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Cross scale spatial and temporal indicators for measuring the effects of landscape heterogeneity on pollination service

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ABSTRACT

Spatial heterogeneity as well as landscape services' provision are a function of spatio-temporal scales, therefore, pattern–process relationships must be assessed at the multiple scales. In this context, this research aims at: (1) analyzing at the regional scale how pollination service can be affected by landscape heterogeneity, using two landscape indicators useful to quantify the multiscale landscape composition and landscape configuration simultaneously; and (2) assessing the effect that the infection of *Xylella fastidiosa* has exerted on the pollination services. The multi-scale spatial assessment has been focused on two land-covers: forests and olive groves that can act as source of pollination services. The multi-temporal analysis, based on the annual NDVI, has been used to assess the functionality of olive groves before and at the beginning of the infection of *Xylella fastidiosa*, and currently. The results have shown that in 2012 the most representative cluster (C1) (73.6% for forests and 63% for olive groves) is in the lower left part of the multiscale metric space, meaning that both land-covers show a fragmented spatial configuration at small spatial scales and tend to be aggregated at large scales. The multi-temporal analysis has allowed to show the evident change in the landscape functioning in the provinces interested by the infection of *Xylella fastidiosa* (Lecce, Brindisi and Taranto) from 2013 to 2021, highlighting that the stability of the landscape has resulted completely changed for the loss of permanent land-covers (olive groves). In this study the spatio-temporal analyses have helped in giving a more complete indication in the assessment of landscape services where different factors can play a crucial role. The analysis of spatial patterns along a continuum of scale has been implemented by the analysis of multi-temporal dynamics to consider the effect of *Xylella fastidiosa* infection on pollination. The temporal behavior of NDVI has resulted completely changed in the provinces interested by this infection, meaning that recovering policies need to be undertaken to regenerate the landscape. When studying landscape services, some considerations must be considered in choosing the suitable spatial and temporal scale for its assessment. One of the recent drivers of change, represented by the infection of *Xylella fastidiosa*, and the planning of landscape functionality recovery interest higher spatial scales and will affect the scale at which landscape services, included pollination, are delivered.

1. Introduction

Traditionally, the ecological research has been focused on two main spatial units: ecosystems and landscapes, which are theoretically dissimilar, but often they have been used in overlapped ways, generating confusion in their application (Naveh, 2010). The holistic nature can be attributed to both concepts, but they differ in terms of their spatial dimension and arrangement (spatial homogeneity vs heterogeneity), as well as for the human presence (O'Neill et al., 1986). More specifically, in the ecosystem perspective a spatial homogeneity is assumed within the ecosystem, while it is expected the spatial heterogeneity within the landscape (Allen and Starr, 1982; Salthe, 1985; O'Neill et al., 1986; O'Neill, 2001; Ahl and Allen, 1996; Wu and David, 2002; Naveh, 2010). Therefore, the landscape approach seems to fit better the real ecological world (O'Neill, 2001). Furthermore, the ecosystem theory considers humans as external drivers, while the landscape theory is based on the "humans-in-nature" perspective (Berkes et al., 1998; Gunderson and Holling, 2002; Raymond et al., 2013), where the landscapes are considered the results of millennial human-nature interactions (Herrero-Jàuregui et al., 2018).

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These different perspectives affect the assessment of the benefits provided by nature to humans – ecosystem services (ES) (Costanza et al., 1997): the holistic approach provided by the landscape assessment contributes better to the analysis of the overall complexity of socio-ecological systems (Levin, 1999; Zurlini et al., 2018), to identify suitable environmental management strategies.

In this context, this research aims at analyzing at regional scale how pollination service can be affected by landscape heterogeneity, using two landscape indicators helpful to quantify the multiscale landscape composition and configuration simultaneously. This is a novelty, considering that the mapping of ecosystem services, which is a common tool to assess the capacity of an ecosystem to provide services, it is often based only on landscape composition (the amount of land covers as a proxy of the potential capacity to provide ecosystem services) (Foody, 2015; Tan et al., 2020; Akhtar et al., 2020; Aziz, 2020; Hardaker et al., 2020; González-García et al., 2020; Petrosillo et al., 2021). Instead, how those land-covers are spatially arranged (landscape configuration) (Verhagen et al., 2016; Marinelli et al., 2020; Zhang et al., 2020; Haan et al., 2020; Von Thaden et al., 2021; Joseph et al., 2020; Villa et al., 2020) has been often neglected, assuming that a land cover supplies the same quantity of ecosystem services independently on its inner spatial heterogeneity, its position within the landscape, and its management history (more conservative or more impactful) (Plummer, 2009). On the contrary, the multiscale landscape approach allows analyzing each land-cover in its spatial context in terms of fragmentation with potential risk to lose the provision of specific services. Finally, as a first attempt, this research intends to assess the effect of the infection of *Xylella fastidiosa* on landscape configuration and, indirectly, on pollination service.

2. Theoretical background

2.1. Landscape heterogeneity and landscape services

Spatial heterogeneity is a key aspect characterizing a given landscape in terms of processes and functions (Forman and Godron, 1986; Turner et al., 2001), and it is given by two main components (Li and Reynolds, 1994; Gustafson, 1998; Riitters et al., 2000; Neel et al., 2004; Zurlini et al., 2006, 2007, 2010, 2014; Proulx and Fahrig, 2010; Jones et al., 2013):

- landscape composition, given by the quantity of patches in a landscape, such as the number of land-cover classes in a map, their proportion, and diversity (Gustafson, 1998); and
- landscape configuration, given by the contagion of different patches; it provides a measure of the spatial aggregation of different patches of the same land-cover class in a landscape (McGarigal and Marks, 1995; Schumaker, 1996; O'Neill et al., 1988; Ritters et al., 1996).

In the ongoing environmental change, understanding how landscape components are related to the predictability of services' provision is crucial (Lázaro and Alomar, 2019). In this perspective, the concept of landscape services (Termorshuizen and Opdam, 2009) is preferred to ecosystem services in this research, since it directly or indirectly emphasizes that their provision depends on the heterogeneous pattern of the landscape (Opdam, 2013), crucial for landscape management (Bennett et al. 2009; Jones et al. 2013; Westerink et al., 2017).

Furthermore, spatial heterogeneity of landscape services' providers is a function of spatial–temporal scales (Wiens, 1989; Allen and Hoekstra, 1992; de Groot and Hein, 2007; Pérez-Soba et al., 2008; Costanza, 2008). This means that to assess properly landscape services, landscape pattern–process relationships must be assessed at the multiple scales in a range appropriate to the inherent structure of the system (or process) (Levin, 1992; Turner et al., 2001; Levin, 1992), or to the perception of the organism(s) under study (Wiens, 1989; Wiens and Milne, 1989). In this context, it is important to focus on the scale at which a specific ecological process operates, and/or a particular organism(s) responds to landscape heterogeneity (Wiens, 1989). However, it is fundamental to consider that spatial heterogeneity plays an important role from local to regional scale (where environmental management policies take place), given that at a national and global level the effects of local heterogeneities are flatten out (Verhagen et al., 2016).

