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Multiscale Effects of *Xylella fastidiosa* on Landscape Services

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Abstract: The spread of *Xylella fastidiosa* since 2013 in the Mediterranean olive groves of the Apulia region has modified the landscape. The aims of this research are focused on the analysis of its effects on the following: (1) Landscape multifunctionality supported by olive groves in terms of landscape service provision; (2) The functional relations among the main Mediterranean land covers in terms of landscape service supply and demand. (3) The landscape fragmentation at different spatial scales. The landscape has completely changed, mainly in those land covers that, in the past, acted as stabilizing factors (croplands and olive groves), which has been replaced by grasslands in 2021. The main effects of *Xylella fastidiosa* were on the multifunctionality of olive grove landscape in terms of food production, water regulation, carbon sequestration, and pollination, as well as on landscape cultural value. Ecosystem service supply is mainly related to olive groves, tree covers, shrublands, and wetlands. The province of Lecce showed the highest fragmentation, as demonstrated by the number of patches, the mean patch area, and the DIVISION metric, while the province of Brindisi was the least fragmented, with a DIVISION metric similar in 2011 and in 2021. The multiscale assessment of "olive groves" fragmentation has helped in better analyzing the effect of its spatial configuration on the provision of landscape services and in identifying the right spatial scale for each landscape service provision. It is essential to analyze landscape service flow to enlarge the understanding of the ways in which their supply is maintained through a landscape regeneration policy toward the socio-economic–ecological recovery.

Keywords: landscape metrics; ecosystem services; Mediterranean olive groves; landscape fragmentation

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1. Introduction

The landscape is envisioned as a highly dynamic system, where the natural and cultural subsystems are closely interconnected in a way that is useful for the provision of ecosystem services and, thus, for sustaining human well-being [1]. In this perspective, a crucial task of the current research in ecology is to deal with the interaction between humans and their modified landscapes in the context of global changes. This is not a simple task since human–nature interaction can have consequences for people in terms of traditions, well-being, security, social cohesion, economic growth, and landscapes with regard to resilience, integrity, adaptability, and capacity to provide ecosystem services [2–5]. Given these strong interrelations, the European Landscape Convention (ELC) in 2000 has also highlighted the need to protect the landscapes seen as humans-in-nature systems [6]. In this perspective, the socio-ecological landscape value can be considered the synthesis of a series of physical–structural values and a series of values dependent on the human historical process, transformation, and use of natural resources, through which the community builds up its local identity [7].

Socio-ecological landscapes are multifunctional, thanks to their heterogeneity, which is the basis for the diversity of landscape ecological functions. More specifically, landscape multifunctionality is the multiscale capacity of the landscape to provide multiple interacting functions [8], which can be seen as multiple landscape services (LS) [9,10]. This concept has been introduced to strengthen the idea that services are not only provided by natural systems but also by the multifunctionality of landscape given by the interactions among its biophysical, anthropogenic, and perceived dimensions [11–15].

However, one of the major threats to landscape multifunctionality is the potential homogenization caused by land-cover conversion in one single class. Often, such a transformation has been seen in a single direction since, in the past, for socio-economic reasons, people have converted natural (forests, grasslands, etc.) lands into cultivated lands. However, it is possible to also see a decrease in landscape functionality in the case of changes caused by a transition from croplands to land abandonment. This is of particular concern when these croplands have seen traditional land-uses with a cultural value as part of the local traditions.

