Modeling of Landscape for the Integration of Agrivoltaics Using a GIS Approach

Grazia Fattoruso[1(✉)], Alessandra Scognamiglio[2], Andrea Venturo[3], Domenico Toscano[4], Giulia Nardella[3], and Massimiliano Fabbricino[3]

[1] Photovoltaic and Sensor Applications Laboratory, ENEA RC Portici, P.le E. Fermi 1, 80055 Naples, Italy
grazia.fattoruso@enea.it
[2] Innovative Devices Laboratory, ENEA RC Portici, P.le E. Fermi 1, 80055 Naples, Italy
[3] Department of Civil, Architectural and Environmental Engineering, University of Naples Federico II, Via Claudio 21, 80125 Naples, Italy
[4] Department of Chemical, Materials and Production Engineering, University of Naples Federico II, P.le V. Tecchio 80, 80125 Naples, Italy

Abstract. Italy, with the highest number of UNESCO heritage sites worldwide and among the countries with the most ambitious renewable (i.e., photovoltaic) energy targets in Europe, is a living lab for experimenting with contradictions and synergies between a traditional idea of landscape preservation, and the new challenges offered by the introduction of photovoltaics in the landscape. The agrivoltaics has been emerging as a novel paradigm of integrated PV, making dual and synergic use of land for agriculture and PV generation. However, the design of agrivoltaic systems follows criteria that do not explicitly consider the landscape features. The landscape preservation is mainly conceived as protection of certain areas, and many projects only consider normative limits to realize the systems. The objective of this research work has been to develop a GIS-based tool able to implement the commonly descriptive approach used to address the integration of agrivoltaics into the landscape pattern. Metrics have been properly defined and evaluated to describe the landscape structure, its composition and spatial arrangement. They are applied to describe single landscape elements by such features as size, shape, number or for whole landscape by describing the arrangement of landscape elements. A quantitative analysis of the landscape, given by this spatially explicit approach, will provide preliminary inputs for the design of the agrivoltaic patterns in order to achieve the most relevant landscape integration criteria based on archetypes. This GIS tool is targeted at the policy makers as well as PV project developers.

Keywords: Sustainable Agrivoltaics · Landscape · GIS tools

1 Introduction

Achieving energy transition goals to address global climate change and increasing energy needs requires significant investments in solar energy. The expansion of utility-scale solar development across the globe has increased the pressure on land resources for

O. Gervasi et al. (Eds.): ICCSA 2023 Workshops, LNCS 14110, pp. 70–80, 2023.
https://doi.org/10.1007/978-3-031-37123-3_6

energy generation and other land uses (e.g., agriculture, biodiversity conservation) [1]. To address this growing issue, greater emphasis has been placed on integrated solar development strategies such as the development of agrivoltaic systems that co-locate solar energy production and agricultural land uses.

Originally, developing agrivoltaics meant merely dividing a piece of land for agriculture and energy [2]. Only in the last decades, the concept of agrivoltaics, making dual and synergic use of land for agriculture and photovoltaic (PV) generation has been emerging, with a large variety of novel agrivoltaic systems.

Beyond achieving the renewable energy goals in the near future, the agrivoltaics development might meet the effort to mitigate the climate change's impacts on the agriculture. In fact, it has also been emerging as a promising approach to improve the land productivity, achieve water saving, more generally increase the resilience to climate change.

Here, we refer to agrivoltaic systems as the co-location in synergy of ground-mounted photovoltaic development, though with specific configurations (i.e. raised PV panels, high porosity, etc.) and one or more of the following agricultural activities: crop cultivation, animal husbandry (e.g., livestock grazing, apiaries), or habitat enhancement to improve ecosystem services [3–5].

Ecosystem services are the direct and indirect benefits that ecosystems provide to humans. Agrivoltaic systems have the potential to influence positively different ecosystem services depending on priorities and implementation goals. Most clearly, agrivoltaic systems produce electricity and thus contribute directly to energy and economy. Their configurations can also support other services. Crops and livestock can be grown or supported on land co-located with agrivoltaic systems; natural habitat implemented at agrivoltaic systems can support plant and animal biodiversity, achieving conservation goals; thoughtful management can also result in beneficial regulating services, including carbon sequestration and water and soil conservation [1].