Nowadays, an assessment considering together the effects of multi-scale landscape composition and configuration on services is still missing. There are only few examples considering the spatial composition and configuration (Cong et al., 2016; Li et al., 2021; Metzger et al., 2021; Xia et al., 2021; Lyu et al., 2022; Lei et al., 2021). This lack of studies hinders landscape management for multiple services and does not provide specific guidance, unless generically that heterogeneity can affect positively the provision of a bundle of services (Macfadyen et al., 2012).

2.2. Theoretical effects of landscape heterogeneity on pollination service

Pollination is an essential landscape service supported by natural and semi-natural areas within agricultural landscapes, which provide suitable habitats for wild pollinators (Steffan-Dewenter and Tscharntke, 2001; Potts et al., 2003; Ricketts et al., 2008; Lázaro and Alomar, 2019). Pollinators include a range of different insects, but commonly agricultural fields are most effectively pollinated by bees (Klein et al., 2007), which are central-place foragers (Ricketts et al., 2006). Therefore, how much proximal are nesting habitats (pollinators' sources) to agricultural fields (pollinators sinks) is crucial for the maintenance of pollination service at landscape scale (Ricketts et al., 2008).

In the perspective of source-sink relation, some land-covers can act as a source and some others as a sink of pollinators in a landscape. Therefore, it is important the amount of land-cover source or sink (landscape composition) as well as their spatial configuration (Cong et al., 2016; Li et al., 2021; Metzger et al., 2021; Xia et al., 2021; Lyu et al., 2022; Lei et al., 2021; Warzecha et al., 2021). Theoretically, setting landscape composition in 50 % pollinators' source and 50 % pollinators sink patches, the level of fragmentation can affect the contagion among patches with effects on the provision of pollination service.

However, in real landscape the cross-scale interactions make the source-sink relation at one single scale much more complex, therefore simulated cross-scale patterns generated by neutral landscape models (NLMs) (Gardner et al., 1987), can give a general vision of spatial patterns through simple binary maps. The pattern transition space (Fig. 1) shows the amount of pollinators' source patches (black) together with the connectivity in terms of spatial autocorrelation among adjacent cells (H) (Neel et al., 2004). In general, if a given composition value is set, it is possible to observe a transition from more to less fragmented landscapes as the connectivity (H) increases (from left to right).

The emphasis on the spatial aggregation of patches acting as a source of pollinators is crucial because changes in their aggregation can have possible effects on the provision of pollination service, which can decline with increasing isolation of suitable patches in a range from 0 to 3,000 mt (Neel et al., 2004; Li et al., 2004; Ricketts et al., 2008).

The effect of isolation/aggregation on the spatial configuration of land-cover sources of pollinators is schematically represented in Fig. 2, where, for simplicity, two different spatial scales (1,000mt × 1,000mt, and 5,000mt × 5,000mt) with two different landscape configurations (one more clumped -right side and one more fragmented -left side) are taken into account. These two spatial scales are two examples to show how 100 % visitation rate with a foraging distance of 500mt is more or less guaranteed at small spatial scales (1,000mt × 1,000mt), independently from the landscape configuration. When the spatial scale increases (5,000mt × 5,000mt), the 100 % of visitation rate is not guaranteed in both spatial configurations, while the 50 % of visitation rate, based on a foraging distance of 1,000mt, seems to be guaranteed when the land-cover source of pollinators are more diffuse in the landscape.

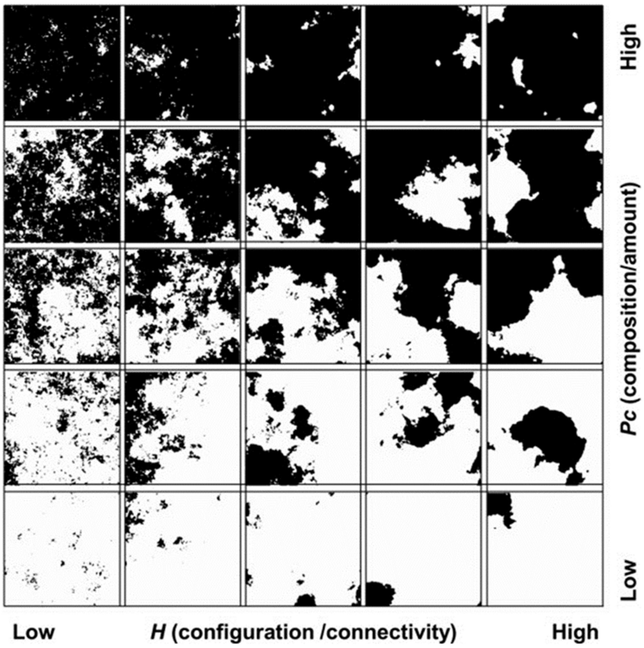

Fig. 1. Pattern transitions space composed by twenty-five binary multi-fractal neutral landscape maps (256 × 256 cells–pixels), ordered by the amount of the focal land cover type (*Pc*) and connectivity given by the degree of spatial autocorrelation among adjacent cells (H) of pollinators' source land-covers (black).

3. Materials and methods

3.1. Study area

The study area is represented by the Apulia region in southern Italy, characterized by a millennian interrelationship between man and nature. Fig. 3 shows the CORINE land-cover 2018, where it is possible to notice that the region is mainly characterized by agricultural land-covers (about 85 %), where olive groves represent the 25.6 % of the whole region.

Table 1 reports the main CORINE land covers in the Apulia region at a scale of 1:100,000 (Fig. 3) with a 25-ha minimum mapping unit. Overall, the region contains arable lands (38.9 %), extensive olive groves (25.0 %), and permanent crops (10.5 %). Major towns and small urban settlements account for 6.9 % of the entire region. The forests class represents the 8.1 %, while natural areas and agroecosystems classes represented by pastures, heterogeneous agricultural areas, and shrub and/or herbaceous vegetation association account for the 9.9 % of the region. At the province level, Bari and Lecce show the highest percentages of olive groves (about 35 %), while Foggia is characterized by the highest percentage of forests (86.9 %).

3.2. Multiscale spatial analysis

The spatial patterns of two land-covers mainly related to the provision of pollination services have been detected and quantified, using a conceptual framework that is suitable for characterizing multi-scale landscape patterns, and that has been based on the use of satellite imagery (year 2013) of the Apulia region. Such an approach has been previously used and validated to study the multiscale behavior of disturbance pattern related to human activities (Zurlini et al., 2007; Zaccarelli et al., 2008), as well as the effect of multiscale disturbance on ecosystem services' providers (Petrosillo et al., 2010). The assessment has been focused on two land-covers: forests and olive groves that can act as source of pollination services. In order to detect the landscape profiles, we have used the moving window technique, which is a consolidate approach to carry out cross-scale assessments. Through this analysis, each location has been associated with the landscape context surrounding it in each spatial window. Each window size represents a specific spatial scale of the analysis.