This is the case of olive groves in the Mediterranean landscape. Olive groves together with a few other crops (vines and durum wheat), have historically shaped the Mediterranean landscapes [16–18]. In the last decade, olive groves have faced a significant change in the Apulia Region (southern Italy) caused by the spread of *Xylella fastidiosa* subsp. pauca. It is one of the most dangerous phytopathogenic bacteria in the world, causing important agricultural, environmental, and social impacts [19]. This bacterium colonizes the xylem of trees, which blocks water and nutrient uptake, causing a fatal complex of symptoms that has been termed Olive Quick Decline Syndrome (OQDS [20]). It has led to the severe drying out of the branches and the rapid death of the olive trees, bringing the olive grove landscape to a serious crisis. This has caused a significant conversion from intensive agriculture to land abandonment, with consequences on landscape multifunctionality [21] and on the provision of landscape services [22,23]. This is because the agricultural olive-grove landscapes, when traditionally managed, have represented an important provider of several landscape services. These agricultural systems have been rainfed permanent crops with low intensity practices and with a low density (less than 150 trees per hectare) [24] of old or very old olive trees, with some plants over 1000 years old [25]. This landscape has provided several services in terms of biodiversity conservation, pest and disease control, soil formation and composition, and carbon storage [26–29], together with identity values and provisioning services, given by the production of table olives and olive oil [30]. Regarding the several landscape services, it is possible to list their support of biodiversity since this landscape contributes to the conservation of vegetation species such as Mediterranean orchids [31], considering their capacity to maintain herpetofauna [32], soil and tree canopy arthropods [33,34], and pollinators [15]. Traditional olive groves can support farmland birds and bats of high conservation concern and wintering bird communities, which cannot be sustained by the irrigated and intensively-managed olive groves [35–37]; this represents a simplification of landscape heterogeneity [38]. As forested areas, olive groves play a crucial role as terrestrial sinks of CO_2 [39] and in disturbance regulation, where the interplay of natural areas and permanent olive grove cultivations can act toward disturbance pattern regulation across spatial and temporal scales [40]. This is in line with the results of a study carried out in southern Spain, where the ecosystem services generated by the mountain olive groves have been assessed based on the opinion of 16 expert respondents. The results have shown that the experts mostly value the regulation role played by olive groves (41%), followed by socio-cultural value (30%) and food production (29%) [41]. Similar results have been presented in another study in Andalusia, where a high percentage of respondents valued mostly cultural and regulating services associated with olive groves [30]. In general, the traditional century-old olive groves can guarantee high socio-ecological benefits while maintaining the Mediterranean landscape and giving habitats to endangered species, which would be impacted by agricultural intensification [42].

Given the socio-ecological importance of olive grove landscape, this research aims at analyzing the following: (1) How the landscape multifunctionality supported by traditional olive groves has been affected by *Xylella fastidiosa* in terms of landscape service provision; (2) The effects of *Xylella fastidiosa* on the functional relations among the main Mediterranean land covers in terms of landscape service supply and demand; (3) The effects of *Xylella fastidiosa* on olive grove fragmentation at different spatial scales in order to identify possible recovery strategies of landscape multifunctionality and, thus, of landscape services.

2. Study Area

Given the extent and cultural importance of olive grove landscapes, the Apulia Region administration in southern Italy has introduced the Regional Law n. 14/2007 devoted to "The protection and valorization of the landscape of the monumental olive trees of Puglia". This demonstrates the importance given to this specific landscape with conservation measures to protect and valorize the century-old olive trees, even when isolated, for their ecological and hydrogeological role and as a crucial element of the history and culture of the traditional Mediterranean landscape. The study area is represented by the Salento peninsula in the Apulia Region (southern Italy), and it extends for 220,790 ha (Figure 1). It includes the provinces of Brindisi, Taranto, and Lecce, which have been the most affected by *Xylella fastidiosa* since 2013.

