy.da.SearchCursor("in_memory/polygons", ["AREA_HECTARES"], '"GRIDCODE" = {}'.format(class_value)) as cursor:
    for row in cursor:
        class_area += row[0]

# Count patches with specified class value
patch_count = 0
with arcpy.da.SearchCursor("in_memory/polygons", ["GRIDCODE"]) as cursor:
    for row in cursor:
        if row[0] == class_value:
            patch_count += 1

# Calculate percentage
if patch_count!= 0:  # Avoid division by zero
    mean_patch_area = (class_area / patch_count)
else:
    mean_patch_area = 0

# Set output value
parameters[2].value = mean_patch_area
```

Figure 3. Snippet of ArcGIS toolbox python code to compute mean patch area

2.3 Metric Calculation and Validation

The ArcGIS tools were then used within ArcGIS Pro to calculate the various landscape metrics for each dataset at each resolution. To validate the accuracy of the custom tools, the 'landscapemetrics' package was used in R to compute the same landscape metrics for the same datasets and resolutions. Four directions were used to simplify the analysis by considering only immediate in the horizontal and vertical directions (Hesselbarth, 2024).

```r
#Mean Patch Area
lsm_c_area_mn(trinidad10,directions = 4)
lsm_c_area_mn(trinidad20,directions = 4)
lsm_c_area_mn(trinidad50,directions = 4)

#Percentage Landcover
lsm_c_pland(leeds10, directions = 4)
lsm_c_pland(leeds20, directions = 4)
lsm_c_pland(leeds50, directions = 4)