The cross-scale analysis has produced many profiles and if profiles of two different pixels of the same class are similar, this means that both pixels can support in the same way the pollination service across the spatial scales. In principle, each pixel could have a unique pollination service profile, but in practice, the analysis intends to group pixels according to the similarity of their profiles, based on two indicators: Ps representing the probability of supporting pollinators within each window for different window sizes, and Pss that is the probability that a pixel supporting pollinators is adjacent to another pixel with the same characteristic. Ps and Pss metrics affect naturally each other because the configuration of land-cover pollination source is physically determined by the amount of that specific land-cover in a spatial window. Therefore,

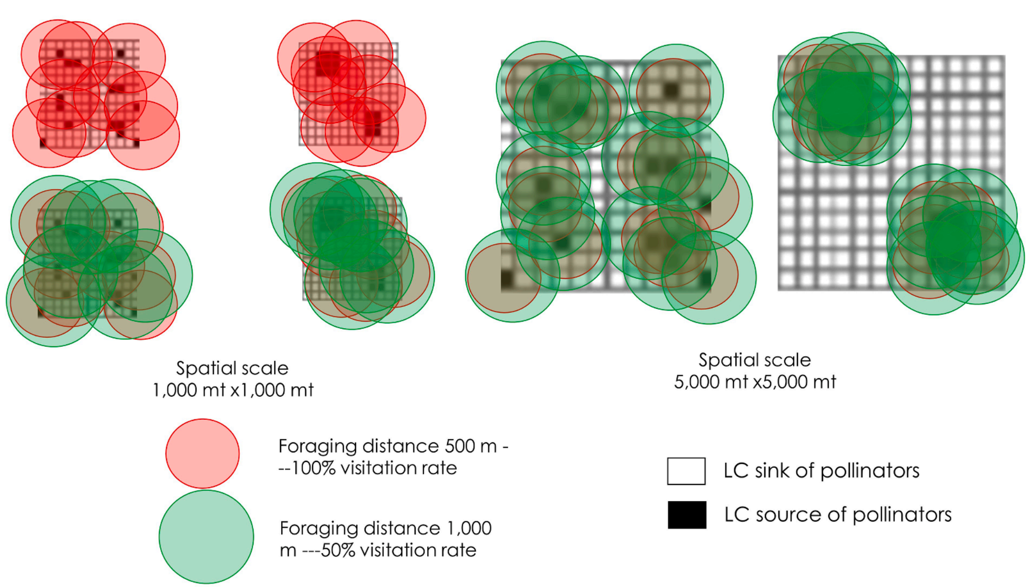

Fig. 2. Representation of the effect of spatial aggregation on pollination services at two spatial scales (1,000 mt × 1,000mt and 5,000mt × 5,000mt). Black squares represent the land-covers acting as source of pollinators, while the white squares are the land-covers that need the pollination service.

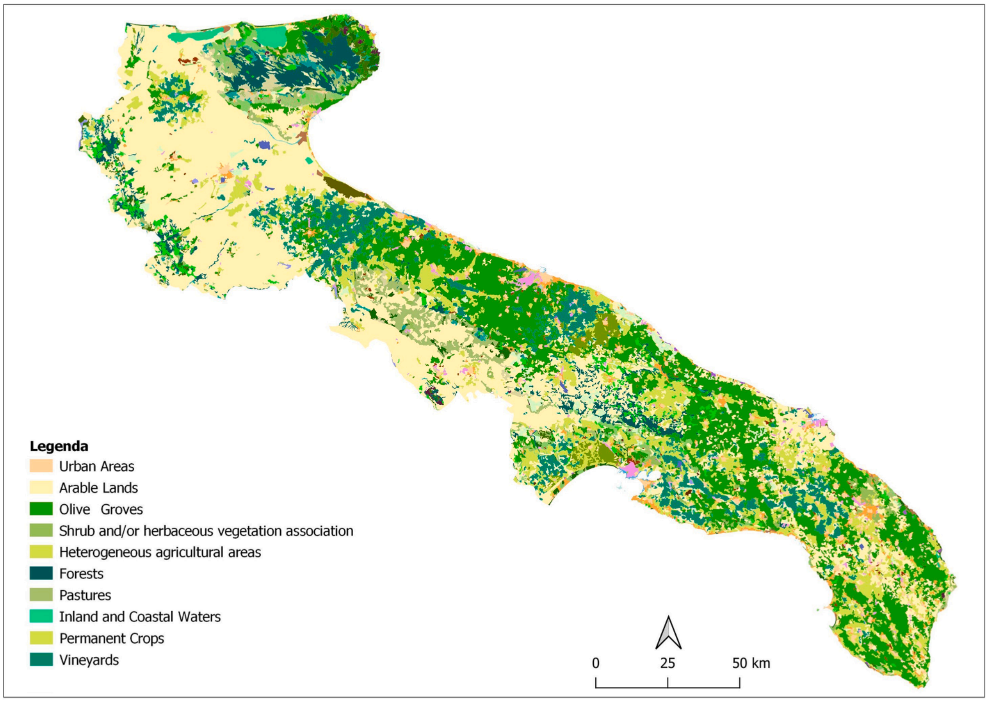

Fig. 3. Simplified CORINE land cover map 2018 at the scale of 1:100,000 with a 25-ha minimum mapping unit.

Table 1
The CORINE land use and land cover composition of the Apulia Region and its six provinces in percentage.

Description	CORINE Codes	Provinces (%)[a]						Region (%)[a]
		Bari	Brindisi	BAT	Lecce	Taranto	Foggia	%
Urban Areas	1.2, 1.3, 1.1.1, 1.1.2, 1.4	30.5	15.4	8.7	35.5	22.3	19.2	6.9
Arable Lands	2.1	24.5	8.5	8.0	10.9	11.3	84.9	38.9
Olive Groves	2.2.3	35.0	26.1	11.4	35.1	10.1	14.4	25.6
Permanent Crops	2.2.2, 2.2.1	30.3	7.3	23.5	12.5	32.0	26.8	10.5
Pastures	2.3	16.7	6.9	11.6	55.8	34.7	5.8	1.6
Heterogeneous agricultural areas	2.4.1, 2.4.3, 2.4.4	37.3	14.3	1.9	8.0	21.6	49.5	4.0
Forests	3.1	15.9	2.3	4.0	3.0	21.0	86.9	8.1
Shrub and/or herbaceous vegetation association	3.2	44.2	1.2	20.1	4.1	27.9	95.1	4.3

[a] Inland and Coastal Waters were treated as missing values.

the k-means algorithm (Legendre and Legendre, 1998) has been applied to group pixels according to the similarity of the amount of Ps values and Pss values over 10 window sizes. The k-means procedure has identified a pre-specified number of clusters by using an iterated centroid sorting algorithm to assign individual pixels to each cluster. In this research eight clusters have been identified.

3.3. Multi-temporal analysis

Since 2013 the Provinces of Lecce, Brindisi and Taranto have been interested by the infection of *Xylella fastidiosa*, which has destroyed almost completely the olive groves present in these three provinces. Currently, the CORINE land-cover classification still considers these olive groves as functional, even if they are not able to provide any landscape service (photosynthetic activity, gross primary production, water regulation, etc.), therefore, nowadays this land-cover is not able to play the role of pollination service source as in the past.