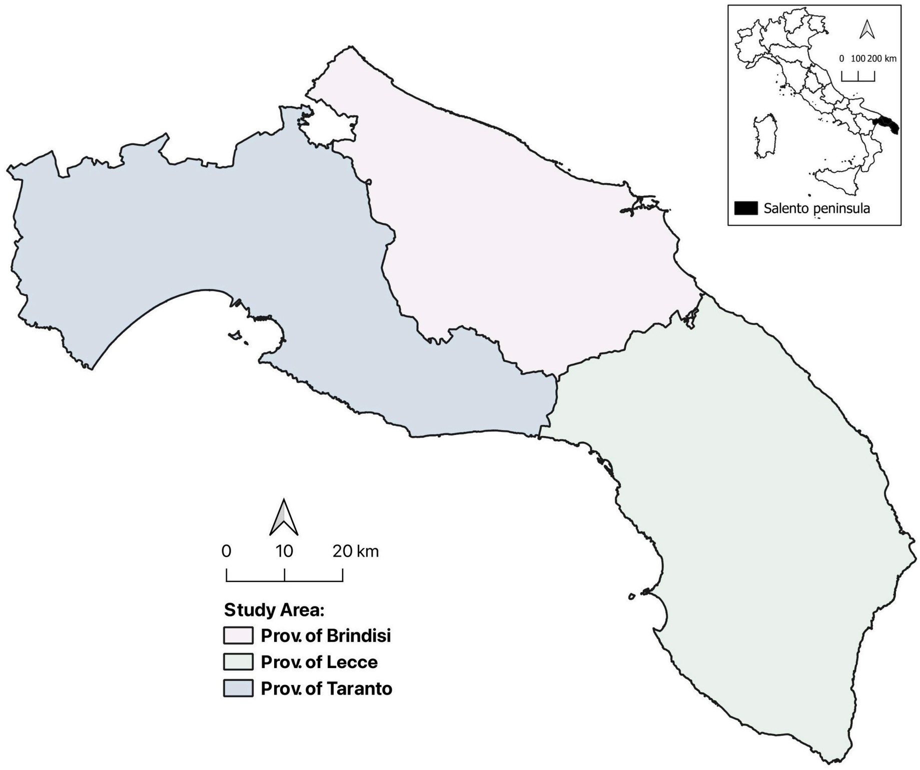

Figure 1. Study area represented by the Salento Peninsula in southern Italy, with the identification of the provinces of Brindisi, Lecce, and Taranto.

3. Materials and Methods

The methodology has been divided into 3 steps (Figure 2): (1) Updating land-cover maps in 2011 and in 2021; (2) Assessing the effects of *Xylella fastidiosa* on landscape service (LS) provision and on the functional relations among land covers acting as LS supply and LS demand; (3) Assessing the multiscale olive groves fragmentation to identify possible recovery strategies of landscape multifunctionality.

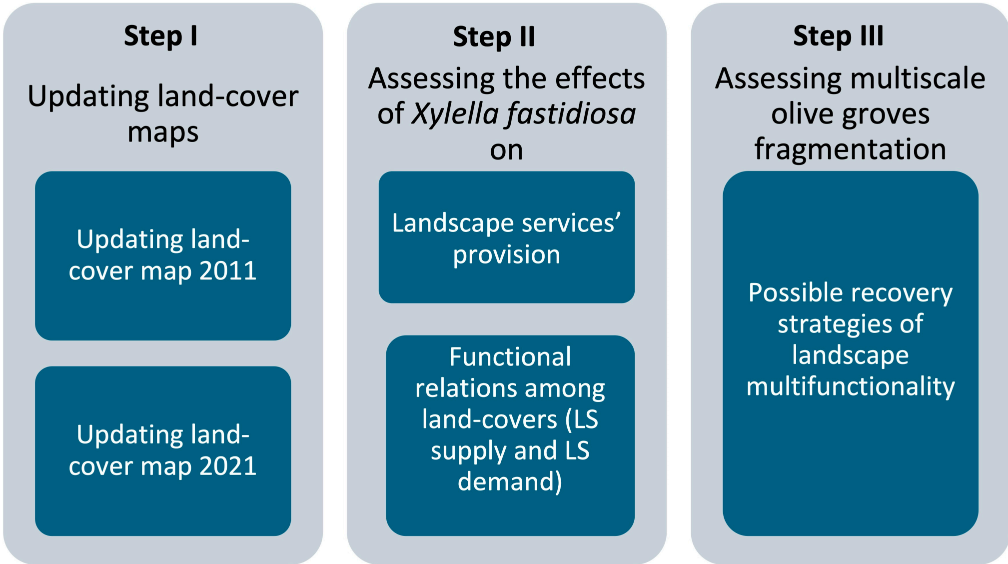

Figure 2. Flowchart of the methodology.