Thought, the large expansion of agrivoltaic systems is cause of concern and debate for the impact on the landscape in terms of landscape transformation and ecosystem services.

Italy, with the highest number of UNESCO heritage sites worldwide and among the countries with the most ambitious renewable (i.e., photovoltaic) energy targets in Europe, is a living lab for experimenting with contradictions and synergies between a traditional idea of landscape preservation, and the new challenges offered by the introduction of agrivoltaics in the landscape.

The authors are promoters at national and European level of a new idea of agrivoltaics, termed sustainable agrivoltaics [6, 7], aimed at maximizing the synergies among energy, food and landscape. Sustainable agrivoltaic systems have to optimize on the same unit of land energy and agriculture achievements making sustainable and harmonious the integration of them within the landscape.

However, the design of these systems follows criteria that do not explicitly consider the landscape features. The landscape preservation is mainly conceived as protection of certain areas, and many projects only consider normative limits to realize the agrivoltaic systems.

To meet the proposed sustainable agrivoltaics paradigm, the design of agrivoltaic systems has to be within-landscape scale including local ecosystems along with agriculture and photovoltaic systems.

At this scope, a spatially centric tool has been developed able to evaluate quantitatively the landscape structure, its composition and spatial arrangement, for supporting a sustainable and harmonious inclusion of agrivoltaic systems into the landscape pattern. This GIS tool is targeted at the policy makers as well as PV project developers.

The objective of this research is to bring together the large-scale deployment of agrivoltaics and landscape preservation. To do that, landscape analysis and management tools, such as that here proposed, are needed for supporting the development of agrivoltaic projects within-landscape scale so that they can be not only efficient but also *beautiful* and sustainable.

2 Material and Methods

2.1 Study Area

The study area is the Region of Campania. It is located in South Italy and lies between longitudes 13 e 16 E and latitudes 39 e 42 N (Fig. 1).

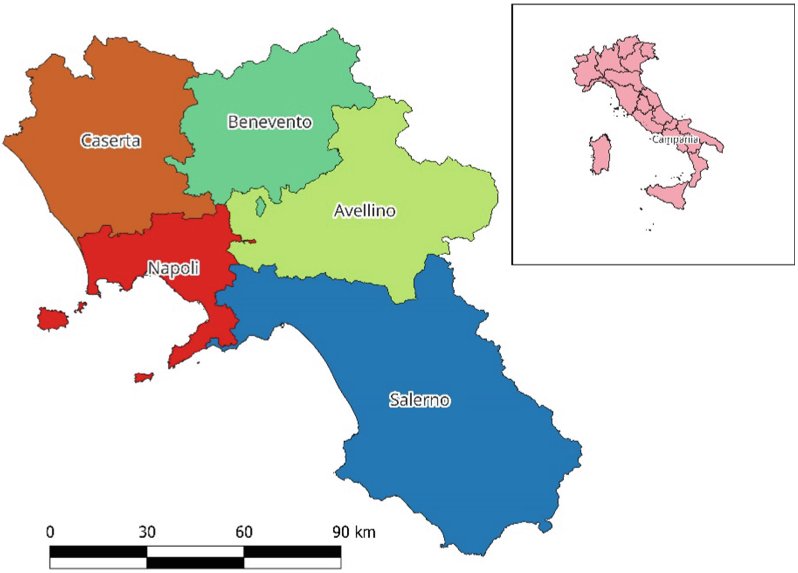


Fig. 1. Location map of the study area – Region of Campania (Southern Italy).

It extends over an area of 13.670 km^2 with a population of about 5.6 million inhabitants and a density of 424,4 inhabitants/km^2.

Its territory consists of 51% hills of 34%, mountains and of 15% plains. The highest mountain has an altitude of 1898 m s.l.m while the largest flat areas are the Plain of Sele and the plain of Volturno. Its climate is mild. Its annual average temperature is about 5 °C in winter and 18 °C in summer with cold winters and dry summers. The annual average precipitation is around 1000 mm. The annual global solar radiation value across this Region varies between 997 kWh/m^2/year and 1664 kWh/m^2/year. The annual average electricity demand is about 18414 GWh covered entirely from national production including only about 5% of photovoltaic energy.