To better characterize the olive groves, a multi-temporal analysis has been used to assess their functionality before and at the beginning of *Xylella fastidiosa* infection. This study has utilized data and processed images obtained from the satellite Landsat 8 OLI, operated by NASA (National Aeronautics and Space Agency). Given the recognition that the normalized difference vegetation index (NDVI) is the most widely used vegetation index used to study vegetation activity in a landscape at different spatial scales (Pettorelli et al., 2005; Matarira et al., 2020), and that has been used to study crop pests and pollinators (Adan et al., 2021), this research has been focused on the annual and seasonal maximums of NDVI. This index has been widely used in several studies focused on vegetation dynamics because of its close correlations with variables of ecological interest such as the photosynthetic activity, health/stress conditions of vegetation cover, crop productivity and biomass (Guyot, 1989; Goward et al., 1991; Özyavuz et al., 2015). In a landscape it ranges from -1 to $+1$: values < 0 are likely related to water presence, values ~ 0 can be due to urban areas, while values > 0 represent vegetation (Krishnaswamy et al., 2009). It can support the analysis and evaluation of land-covers' potential and their contribution to the provision of landscape services.

In this study, Landsat 8 images have been processed in the platform Google Earth Engine, to quantify the primary productivity and, therefore, to get an indication of the changes in landscape functionality because of *Xylella fastidiosa*. Seasonal trends of maximum NDVI have been processed throughout specific time periods shown in Table 2. In particular, the focus on the multi-temporal dynamics of green biomass has helped in analyzing the productivity of olive groves before (2013) and at the beginning (2015) of *Xylella fastidiosa* infection, and currently (2021).

Table 2
Time periods used for the construction of seasonal trends throughout maximum NDVI (Landsat 8 OLI).

Year	Winter Date	Spring Date	Summer Date	Autumn Date
2021	2021/12/21–2022/03/21	2021/03/21–2021/06/21	2021/06/21–2021/09/21	2021/09/21–2021/12/21
2015	2015/12/21–2016/03/21	2015/03/21–2015/06/21	2015/06/21–2015/09/21	2015/09/21–2015/12/21
2013	2013/12/21–2014/03/21	2013/03/21–2013/06/21	2013/06/21–2013/09/21	2013/09/21–2013/12/21

4. Results

To help the interpretation of the results, a graphical model has been used to identify the Ps-Pss metric space. For a fixed value of Ps, when Pss > Ps, the spatial configuration of land-cover that act as source of pollination is aggregated (Fig. 4b and Fig. 4d), given that the probability that two pixels of land-cover source of pollinators are clumped within the spatial window is very high. Conversely, when Pss < Ps on a binary pollination source map, the implication is that the land-covers sources of pollinators are fragmented (Fig. 4a and c).

In Fig. 5, the multiple scales trajectories of the eight clusters' means identified in the Apulia region for forests (a) and olive groves (b) are given. Arrows indicate the path of each cluster displacement from the lowest resolution limit to the coarsest scale (upper limit of extent). All trajectories join into a single convergent point (CP) that represents the extent, given by the overall Ps and Pss at the entire region level. In both cases the cluster 1 is the most representative (73.6 % for forests and 63 % for olive groves), and it is in the lower left part of the Ps-Pss metric space, meaning that both land-covers show a fragmented spatial configuration at small spatial scales and tend to be aggregated at larger scales.

Finally, the spatial pattern of land-covers source of pollinators (forests and olive groves) along a continuum of scales has been mapped (Fig. 6). From the maps it is possible to highlight that the two land-

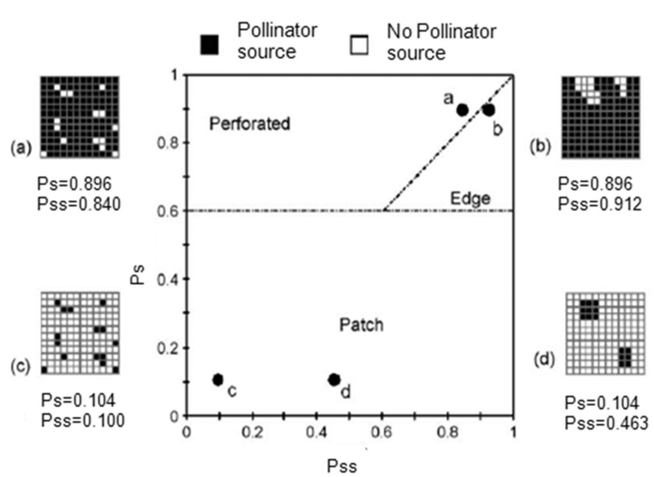

Fig. 4. A graphical model useful to interpret local measurements of Ps and Pss in a fixed-area window. Ps is the proportion of land-covers supporting pollinators within each spatial window for different window size and Pss is the probability that two pixels of pollination source are neighbor (modified after Riitters et al., 2000). Four examples of binary landscapes (a–d) are presented and located on the Ps-Pss space for different combinations of composition and configuration: (a) land-cover pollination source perforated by pollination sink areas, (b) land-cover pollination source but with clumped sink areas, (c) low level and highly fragmented land-cover pollination source, and (d) low level of aggregated land-cover pollination source (Zurlini et al., 2006; Zaccarelli et al., 2008).

covers show a consistent complementary distribution, covering the whole region.

In both maps cluster 8 has represented the pixels of both land-covers more spatially aggregated, while cluster 1, the most common, has grouped the pixels more spatially fragmented. Surprisingly, where one land-cover has resulted more fragmented across spatial scale, the other has shown a more clumped behavior. This has represented a guarantee for the support of landscape pollination service: the landscape spatial pattern of the region has resulted suitable for the maintenance of this service.

Finally, the multi-temporal analysis has allowed to show the evident change in the landscape functioning in the provinces interested by the infection of *Xylella fastidiosa* (Lecce, Brindisi and Taranto). It is worth to notice that at the beginning of the infection (2013), the annual trend of NDVI has shown a decrease of the primary productivity from winter to summer and then an increase when moving towards winter (Fig. 7). During the first stage of the infection (2015), the annual trend of NDVI has shown some changes in the first half of the year: it is possible to observe a stability of the primary productivity from winter to spring and then a strong decrease from spring to summer (dry season), typical behavior of herbaceous land covers. This change is much more evident in the first half of the 2021, when the seasonal maximum NDVI has shown a peak for all provinces in spring, since the landscape of the three provinces has resulted deeply interested by the eradication of old olive trees and their replacement by young trees, showing different functional capacity and primary productivity. In the second part of the year the trend is comparable with that of the previous years.

5. Discussion

Pollination is a vital landscape service making its long-term stability a priority for socio-ecological-economic sustainability (Delphia et al., 2022). In this study the spatial and temporal analyses have helped in giving a more complete indication in the assessment of landscape services where different socioecological factors can play a crucial role. First of all, the landscape service under study has been identified as a "local proximal service" (Costanza, 2008), which means that pollination depends on the spatial proximity between land-covers that support pollinators (source) and those that benefit from pollination (sink) like agricultural fields, but also the biodiversity in general.