3.1. Methodology for Updating Land-Cover Map in 2011 and 2021

The land cover classes have been mapped in 2011 and in 2021. The mapping process in 2011 was carried out by simplifying the Corine land-cover map of the study area based on the ESA World Cover classification. In particular, the Corine land-cover map in 2011 was acquired from the Copernicus geo-database (https://land.copernicus.eu/en/products/corine-land-cover/clc-2012, accessed on 8 April 2024), which has a Minimum Mapping Unit (MMU) of 25 ha for areal elements. On the other side, the ESA land cover map of the study area in 2021 has been acquired from the ESA geo-database (https://worldcover2021.esa.int/, accessed on 8 April 2024) with 10 m resolution. The classification has been modified by including the "olive groves" class. Since an updated map of the olive trees that are actually still alive does not exist, the class "Tree cover" mapped by ESA in 2021 has been used since it includes different classes of forests and the residual olive groves. Therefore, through a topological elaboration in QGIS, it has been possible to extract what were still olive groves in 2021 from the class "Tree cover" by considering the map of olive groves in 2011. The homogenization of the classification has made both land-cover maps comparable and based on the following classes:

- **Tree cover and Shrublands**: areas dominated by trees with a cover of 10% or more and areas dominated by natural shrubs having a cover of 10% or more.
- Grasslands: areas dominated by herbaceous plants with coverage of 10% or more.
- Bare/sparse vegetation: areas with exposed soil, sand, or rocks and with vegetative cover never exceeding 10% at any time of the year.
- Permanent water body and herbaceous wetlands: areas covered for most of the year by water bodies and dominated by natural herbaceous.
- Croplands: areas covered by annual croplands, harvested at least once within the 12 months after the planting date.
- Olive groves: areas dominated by olive trees.

3.2. Methodology for Assessing Landscape Services and the Functional Relations Among Land Covers

The assessment of the role played by the different land covers in terms of supply and demand of five landscape services has been based on the methodology proposed by Burkhard et al. in 2009 and in 2012, which remains the most widely used on a European scale. In particular, landscape service supply is intended as the potential capacity of a particular area (land cover) to provide a landscape service within a specified period. On the other side, landscape service demand refers to the need for a specific landscape service by a particular area (land cover) over a given time [43]. In this sense, it is possible to define the relations among land covers: for instance, croplands need forested areas that are potentially able to support pollinators and need wetlands for their capacity to regulate water availability. The methodology has been divided into two subsequent steps:

1. The assessment of land cover potentiality in 2011 and in 2021 for providing five landscape services (LSs): pollination, water regulation, climate regulation, food provision, and recreation. The analysis was based on a literature review and linked the five LSs with the land covers characterizing the study area. The literature review was conducted in Scopus by analyzing the interaction between each of the seven land-cover classes (except for the built-up class) and each of the five LSs. According to the results, each land cover has been classified from low to high capacity to provide each of the five landscape services under study. The potential capacity to provide LS has been mapped through the software QGIS (https://www.qgis.org/, accessed on 10 October 2023), and it has been used as a first assessment of the role played by the land covers to act as LS supply.
2. The identification of the main functional interdependencies between land covers has been carried out by analyzing the LS demand based on a literature review that potentially links the seven land-cover classes to the needs of the five landscape services under study. The evaluation approach was based on Burkhard's methodology, which focused on the assessment of land cover needs for landscape services (LSs demand). Also, in this case, the potential demand for LSs has been carried out and mapped in 2011 and 2021 using QGIS software.