According to the Corine Land Cover Classification, agricultural areas in Campania correspond to about 54% (5555 km^2) of the total available are, followed by forest and seminatural areas with 3953 km^2 (38%). In the category of agricultural areas, permanent crops account for approximately 21% of the total, divided into 9.7% for fruit trees and berry plantations, 10.9% for olive groves and 0.7% for Vineyards. Also, in the category of agricultural areas a significant percentage is covered by non-irrigated arable land and Complex cultivation patterns, which cover about 20% and 32% respectively.

A site suitability map for agrivoltaic systems was performed by the authors for the Campania [8]. It returns that the eligible regional area is 342,305 ha, with 52% of the agricultural land being highly suitable for agrivoltaic systems and 47% being moderately suitable.

For the scope of this work, two study areas have been selected. The first study area is within the Basso Volturno Landscape Unit as identified by the Landscape Plan of the Campania Region. The second area is within the Vallo di Diano Landscape Unit as identified by the "Landscape Plan" of the Campania Region [9]. These study areas cover a surface of about 220 ha and 80 ha, respectively.

These landscapes have been selected due to their different structure, one with small land parcels and the other one with larger land parcels. They have been characterized evaluating the patches geometry and density.

2.2 Methodology

The objective of this research work has been to develop a spatial pattern analysis tool able to quantify the landscape structure in order to support a sustainable and harmonious introduction of agrivoltaics into the landscape pattern.

This approach aims to support the sustainable agrivoltaics development making dual and synergic use of land for agriculture and photovoltaic generation and minimizing the impact on the landscape pattern.

There is no a priori way to ensure that the integration of an agrivoltaic system into the landscape is effective i.e., sustainable, and harmonious, as this is mediated by the quality of the agrivoltaic project, which must be not only a technical project but also a landscape project.

What this means? It may occur that: (1) the land area occupied by the agrivoltaic system is too large with respect to the other elements of the landscape; (2) the orientation of the modules towards the Sun (South in the Northern hemisphere and North in the Southern one) determines a pattern with a single predominant direction (namely the

East West) determined by the parallel rows, and this can be striking with respect to the other geometric features of the landscape; (3) the density of the photovoltaic pattern (Land Area Occupation Ratio- LAOR) can be too high compared to the landscape pattern, resulting a strong sense of artificiality that does not suit the features of the landscape, especially when natural or agrarian [10].

So, keeping that in mind, a set of landscape metrics has properly been defined for evaluating quantitatively the landscape composition and configuration.

These metrics will have to provide preliminary inputs for the design of the agrivoltaic patterns to fulfill the most relevant landscape integration criteria (e.g., shape and size of the whole agrivoltaic systems, porosity of the systems, etc.), based on archetypes.

Defining Metrics

The landscape ecology [11–13] has provided the conceptual and theoretical framework for defining the landscape metrics for analyzing the landscape patterns to be applied in the agrivoltaic projects.

Landscape ecologists view landscapes as an heterogeneous spatial mosaic of discrete patches (i.e. basic elements that make up a landscape), each representing a zone of relatively homogeneous conditions, where the size, shape and configuration of patches can affects key ecosystem functions (i.e. biodiversity and fluxes of organisms and materials) as well as visual attractiveness of landscape [14].

The patches comprising the landscape are not self-evident; they are defined relative to the phenomenon under investigation. For our scopes, the patches are essentially identified as agricultural land parcel and they are extracted from remote sensing images. The patches are generally grouped by class according to the category of land cover and use.

Of these patches, the matrix is the most extensive and most connected landscape element type and therefore plays the dominant role in the functioning of the landscape (Fig. 2). The corridor is a linear connection unit between patches [15].

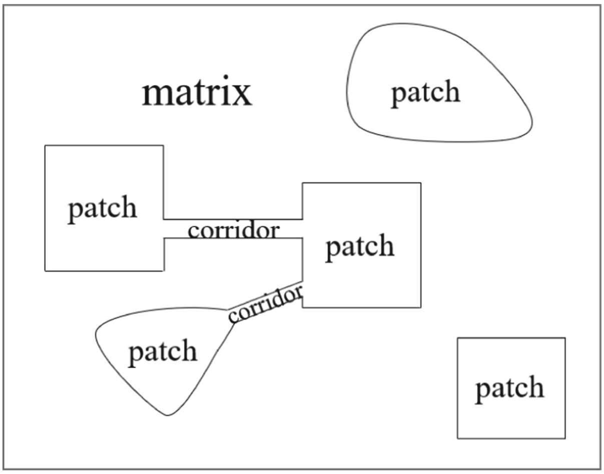


Fig. 2. A landscape Model

A landscape can be characterized by both its composition and configuration (or pattern). These two aspects of the landscape represent the landscape structure.