It is well-known the contributions of natural habitats for supporting wild pollinators to provide pollination services to proximal agricultural farms (Tibesigwa et al., 2019; Sitotaw et al., 2022). However, to guarantee this service, it is important to analyze if the landscape context is suitable for its provision. In this perspective, the multi-spatial scale approach, used in this study, has allowed investigating the landscape suitability for the provision of pollination. This perspective is a novelty, since it has allowed analyzing simultaneously the number of land-covers acting as source of pollinators and their spatial configuration, and this is extremely important when we intend to manage the landscape to foster local proximal services, like pollination.

The analysis of spatial patterns along a continuum of scale has been implemented by the analysis of multi-temporal dynamics to consider the effect of *Xylella fastidiosa* infection on pollination. The temporal behavior of NDVI has resulted completely changed in the provinces interested by this infection, meaning that recovering policies need to be undertaken for landscape restoration.

However, old olive groves have played in the Apulia region several socio-ecological roles: the production of high-quality olive oil (economic role), the maintenance of local biodiversity, pollination service provision, as well as the ability to fix the soil, fight against erosion, and draw water in depth (ecological role). Century-old olive groves have shaped the landscape and have replaced the previous forest of *Quercus ilex* playing a cultural and heritage role.

Finally, the infection of *Xylella fastidiosa* has caused a change from a more stable land-cover (olive groves), able to regulate the landscape, to

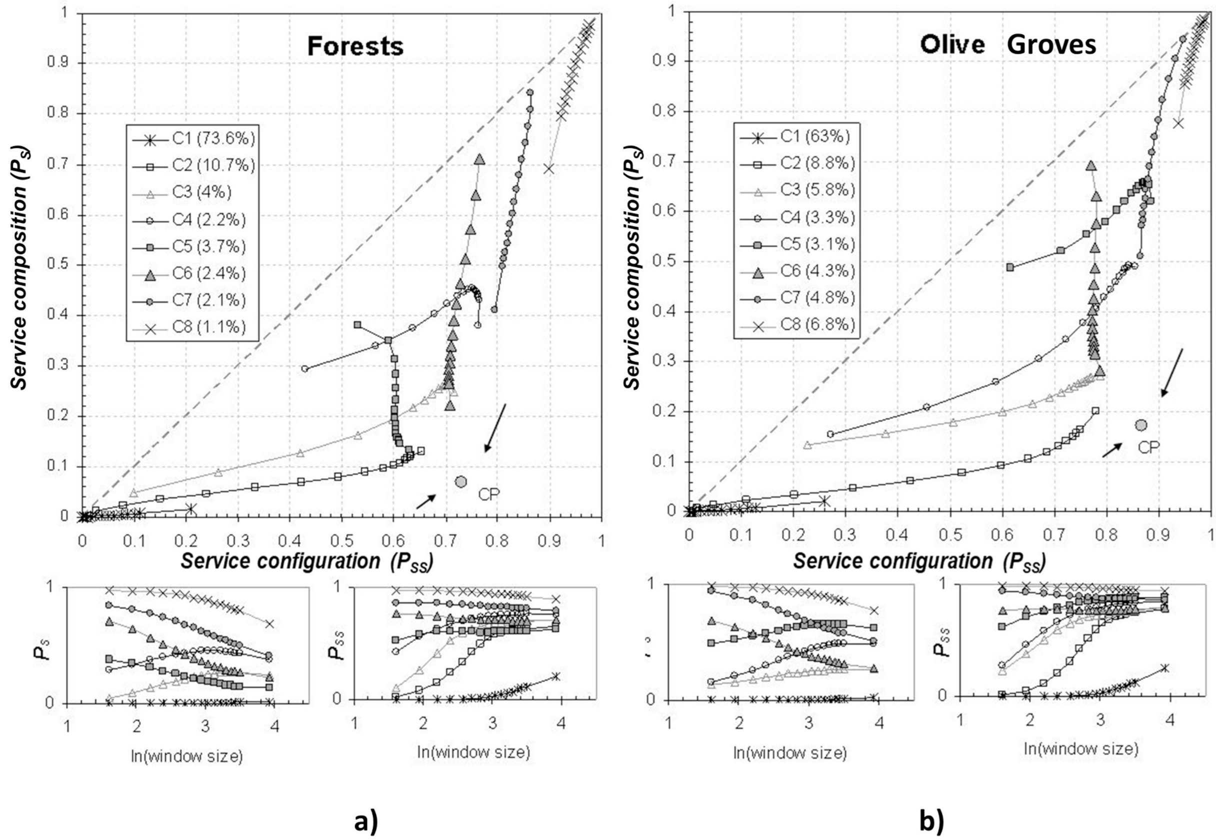

Fig. 5. The cross-scales trajectories of the eight clusters identified in the Apulia region for forests (a) and olive groves (b). Arrows specify the direction of each cluster displacement from the finest (lower resolution limit) to the coarsest scale (upper limit of extent).

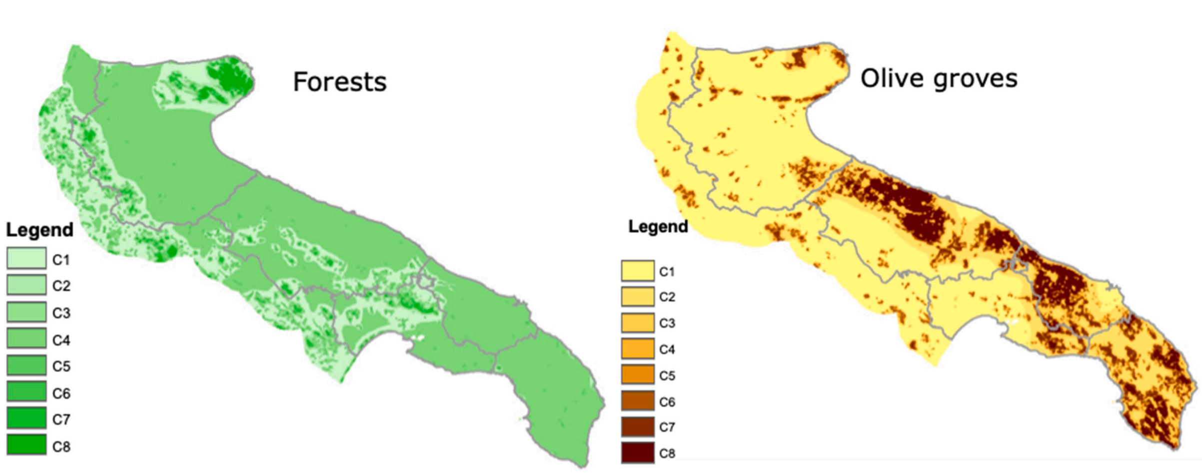

Fig. 6. Maps of the spatial model of the pollinator source land covers (forests and olive groves) along a continuum of scale, which show how they show a complementary distribution, covering the entire region.

a more ephemeral vegetation coverage, because of the land abandonment for their economic unproductivity. The maturity of an homogeneous landscape characterized by olive groves, with strong relations among species has been hit by an unexpected event causing its collapse in economic, ecological and social terms. The resilience of millennial land-covers has, thus, resulted not enough to face the perturbation caused by *Xylella fastidiosa*, and NDVI has resulted a suitable index for detecting such a kind of ecological collapse, by analyzing land-cover dynamics (Linderholm, 2006; Qu et al., 2020) at different scales. In this perspective, the analysis of recurrent behaviors could give important insights in terms of temporal analysis of landscape service provision (Zurlini et al., 2018).