3.3. Assessing Landscape Fragmentation

Olive groves play a similar ecological role to forests in the Mediterranean landscape [39,40]. This land cover has been analyzed by using three landscape metrics at one single scale for the years 2011 and 2021, using Fragstats software version 4.2 [44]. The landscape metrics used in this study are NP (Number of Patch), MPA (Mean Patch Area), and DIVISION (landscape division index) [45]. In particular, the number of patches (NP) is equal to 1 if the landscape is made by one single land-cover patch [46]. Therefore, the higher the NP, the higher the landscape fragmentation [47]. MPA is used as a metric of fragmentation in a relative more than in an absolute sense since a landscape with a small MPA for a specific land-cover class can be considered more fragmented than a landscape with a higher MPA for the same land-cover class [48]. Finally, DIVISION is a metric that deals with landscape configuration, and it is based on the probability that two randomly selected pixels of a land cover are not included in the same land-cover patch. DIVISION is equal to 0 in the case the landscape is made by one single land-cover patch [46].

For the multiscale spatial analysis of fragmentation, the Guidos Toolbox 3.3, rev.2, (GTB) software [49] has been applied to the "Olive groves" class in 2011 and in 2021. This software provides an integrative framework for a set of generic digital image analysis schemes tailored to locate, measure, and map essential image patterns and object attributes in a universal and consistent manner. This software is useful for studying the spatial pattern of a specific phenomenon, also through a multiscale approach based on moving window routines [50], which allows us to quantify the aggregation and texture of the landscape, with particular reference to the class forests and olive groves analyzed together within the spatial context.

4. Results

4.1. Land-Cover Maps Before and After the Infection of Xylella fastidiosa

Figure 3 shows the maps of land covers in 2011 and 2021, where it is possible to underline how the grasslands (in yellow) became the dominant class in the southern part of the study area. The olive groves are represented by a few residuals, which are still asymptomatic patches and are concentrated mainly in the northern part of the study area in 2021. In comparison with the land-cover map in 2011, it is possible to highlight that olive groves (in green) and croplands (in pink) have been replaced by grasslands (in yellow) in 2021.

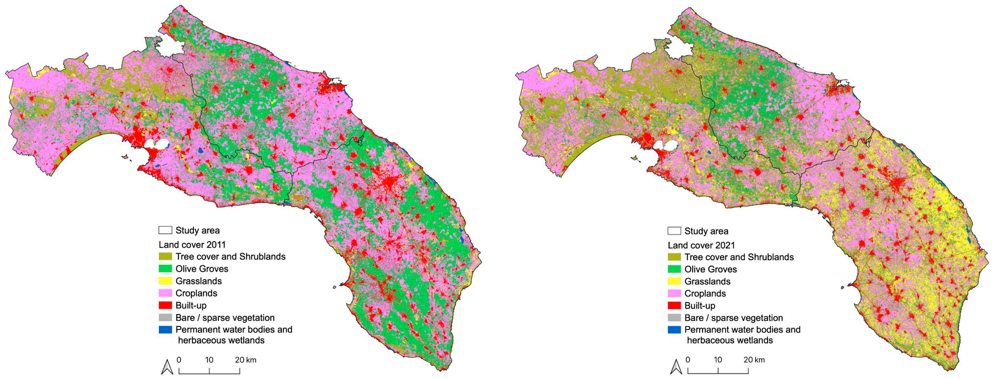

Figure 3. Land-cover maps in 2011 and 2021, before and after the spread of *Xylella fastidiosa*, respectively.

The landscape has completely changed; there is a strong fragmentation of those land covers that, in the past, have acted as stabilizing factors: croplands and olive groves. The main consequence of *Xylella fastidiosa* seems to be land abandonment, which affects not only olive grove productivity but also landscape stability. This causes altered relationships among land covers, which affects ecological processes like desertification, land availability, and gross primary production. This is evident by analyzing the results shown in the Sankey diagram (Figure 4), where it is possible to see how most of the olive groves in 2011 faced a strong conversion in grasslands and partially in croplands in 2021. At the same time, croplands have seen an abandonment, as shown by their transformation into grasslands. Only some of the olive groves have been characterized by some re-forestation through the implementation of recent agro-forestry projects.