Landscape composition refers to features associated with the presence and amount of each patch type within the landscape but without being spatially explicit. In other words, landscape composition encompasses the variety and abundance of patch types within a landscape but not the placement or location of patches within the landscape mosaic (Fig. 2).

Landscape configuration refers to the physical distribution or spatial character of patches within the landscape. Some aspects of configuration are measures of the placement of patch types relative to other patch types, the landscape boundary, or other features of interest. Other aspects of configuration, such as shape and core area, are measures of the spatial character of the patches.

A first set of metrics, capturing patch geometry (i.e., shape and size) as well as patch density, has been selected. They are shown in Table 1. They are evaluated at patch and class level, though here the main class is agricultural.

Table 1. Landscape metrics

Metrics	Description	Formula
Area Class (CA)	Area of the patches of the corresponding class within the statistical zone	$CA = \sum_{i=1}^{n} az_{ij}$
Number of patches per class (NPC)	Number of patches for each corresponding class within the statistical zone	$NPC = nz_i$
Zone Area (ZA)	Area of the statistical zone in which landscape metrics are calculated	$ZA = TAz$
Mean Area (MA)	Average patch area of a given class within the statistical zone	$MA = \frac{CA}{NPC}$
Largest Patch Index (LPI)	Look for the patch covering the largest area within the statistical zone, calculates the area of this patch and identifies the class of that patch	$LPI = \max(az_{ij})$
Total Class Edge (TCE)	Calculates Class Edge length for edges of all patches of the selected class within the statistical zone	$TCE = \sum_{k=1}^{m} ez_{ik}$
Edge Density (ED)	The length of the edges within the statistical zone per area defined by the user	$ED = \frac{TCE}{ZA} \cdot DA$

Evaluating the Metrics

Once defining the set of metrics, a zonal and statistical-vector based approach has been developed for evaluating these metrics [15]. It allows to evaluate the metrics within comparable areas, identifying, through these, any spatial patterns across the entire study area. As recommended in literature, hexagons have been selected as statistical zones for better analyzing the landscape for agrivoltaics development.

For evaluating the metrics, the following steps have been performed. First, the vector layer of land cover and use of the landscape unit has been extracted from remote sensing image by using *image segmentation* algorithms. Then, the extracted layer has been classified according to a specified set of land cover and use classes by *spatially based supervised classification algorithms*. Finally, a vector layer of regular statistical zones has been generated and the selected landscape metrics have been calculated for each class and statistical zone by using ZonalMetrics toolbox [16]. Two options of the ZonalMetric tool have been selected: 1) selecting the hexagons as statistical zones for better analyzing the landscape for agrivoltaics development; 2) performing the "select by centroid" method for selecting only the patches within the statistical zone having the centroid that falls within the zone, in order to guarantee the unique calculation of each patch within the study area. All these steps have been implemented within the ESRI ArcGIS Pro platform.

3 Results

The set of metrics, above defined, aims to characterize the structure of the agricultural landscape, previously evaluated suitable for the agrivoltaic systems with respect to solar and agriculture criteria (e.g., global horizontal radiation, annual average temperature, land slope and orientation, elevation, water deficit, land capability, Corine land cover and reduction percentage of irradiation) [8].

The developed methodology has been applied to two different landscapes falling into land areas evaluated highly suitable for agrivoltaic systems in the site suitability analysis performed by the authors for the entire regional territory of the Campania [8]. The selected landscapes are the Basso Volturno and Vallo Di Diano, in the North-West and South-Eastern of the regional territory respectively. From remote sensing images, the vector layers of the patches has been extracted and classified in 4 land cover and use classes: planted/cultivated, developed, water bodies, vegetation strips (Fig. 3, Fig. 4).

By calculating the selected metrics for the planted/cultivated class and for statistical zones, we have observed that the Basso Volturno landscape is characterized by patches with mean area less than 2 ha and a patch density of least of 10 on a statistical zone of 14 ha.