These analyses represent the first results of a national project that aims at regenerating the landscape in the perspective of recovering the provision of some landscape services, which have been negatively affected by the infection of *Xylella fastidiosa*. In this perspective, these first results have suggested to start from the spatial landscape configuration restoration to guarantee the seasonal functionality of the landscape, enhancing the landscape heterogeneity instead of the homogeneity in order to foster the landscape adaptive capacity and the

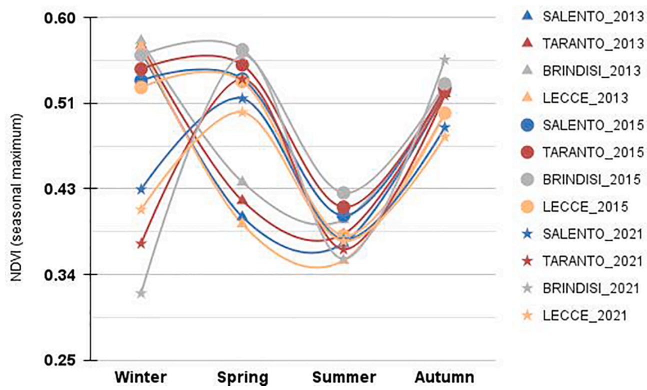

Fig. 7. Annual trend of seasonal maximum Normalized Difference Vegetation Index (NDVI) for the single Provinces of Lecce, Brindisi and Taranto and for the entire Salento.

resilience of landscape services.

6. Conclusions

Scale is a crucial aspect in ecological studies, since landscape services are delivered, used, and managed at different spatial and temporal scales. The common way to evaluate the land-covers' capacity to deliver landscape services does not consider that, frequently, phenomena are unevenly distributed in space and time and diversely aggregated.

When studying landscape services, precautions must be considered in choosing the suitable spatial and temporal scale for their assessment. In the case of pollination, the upper spatial limit has been set considering the reduced capacity of visitation rate when the distance increases till 3 km, with effects on pollination sinks (those land-covers needing pollination). One of the recent drivers of change, represented by the infection of *Xylella fastidiosa*, and the planning of landscape functionality recovery interest higher spatial scales, and will affect the scale at which landscape services, included pollination, are delivered.

The cross-scales assessment represents a clear novelty that needs to be deepened in ecological studies focused on landscape services and to be considered in planning and management, since landscapes differ in their spatial heterogeneity and can provide different kinds and amounts of landscape services, requiring suitable and specific management choices and recovery strategies.

Landscape stability at local scale can play a crucial role in guaranteeing the provision of local proximal services such as disturbance regulation, the provision of habitats, and pollination (Wang et al., 2022). Landscape service provision can be sustained by the right level of heterogeneity, since fragmentation of land-covers, at a certain level and at the right scale, can increase the flow of some landscape services to more beneficiary land-covers by enhancing for instance the "edge effect". The methodological approach presented in this paper can represent an example suitable also for the assessment of other local proximal services, based on the functional connections between landscape service providers (sources) and beneficiaries (sinks).

CRediT authorship contribution statement

Irene Petrosillo: Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Maria Victoria Marinelli:** Data curation, Visualization. **Giovanni Zurlini:** Methodology, Writing – review & editing. **Donatella Valente:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision.

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

Data will be made available on request.

References

Adan, M., Abdel-Rahman, E.M., Gachoki, S., Muriithi, B.W., Lattorff, H.M.G., Kerubo, V., Landmann, T., Mohamed, S.A., Tonnang, H.E.Z., Dubois, T., 2021. Use of earth observation satellite data to guide the implementation of integrated pest and pollinator management (IPPM) technologies in an avocado production system. Remote Sens. Appl. 23, 100566.
Ahl, V., Allen, T.F.H., 1996. Hierarchy Theory: A Vision, Vocabulary, and Epistemology. Columbia University Press, New York.
Akhtar, M., Zhao, Y., Gao, G., Gulzar, Q., Hussain, A., Samie, A., 2020. Assessment of ecosystem services value in response to prevailing and future land use/cover changes in Lahore, Pakistan. Region Sustain. 1 (1), 37–47.
Allen, T.H.F., Hoekstra, T.W., 1992. Toward a Unified Ecology. Colombia University Press, New York.
Aziz, T., 2020. Changes in land use and ecosystem services values in Pakistan, 1950–2050. Environ. Dev. 100576.
Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.
Berkes, F., Folke (eds), C., 1998. Linking Social and Ecological Systems: Management Practices and Social Mechanisms for Building Resilience. Cambridge Univ Press, Cambridge, UK.
Cong, R.-G., Ekroos, J., Smith, H.G., Brady, M.V., 2016. Optimizing intermediate ecosystem services in agriculture using rules based on landscape composition and configuration indices. Ecol. Econ. 128, 214–223.
Costanza, R., 2008. Ecosystem services: Multiple classification systems are needed. Biol. Conserv. 141, 350–352.
Costanza, R., Darge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., Oneill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
de Groot, R., Hein, L., 2007. Concept and valuation of landscape functions at different scales. Multifunct. Land Use 15–36.
Delphia, C.M., O'Neill, K.M., Burkle, L.A., 2022. Proximity to wildflower strips did not boost crop pollination on small, diversified farms harboring diverse wild bees. Basic Appl. Ecol. 62, 22–32.
Foody, G.M., 2015. Valuing map validation: The need for rigorous land cover map accuracy assessment in economic valuations of ecosystem services. Ecol. Econ. 111, 23–28.
Forman, R.T., Godron, M., 1986. Landscape Ecology. John Wiley and Sons, New York.
Gardner, R.H., Milne, B.T., Turner, M.G., O'Neill, R.V., 1987. Neutral models for the analysis of broad-scale landscape pattern. Landscape Ecol. 1, 19–28.
González-García, A., Palomo, I., González, J.A., López, C.A., Montes, C., 2020. Quantifying spatial supply-demand mismatches in ecosystem services provides insights for land-use planning. Land Use Policy 94, 104493.
Goward, S.N., Markham, B., Dye, D.G., Dulaney, W., Yang, J., 1991. Normalized difference vegetation index measurements from the advanced very high-resolution radiometer. Remote Sens. Environ. 35 (2–3), 257–277.
Gunderson, L.H., Holling, C.S. (Eds.), 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, DC, USA.
Gustafson, E.J., 1998. Quantifying landscape spatial pattern: what is the state of the art? Ecosystems 1, 143–156.
Guyot, G., 1989. Signatures Spectrales Des Surfaces Naturelles, vol. 5. Collection Teledetection Satellitaire, Paradigme, p. 178.
Haan, N.L., Zhang, Y., Landis, D.A., 2020. Predicting landscape configuration effects on agricultural pest suppression. Trends Ecol. Evol. 35 (2), 175–186.
Hardaker, A., Pagella, T., Rayment, M., 2020. Integrated assessment, valuation and mapping of ecosystem services and dis-services from upland land use in Wales. Ecosyst. Serv. 43, 101098.
Herrero-Jàuregui, C., Arnaiz-Schmitz, C., Reyes, M., Telesnicki, M., Agramonte, I., Easdale, M., Schmitz, M.F., Aguiar, M., Gòmez-Sal, A., Montes, C., 2018. What do we talk about when we talk about social-ecological systems? A literature review. Sustainability 10, 2950.
Jones, K.B., Zurlini, G., Kienast, F., Petrosillo, I., Edwards, T., Wade, T.G., Li, B.L., Zaccarelli, N., 2013. Informing landscape planning and design for sustaining ecosystem services from existing spatial patterns and knowledge. Landscape Ecol. 28, 1175–1192.
Joseph, J., Santibáñez, F., Laguna, M.F., Abramson, G., Kuperman, M.N., Garibaldi, L.A., 2020. A spatially extended model to assess the role of landscape structure on the pollination service of Apis mellifera. Ecol. Model. 431, 109201.
Klein, A.M., Vaissiere, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proc. R Soc. B Biol. Sci. 274, 303–313.
Krishnaswamy, J., Bawa, K.S., Ganeshaiah, K.N., Kiran, M.C., 2009. Quantifying and mapping biodiversity and ecosystem services: utility of a multi-season NDVI based Mahalanobis distance surrogate. Remote Sens. Environ. 113, 857–867.