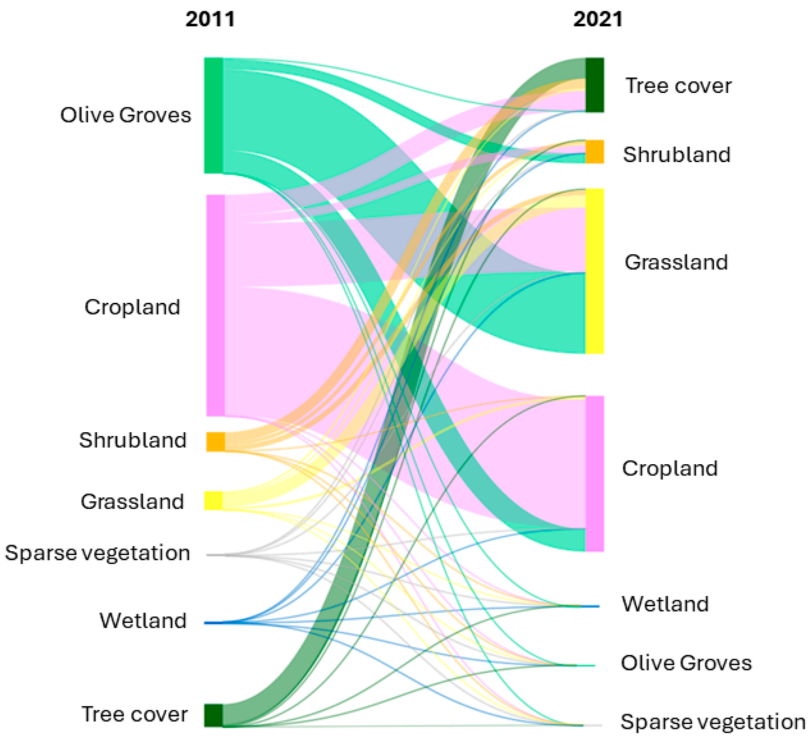

Figure 4. Sankey diagram of land-cover conversion from 2011 to 2021.

4.2. Landscape Services and Ecological Functional Relations Among Land Covers

A detailed analysis of the potentiality of land covers as landscape services suppliers or demanders has helped in disentangling the role of the new landscape configuration and identifying possible restoration measures to recover the past landscape capacity to provide services.

On the basis of a literature review, the five landscape services (pollination, water regulation, carbon sequestration, food production, and recreation) have been associated with the six land covers (Table 1).

Table 1. Results of the literature review linking the six land covers with the five landscape services under study.

Land Cover	Pollination	Water Regulation	Carbon Sequestration	Food Production	Recreation
Tree cover and Shrublands	[15,51–54]	[55–57]	[58–61]	[62,63]	[64–66]
Grasslands	[67–69]	[70–73]	[74–77]	[78–81]	[82–85]
Bare/sparse vegetation	[86–88]	[80,89,90]	[91,92]		
Permanent water body and herbaceous wetlands	[93,94]	[95,96]	[95,97,98]	[99–101]	[65,102–104]
Croplands	[105,106]	[107,108]	[109–112]	[113–115]	[116,117]
Olive groves	[15,117,118]	[26,36,42,119]	[39,119]	[26,42,120,121]	[30,42,115]

The methodology proposed by Burkhard et al. [43,122] has been applied to the land covers, with the exception of built-up class, and their potential capacity to provide landscape services has been analyzed and classified into 5 classes (0 = no supply, 1 = very low supply, 2 = low supply, 3 = medium supply, 4 = high supply, and 5 = very high supply) (Table 2). The literature review has allowed the recognition of the important role played by "Tree cover and shrublands" and "Olive groves" in carbon sequestration, water regulation, and recreational services. "Croplands" and "Olive groves" contribute strongly to food production service, while "Permanent water body and herbaceous wetlands" affects positively water regulation service.

Table 2. Evaluation matrix illustrating the potential capacity of land-cover classes to supply LS and ratings assigned, based on the literature review (Table 1) and based on the methodology presented by Burkhard et al. [43,122].