#Class Area
lsm_c_ca(leeds10, directions = 4)
lsm_c_ca(trinidad20, directions = 4)
lsm_c_ca(trinidad50, directions = 4)
```

Figure 4. Example code of the computation of landscape metrics in R

The mean percentage difference is a valuable metric for assessing the degree of agreement or discrepancy between outputs generated by different software platforms (Takeshima et al., 2014). Standardising the data using percentages accounts for differences in dataset sizes, providing a clearer comparison and demonstrating that both platforms produce comparable results even for larger datasets.

$$\frac{(Mean\ Experimental\ variable - Mean\ Control\ Variable)}{((Mean\ Experimental\ Variable + Mean\ Control\ Variable)/2)*100}$$

The percentage range provides standardised insights into the degree of variability exhibited by landscape metrics across different resolutions regardless of spatial scale.

$$\frac{(Max\ variable - Min\ Variable)\ /\ 2}{Max\ Variable}$$

3. Results and Analysis

3.1 User Interface

The user interface developed for this project is integrated into ArcGIS Pro using custom Python toolboxes. The custom tools are designed to streamline the workflow, enabling users to analyse landscape metrics of various datasets without needing extensive programming knowledge. Figure 3 illustrates how the tools are incorporated into the software environment.

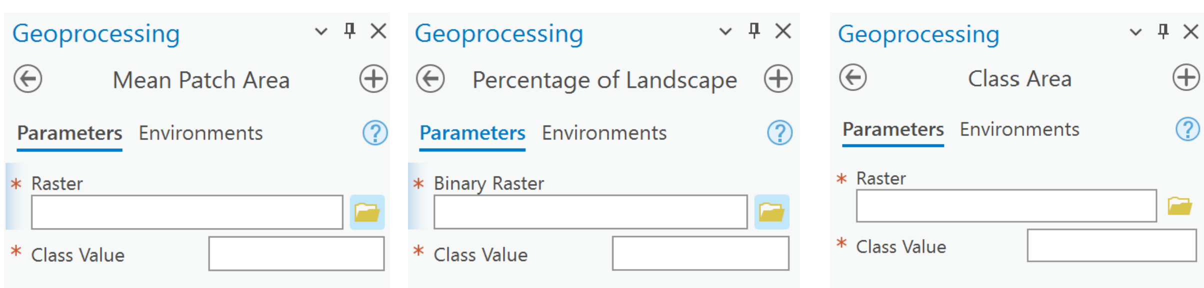

Figure 5. The ArcGIS Pro user interface resulting from the Python Toolboxes

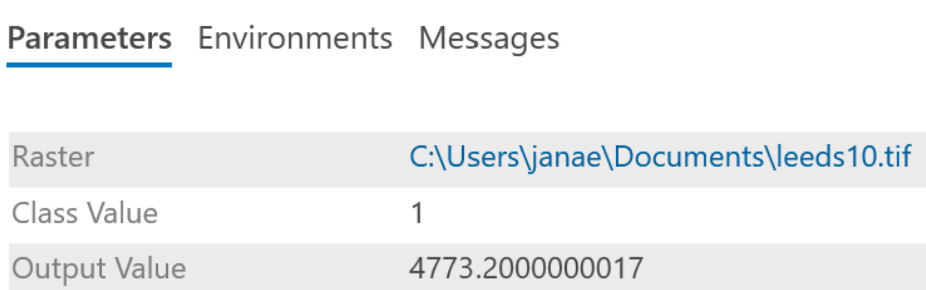

Figure 6. Example output resulting from the Python Toolbox

3.2 Validation of Algorithm

The validation of the algorithm is based on comparison of the results generated using the ArcGIS tools with those produced by the established 'landscapemetrics' package in R.

Table 2. CA results in ArcGIS and R for three spatial datasets at three resolutions

Resolution	Leeds (ArcGIS)	Leeds (R)	Rome (ArcGIS)	Rome (R)	Trinidad (ArcGIS)	Trinidad (R)
10M	4773.20	4773.00	14242.70	14243.00	364936.91	364397.00
20M	4778.64	4779.00	14236.10	14236.00	364470.44	364470.00
50M	4773.25	4773.00	14226.20	14226.00	364554.25	364554.00
Relative Range (%)	0.11	0.13	0.12	0.12	0.13	0.04
Mean Difference (%)	0.001		0.000		0.049	

Table 3. PLAND results in ArcGIS and R for three spatial datasets at three resolutions

Resolution	Leeds (ArcGIS)	Leeds (R)	Rome (ArcGIS)	Rome (R)	Trinidad (ArcGIS)	Trinidad (R)
10M	8.65	8.65	11.10	11.10	75.18	75.20
20M	8.66	8.66	11.10	11.10	75.14	75.10
50M	8.65	8.67	11.10	11.10	75.05	75.00
Range (%)	0.01	0.02	0.00	0.00	0.13	0.20
Mean Difference (%)	0.010		0.000		0.020	

Table 4. MPAs results in ArcGIS and R for three spatial datasets at three resolutions

Resolution	Leeds (ArcGIS)	Leeds (R)	Rome (ArcGIS)	Rome (R)	Trinidad (ArcGIS)	Trinidad (R)
10M	0.73	0.74	1.25	1.25	17.11	17.10
20M	0.73	0.73	1.25	1.25	17.11	17.11
50M	1.13	1.13	2.07	2.07	35.34	35.3
Relative Range (%)	35.40	35.40	39.61	39.61	51.58	51.56
Mean Difference (%)	0.345		0.000		0.719	

Spatial resolution has been shown to affect both the characterisation of landscape and ecological analysis (Lechner and Rhodes, 2016) including the quantification of landscape metrics. Developing meaningful interpretations of these metrics necessitates a comprehensive understanding of the landscape's change response to disturbance which in turn, relies on an understanding of the effects of spatial extent and resolution (Wu et al., 2002). In a study of 18 landscape indices, Baldwin et al. (2004) found significant effects on 17 indices with changes in spatial extent and on 13 indices with changes in spatial resolution. Numerous studies align with these results noting significant effects of spatial extent and spatial resolution on various landscape metrics (Kendall and Miller, 2008; Qi and Wu, 1996; Varol et al., 2023).

The results for CA show negligible differences between the ArcGIS and R outputs across all datasets and resolutions, with a mean difference of <0.5% and a range of <0.15% for all datasets. Similarly, the PLAND the values are nearly identical across both platforms for all datasets and resolutions, with a negligible mean difference of <0.01% and a range of <0.13% for all datasets. This consistency and negligibility across and within datasets confirms that the ArcGIS tools are reliable and accurate across different spatial scales and resolutions for these metrics. The ability of the ArcGIS tools to produce stable CA and PLAND metrics regardless of dataset size or resolution suggests that these tools can be confidently used in a variety of ecological and geographical studies, ensuring accurate landscape metric calculations.

Additionally, MPA shows negligible differences between the ArcGIS and R outputs across all datasets and resolutions, with a mean difference of <0.7%. However, this metric shows high sensitivity to both resolution and spatial scale in both programs. The ranges in both ArcGIS and R are large across each dataset, increasing significantly when resolution is decreased from 20m to 50m. Additionally, the range of MPA increases for both programs as the size of the dataset increases, highlighting sensitivity to spatial scales. This underscores the importance of considering spatial resolution and spatial scale when comparing landscape metrics across studies (Varol et al., 2023).

Landscape patterns based on raster input data can be highly biassed by the spatial resolution, since most indices rely on the number of adjacent pixels (Varol et al., 2023). Therefore, lower resolutions can lead to an underestimation of the number of patches as smaller patches fall below the detection threshold. Calculation of MPA relies on the number of patches within the landscape (Hesselbarth et. al, 2024). Thus, the underestimation of patches at lower resolutions results in higher MPA values. This limitation underscores the need for caution when interpreting results from different scales as this can result in misleading conclusions if not properly accounted for. Additionally, as the spatial scale of the dataset increases, the range of MPA also increases as larger extents may capture more variability. Class Area (CA) and Percentage of Landscape (PLAND) may be less affected by scale and resolution as they are based on total area. However, discrepancies can still arise from differences in how small patches are handled and merged.

4.0 Conclusion

This study effectively demonstrates the creation of and implements new tools for the calculation of landscape metrics while emphasising the importance of spatial resolution and scale. The developed tools were validated through a comparison between outputs from ArcGIS and R with high consistency between programs on all three metrics. Thereby, confirming the reliability and accuracy of the created tools.

Future research should focus on implementing landscape metric calculations directly on raster data within the ArcGIS Pro toolbox without the raster to polygon conversion. Utilising ArcPy's raster analysis capabilities, such as the arcpy.sa.RegionGroup function (ESRI, 2024) can help identify contiguous raster patches and calculate MPA without the need for polygon conversion. This alternative methodology can help maintain the integrity of the patches as defined in the raster data and ensure consistency in patch identification.

Additionally, future studies should encompass a wider range of environmental contexts to ensure that these tools are applicable across various landscape types while expanding the scope of the analysis to include a broader range of landscape metrics. Thereby, further simplifying the process of calculating landscape metrics directly in ArcGIS while providing a more comprehensive understanding of how spatial resolution and scale affect various ecological analyses. Sensitivity and correlation analyses can also prove a valuable tool in understanding how these metrics function at different resolutions, scales and within different algorithms. These can be used in future studies to identify thresholds where metrics stabilise and reduce biases.

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