Lázaro, A., Alomar, D., 2019. Landscape heterogeneity increases the spatial stability of pollination services to almond trees through the stability of pollinator visits. Agric. Ecosyst. Environ. 279, 149–155.

Legendre, P., Legendre, L. (Eds.), 1998. Numerical Ecology. 2nd, English edition. Elsevier Science B.V, Amsterdam.

Lei, J.-C., Wang, S., Wu, J., Wang, J.W., Xiong, X., 2021. Land-use configuration has significant impacts on water-related ecosystem services. Ecol. Eng. 160, 106133.

Levin, S.A., 1992. The problem of pattern and scale in ecology. Ecology 73, 1943–1967.

Levin, S.A. Fragile Dominion: Complexity and the Commons; Perseus Books: Reading, MA, USA, 1999.

Li, X., He, H.S., Wang, X., Bu, R., Hu, Y., Chang, Y., 2004. Evaluating the effectiveness of neutral landscape models to represent a real landscape. Landscape Urban Plan. 69, 137–148.

Li, H., Reynolds, J.F., 1994. A simulation experiment to quantify spatial heterogeneity in categorical maps. Ecology 75, 2446–2455.

Li, J., Zhou, K., Xie, B., Xiao, J., 2021. Impact of landscape pattern change on water-related ecosystem services: Comprehensive analysis based on heterogeneity perspective. Ecol. Indic 133, 108372.

Linderholm, H.W., 2006. Growing season changes in the last century. Agric. Forest. Meteorol. 137 (1–2), 1–14.

Lyu, R., Zhao, W., Tian, X., Zhang, J., 2022. Non-linearity impacts of landscape pattern on ecosystem services and their trade-offs: a case study in the City Belt along the Yellow River in Ningxia, China. Ecol. Indic. 136, 108608.

Macfadyen, S., Cunningham, S.A., Costamagna, A.C., Schellhorn, N.A., 2012. Managing ecosystem services and biodiversity conservation in agricultural landscapes: are the solutions the same? J. Appl. Ecol. 49, 690–694.

Marinelli, M.V., Valente, D., Scavuzzo, C.M., Petrosillo, I., 2020. Landscape service flow dynamics in the metropolitan area of Córdoba (Argentina). J. Environ. Manage. 280, 111714.

Matarira, D., Mutanga, O., Dube, T., 2020. Landscape Scale land degradation mapping in the semi-arid areas of the Save catchment, Zimbabwe. S. Afr. Geogr. J. 1–21.

McGarigal, K. and Marks, B. J. 1995. Fragstats: spatial pattern analysis program for quantifying landscape structure. U. S. Forest Service General Technical Report PNW: 351. Portland, OR, USA.

Metzger, J.P., Villarreal-Rosas, J., Suárez-Castro, A.F., López-Cubillos, S., González-Chaves, A., Runting, R.K., Hohlenwerger, C., Rhodes, J.R., 2021. Considering landscape-level processes in ecosystem service assessments. Sci. Total Environ. 796, 149028.

Naveh, Z., 2010. Ecosystem and landscapes – A critical comparative appraisal. J. Landsc. Ecol. 3 (19), 64–81.

Neel, M.C., McGarigal, K., Cushman, S.A., 2004. Behavior of class-level landscape metrics across gradients of class aggregation and area. Landscape Ecol. 19, 435–455.

O'Neill, R.V., 2001. Is it time to bury the ecosystem concept? (with full military honors of course!). Ecology 82, 3275–3284.

O'Neill, R.V., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. A Hierarchical Concept of Ecosystems. Princeton University, Princeton.

O'Neill, R.V., Krummel, J.R., Gardner, R.H., Sugihara, G., DeAngelis, D.L., Milne, B.T., Turner, M.G., Zygmunt, B., Christensen, S.W., Dale, V.H., Graham, R.L., 1988. Indices of landscape pattern. Landscape Ecol. 1, 153–162.

Opdam, P.F.M., 2013. Using ecosystem services in community-based landscape planning: science is not ready to deliver. In: Fu, B., Jones, K.B. (Eds.), Landscape Ecology for Sustainable Environment and Culture. Springer, Dordrecht, pp. 77–101.

Özyavuz, M., Bilgili, C., Salici, A., 2015. Determination of vegetation changes with NDVI method. J. Environ. Prot. Ecol. 16, 264–273.

Pérez-Soba, M., Petit, S., Jones, L., Bertrand, N., Briquel, V., Omodei-Zorini, L., Contini, C., Helming, K., Farrington, J.H., Mossello, M.T., Wascher, D., Kienast, F., Groot, R., 2008. Land use functions—a multifunctionality approach to assess the impact of land use changes on land use sustainability. Sustain. Impact Assess. Land Use Changes 375–404.

Petrosillo, I., Zaccarelli, N., Zurlini, G., 2010. Multi-scale vulnerability of natural capital in a panarchy of social-ecological landscapes. Ecol. Complex. 7, 359–367.

Petrosillo, I., Valente, D., Mulder, C., Li, B.-L., Jones, K.B., Zurlini, G., 2021. The resilient recurrent behavior of mediterranean semi-arid complex adaptive landscapes. Land 10, 296.

Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J., Stenseth, N.C., 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. Trends Ecol. Evol. 20 (9), 503–510.

Plummer, M.L., 2009. Assessing benefit transfer for the valuation of ecosystem services. Front Ecol. Environ. 7, 38–45.

Potts, S.G., Vulliamy, B., Dafni, A., Ne'eman, G., Willmer, P., 2003. Linking bees and flowers: how do floral communities structure pollinator communities? Ecology 84, 2628–2642.

Proulx, R., Fahrig, L., 2010. Detecting human-driven deviations from trajectories in landscape composition and configuration. Landscape Ecol. 25, 1479–1487.