LULC Class	Pollination	Water Regulation	Carbon Sequestration	Food Provision	Recreation and Aesthetic Values
Tree cover and Shrublands	3	5	5	3	5
Grasslands	3	1	1	2	3
Bare/sparse vegetation	1	1	1	0	0
Permanent water body and herbaceous wetlands	1	5	4	1	3
Croplands	3	1	3	5	2
Olive groves	5	5	5	5	5

The same methodology has been used to classify the land covers in terms of ecosystem service demand into five classes (0 = no demand, 1 = very low demand, 2 = low demand, 3 = medium demand, 4 = high demand, 5 = very high demand) (Table 3). In particular, "Grasslands" and "Croplands" resulted in classes that need pollination and water regulation services.

Table 3. Evaluation matrix illustrating the demand for LS of different land-cover classes and ratings assigned, based on the literature review (Table 1) and based on the methodology presented by Burkhard et al. [43,122]).

Land Use/Cover Class	Pollination	Water Regulation	Carbon Sequestration	Food Provision	Recreation and Aesthetic Values
Tree cover and Shrublands	3	0	0	0	0
Grasslands	5	4	0	0	0
Bare/sparse vegetation	2	2	0	0	0
Permanent water body and herbaceous wetlands	3	0	0	0	0
Croplands	5	5	0	0	0
Olive groves	0	2	0	0	0

The total values of LS supply in 2011 and 2021 are shown in Figure 5a,b. It is possible to highlight how the high and very high capacity for providing landscape services was related only to smaller areas in 2021 compared to 2011 when such areas were distributed across the entire study area.

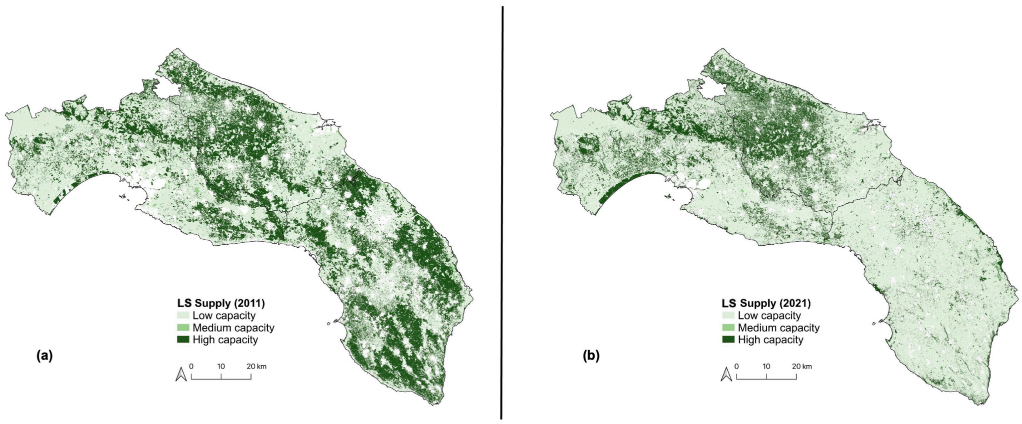

Figure 5. (**a**) Map of the total value of LS supply provided by the land-cover classes of the study area in 2011. (**b**) Map of the total value of LS supply provided by the land-cover classes of the study area in 2021 after *Xylella fastidiosa*.

In general, the land covers that contribute most to the LSs supply are the residual olive groves, tree covers and shrublands, and wetlands, which are mainly distributed in the northern part of the study area and along the coasts of the province of Lecce (Figure 5b). As shown in Table 2, bare/sparse vegetation is the land cover that has shown a very low capacity to supply LSs. Croplands, although uniformly distributed throughout the territory, have shown a medium capacity to provide LSs.

The distribution of LS demand potentially associated with the land covers has been mapped in 2011 (Figure 6a) and in 2021 (Figure 6b). It is possible to underline that the demand has increased from 2011 to 2021 in the areas characterized by the infection of *Xylella fastidiosa* because olive growth has seen a conversion in land covers with an increased demand for more services.