Fig. 3. Map of the agrivoltaics (high) suitable area of Basso Volturno (South Italy) including land cover and use layer and landscape structure layer.

Fig. 4. Map of agrivoltaics (high) suitable area of Vallo Di Diano (South Italy) including land cover and use layer and landscape structure layer.

For the Vallo Di Diano landscape, we have observed that it is characterized by patches with very low mean area (i.e. values between 0,1–0,2 ha) and a high patch density on a statistical zone of 3,5 ha (30–50 patches).

The zonal approach has allowed to evaluate the spatial pattern of the calculated metrics for the planted/cultivated class at landscape level.

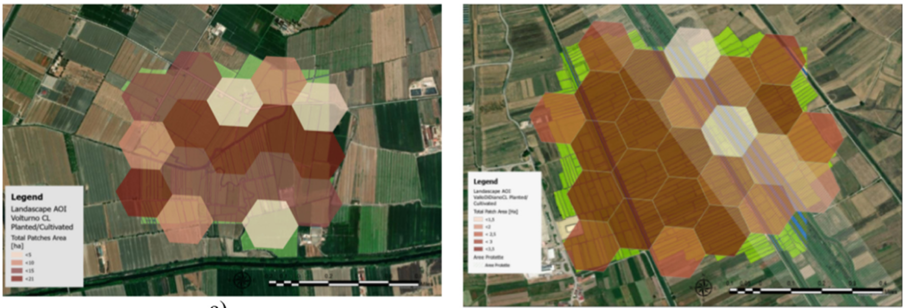
In particular, for the Basso Volturno landscape, the Figs. 4a shows two continuity profiles related to the landscape feature *total area*, located in the central-south area of the landscape. They are characterized by a total area between 10–15 ha and 15–21 ha respectively.

The Fig. 6a shows that the zones with a lower number of patches (≤10) are mainly at North and East of the landscape while the zones with higher number of patches are located in the South-West of the landscape,

Therefore, 94% of the statistical zones are characterized by an average patch area of less than 2 ha. Patches with an average area greater than 2 ha are located in a single statistical area in the North-West of the landscape (Fig. 5a).

For the Vallo Di Diano landscape, the Fig. 5b shows that the landscape area at West of Tanagro River is characterized by zones with higher total patch area values between 3–3.5 ha. Figure 6b shows that the landscape is mainly characterized by zones with a low number of patches (≤30). Then, the zones with a higher number of patches (between 30 and 50 patches) are located mainly at West of Tanagro River.

Finally, the Fig. 7b shows that the landscape is characterized by patches with a very low average area, between 0.1–0.2 ha and by a very high patch density at the zone level (30–50 patches in 3.5 ha).

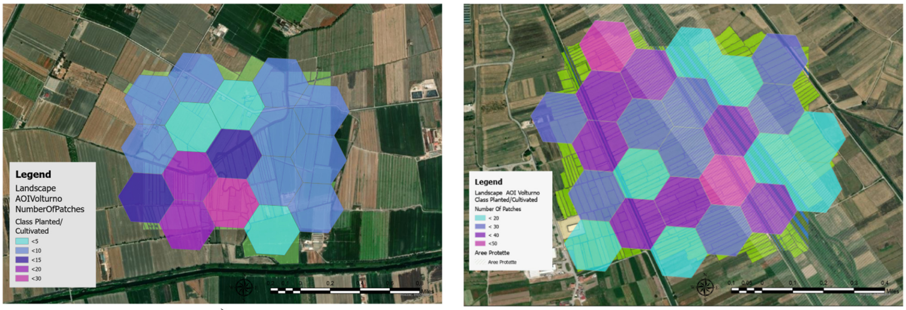


a) b)

Fig. 5. Map of the landscape feature *total patch area* calculated for the planted/cultivated class and for each statistical zone. a) Basso Volturno landscape. b) Vallo di Diano landscape

a) b)

Fig. 6. Map of the landscape feature *average patch area* calculated for the planted/cultivated class for each statistical zone. a) Basso Volturno landscape. b) Vallo di Diano landscape.



a) b)

Fig. 7. Map of Map of the landscape feature *number of patches* calculated for the planted/cultivated class and for each statistical zone. a) Basso Volturno landscape. b) Vallo di Diano landscape.