Qu, S., Wang, L., Lin, A., Yu, D., Yuan, M., Li, C., 2020. Distinguishing the impacts of climate change and anthropogenic factors on vegetation dynamics in the Yangtze River Basin. China. Ecol. Indic. 108, 10572.

Raymond, C.M., Singh, G.G., Benessaiah, K., Bernhardt, J.R., Levine, J., Nelson, H., Turner, N.J., Norton, B., Tam, J., Chan, K.M.A., 2013. Ecosystem services and beyond: using multiple metaphors to understand human-environment relationships. BioScience 63, 536–546.

Ricketts, T.H., Williams, N.M., Mayfield, M.M., 2006. Connectivity and ecosystem services: crop pollination in agricultural landscapes. In: Sanjayan, M., Crooks, K. (Eds.), Connectivity for Conservation. Cambridge University Press, Cambridge, UK, pp. 255–289.

Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., Gemmill-Herren, B., Greenleaf, S.S., Klein, A.M., Mayfield, M.M., Morandin, L.A., Ochieng, A., Viana, B.F., 2008. Landscape effects on crop pollination services: are there general patterns? Ecol. Lett. 11, 499–515.

Riitters, K., Wickham, J.D., O'Neill, R., Smith, E.R., Jones, K. B., 2000. Global-Scale Patterns of Forest Fragmentation. Ecol Soc 4(2), 3. [online] URL: http://www.consecol.org/vol4/iss2/art3.

Ritters, K.H., O'Neill, R.V., Wickham, J.D., Jones, K.B., 1996. A note on contagion indices for landscape analysis. Landscape Ecol. 11, 197–202.

Salthe, S.N., 1985. Evolving Hierarchical Systems: Their Structure and Representation. Columbia University Press, New York.

Schumaker, N.H., 1996. Using landscape indices to predict habitat connectivity. Ecology 77, 1210–1225.

Sitotaw, T.M., Willemen, L., Meshesha, D.T., Nelson, A., 2022. Sacred church forests as sources of wild pollinators for the surrounding smallholder agricultural farms in Lake Tana Basin, Ethiopia, Ecol. Indic., 137, 108739.

Steffan-Dewenter, I., Tscharntke, T., 2001. Succession of bee communities on fallows. Ecography 24, 83–93.

Tan, Z., Guan, Q., Lin, J., Yang, L., Luo, H., Ma, Y., Tian, J., Wang, Q., Wang, N., 2020. The response and simulation of ecosystem services value to land use/land cover in an oasis, Northwest China. Ecol. Indic. 118, 106711.

Termorshuizen, J.W., Opdam, P.F.M., 2009. Landscape services as a bridge between landscape ecology and sustainable development. Landscape Ecol. 24, 1037–1052.

Tibesigwa, B., Siikam ̈aki, J., Lokina, R., Alvsilver, J., 2019. Naturally available wild pollination services have economic value for nature dependent smallholder crop farms in Tanzania. Sci. Rep. 9 (1).

Turner, M.G., Gardner, R., O'Neil, R.V.O., 2001. Landscape Ecology in Theory and Practice. Pattern and Process, Springer, New York.

Verhagen, W., Van Teeffelen, A.J.A., Baggio Compagnucci, A., Poggio, L., Gimona, A., Verburg, P.H., 2016. Effects of landscape configuration on mapping ecosystem service capacity: a review of evidence and a case study in Scotland. Landscape Ecol. 31, 1457–1479.

Villa, M., Santos, S.A.P., Sousa, J.P., Ferreira, A., Martins da Silva, P., Patanita, I., Ortega, M., Pascual, S., Pereira, J.A., 2020. Landscape composition and configuration affect the abundance of the olive T moth (Prays oleae, Bernard) in olive groves. Agric. Ecosyst. Environ. 294, 106854.

Von Thaden, J., Manson, R.H., Congalton, R.G., López-Barrera, F., Jones, K.W., 2021. Evaluating the environmental effectiveness of payments for hydrological services in Veracruz, México: a landscape approach. Land Use Policy 100, 105055.

Wang, J., Lu, P., Valente, D., Petrosillo, I., Bubu, S., Xu, S., Li, C., Huang, D., Liu, M., 2022. Analysis of soil erosion characteristics in small watershed of the loess tableland Plateau of China. Ecol. Indic. 137, 108765.

Warzecha, D., Diekötter, T., Wolters, V., Jauker, F., 2021. Spatial configuration and landscape context of wildflower areas determine their benefits to pollinator α- and ß -diversity. Basic Appl. Ecol. 56, 335–344.

Westerink, J., Opdam, P., van Rooij, S., Steingröver, E., 2017. Landscape services as boundary concept in landscape governance: building social capital in collaboration and adapting the landscape. Land Use Policy 60, 408–418.

Wiens, J.A., 1989. Spatial scaling in ecology. Funct. Ecol. 3, 385–397.

Wiens, J.A., Milne, B.T., 1989. Scaling of 'landscapes' in landscape ecology, or, landscape ecology from a beetle's perspective. Landscape Ecol. 3, 87–96.

Wu, J., David, J.L., 2002. A spatially explicit hierarchical approach to modeling complex ecological systems: theory and applications. Ecol. Model. 153, 7–26.

Xia, H., Kong, W., Zhou, G., Sun, O.J., 2021. Impacts of landscape patterns on water-related ecosystem services under natural restoration in Liaohe River Reserve. China. Sci. Total Environ. 792, 148290.

Allen, T.F.H., Starr, T.B.,982. Hierarchy: perspectives for ecological complexity. University of Chicago Press, Chicago.

Zaccarelli, N., Petrosillo, I., Zurlini, G., Riitters, K.H., 2008. Source/sink patterns of disturbance and cross-scale effects in a panarchy of social-ecological landscapes. Ecol. Soc. 13 (1), 26.

Zhang, Y., Haan, N.L., Landis, D.A., 2020. Landscape composition and configuration have scale-dependent effects on T agricultural pest suppression. Agr. Ecosyst. Environ. 302, 107085.

Zurlini, G., Zaccarelli, N., Petrosillo, I., 2006. Indicating retrospective resilience of multi-scale patterns of real habitats in a landscape. Ecol. Indic. 6, 184–204.

Zurlini, G., Riitters, K.H., Zaccarelli, N., Petrosillo, I., 2007. Patterns of disturbance at multiple scales in real and simulated landscapes. Landscape Ecol. 22, 705–721.

Zurlini, G., Jones, K.B., Li, B.-L., Petrosillo, I., 2010. Potentials of ecosystem service accounting at multiple scales. The Encyclopedia of Earth Retrieved from http://www.eoearth.org/view/article/51cbeea87896bb431f6996a0.

Zurlini, G., Jones, K.B., Riitters, K.H., Li, B.-L., Petrosillo, I., 2014. Early warning signals of regime shifts from cross-scale connectivity of land-cover patterns. Ecol. Indic. 45, 549–560.

Zurlini, G., Marwan, N., Semeraro, T., Jones, K.B., Aretano, R., Pasimeni, M.R., Valente, D., Mulder, C., Petrosillo, I., 2018. Investigating landscape phase transitions in Mediterranean rangelands by recurrence analysis. Landscape Ecol. 33, 1617–1631.