4 Conclusion

The structure of the landscapes of Basso Volturno and Vallo di Diano has been quantitatively evaluated through specific landscape metrics here properly defined aimed at providing preliminary inputs for the design of sustainable agrivoltaic projects.

These landscapes have represented the study case for the development of a spatial pattern analysis tool able to evaluate quantitatively the landscape structure for sustainable agrivoltaics development. A preliminary set of landscape metrics has been properly defined for evaluating landscape features such as size and number of patches within-zone scale as well as their spatial arrangement across the whole landscape. The innovative vector/zonal based approach proposed allows to evaluate the metrics within comparable areas and to identify any spatial patterns on the entire landscape. The investigated approach aims to support the analysis of the landscape transformation can be inducted by the agrivoltaics expansion within the landscapes as well as support an inclusive and sustainable process of the agrivoltaics development in the surrounding landscape.

Funding. This research is funded by the ongoing projects: Ricerca del Sistema Elettrico - Progetto Integrato Fotovoltaico ad alta efficienza National Project PTR 22-24 and EU HORIZON Project SYMBIOSYST Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship. Prj. N.101096352 - GAP-101096352.

References

1. Walston, L.J., et al.: Opportunities for agrivoltaic systems to achieve synergistic food-energy environmental needs and address sustainability goals. Front. Sustain. Food Syst. **6**, 374 (2022). https://doi.org/10.3389/fsufs.2022.932018
2. Goetzberger, A., Zastrow, A.: On the coexistence of solar-energy conversion and plant cultivation. Int. J. Sol. Energy **1**(1), 55–69 (1982). https://doi.org/10.1080/01425918208909875
3. Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., et al.: Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat. Sustain. **2**, 848–855 (2019). https://doi.org/10.1038/s41893-019-0364-5
4. Hernandez, R.R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., et al.: Techno-ecological synergies of solar energy for global sustainability. Nat. Sustain. **2**, 560–568 (2019). https://doi.org/10.1038/s41893-019-0309-z
5. Proctor, K.W., Murthy, G.S., Higgins, C.W.: Agrivoltaics align with green new deal goals while supporting investment in the US' rural economy. Sustainability **13**, 137 (2021). https://doi.org/10.3390/su13010137
6. Agrivoltaico Sostenibile. https://www.agrivoltaicosostenibile.com/
7. Associazione Italiana Agrivoltaico Sostenibile. https://www.associazioneitalianagrivoltaicosostenibile.com
8. Fattoruso, G., Venturo, A., Toscano, D., Nardella, G., Scognamiglio, A., Fabricino, M., Di Francia, G.: Manuscript in preparation (2023)
9. Piano Paesaggistico Regionale (PPR). https://www.territorio.regione.campania.it/paesaggio-blog/piano-paesaggistico-regionale-ppr
10. Scognamiglio, A.: 'Photovoltaic landscapes': design and assessment. A critical review for a new transdisciplinary design vision. Renew. Sustain. Energy Rev. **55**, 629–661 (2016). https://doi.org/10.1016/j.rser.2015.10.072
11. Forman, R.T.T., Godron, M.: Landscape Ecology. Wiley, New York (1986)
12. Turner, M.G.: Landscape ecology: the effect of pattern on process. Annu. Rev. Ecol. Syst. **20**(1), 171–197 (1989). https://doi.org/10.1146/annurev.es.20.110189.001131
13. Urban D.L., O'Neill R.V., Shugart Jr., H.H.: Landscape ecology. A hierarchical perspective can help scientists understand spatial patterns. Bioscience **37**, 119–127 (1987)
14. McGarigal, K., Cushman, S.A., Neel, M.C., Ene, E.: Spatial pattern analysis program for categorical maps (2002). www.umass.edu/landeco/research/fragstats/fragstats.html
15. Forman, R.T.T.: Land Mosaics: the Ecology of Landscapes and Regions. Cambridge University Press, Cambridge (1995)
16. Adamczyk, J., Tiede, D.: ZonalMetrics-a Python toolbox for zonal landscape structure analysis. Comput. Geosci. **99**, 91–99 (2017). https://doi.org/10.1016/j.cageo.2016.11.005