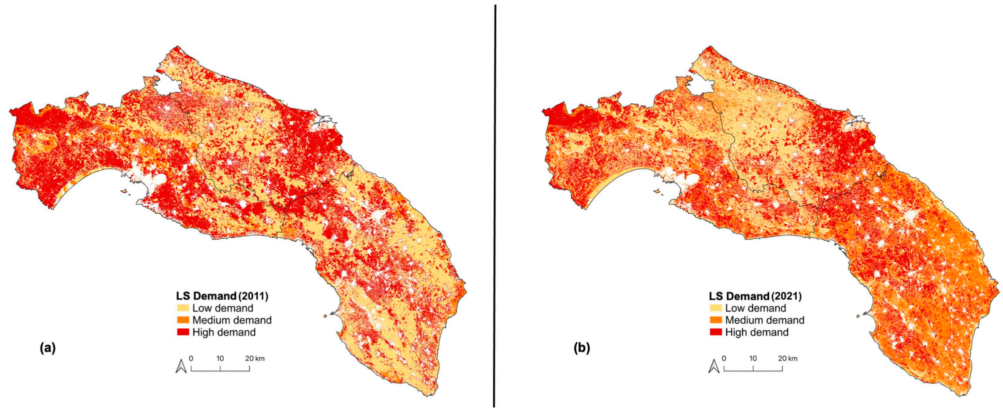

Figure 6. (**a**) Map of the total value of LSs demand for the land-cover classes of the study area in 2011. (**b**) Map of the total value of LSs demand for the land-cover classes of the study area in 2021 after *Xylella fastidiosa*.

4.3. Landscape Fragmentation Post-Xylella fastidiosa

The analysis of olive grove fragmentation at one spatial scale is shown in Table 4, where the landscape metrics for the years 2011 and 2021 have been analyzed in each province of the study area. It can be seen that the province of Lecce, which has been strongly affected by *Xylella fastidiosa*, shows the highest number of patches (NP) in 2021, with an increase higher than 70% in comparison with 2011, while Taranto is the least fragmented province but with an increase of about 60%. In the case of Brindisi, it is possible to highlight in 2021 an increase in the NP of about 80% and a decrease in the Mean Patch Area (MPA) of almost ten times lower than in 2011 (respectively 2.74 ha and 20.31 ha), but with the highest value in the study area. In the case of highly fragmented landscapes, DIVISION tends to 1, as in the case of the provinces of Taranto and Lecce in 2021. However, they have shown different past trajectories. In the case of Taranto, the province was characterized by a fragmented configuration also in 2011 (DIVISION equal to 0.98), and it was maintained in 2021 (DIVISION equal to 0.99). In the case of Lecce, its landscape configuration has seen an increase in spatial fragmentation, as shown by the increase in DIVISION from 0.88 to 0.99 (Table 4). On the contrary, the province of Brindisi has shown a less fragmented spatial configuration with the lowest values of DIVISION in 2011 and 2021.

Table 4. Landscape metrics applied to olive groves class in 2021 and 2011 in each province.

	Total Area (ha)	NP		MPA (ha)		DIVISION	
		2011	**2021**	**2011**	**2021**	**2011**	**2021**
Province of Lecce	275,933.5	6846	23,618	13.63	0.28	0.88	0.99
Province of Taranto	244,012.9	5114	11,885	5.22	1.03	0.98	0.99
Province of Brindisi	183,820.1	3543	16,196	20.31	2.74	0.72	0.82

Moving to the multiscale spatial analysis, we used the Foreground Area Density (FAD) in the Guidos toolbox to assess the olive grove landscape fragmentation at different spatial scales. This is a recent and commonly used metric to analyze landscape fragmentation, and it has been applied to the "Olive groves" land-cover class. Four different spatial scales characterized by a different extent (7 × 7, 13 × 13, 27 × 27, 81 × 81 pixels) have been used for the years 2011 and 2021. In each map, the resulting values have been divided into six classes (rare, patchy, transitional, dominant, interior, and intact) (Figure 7).

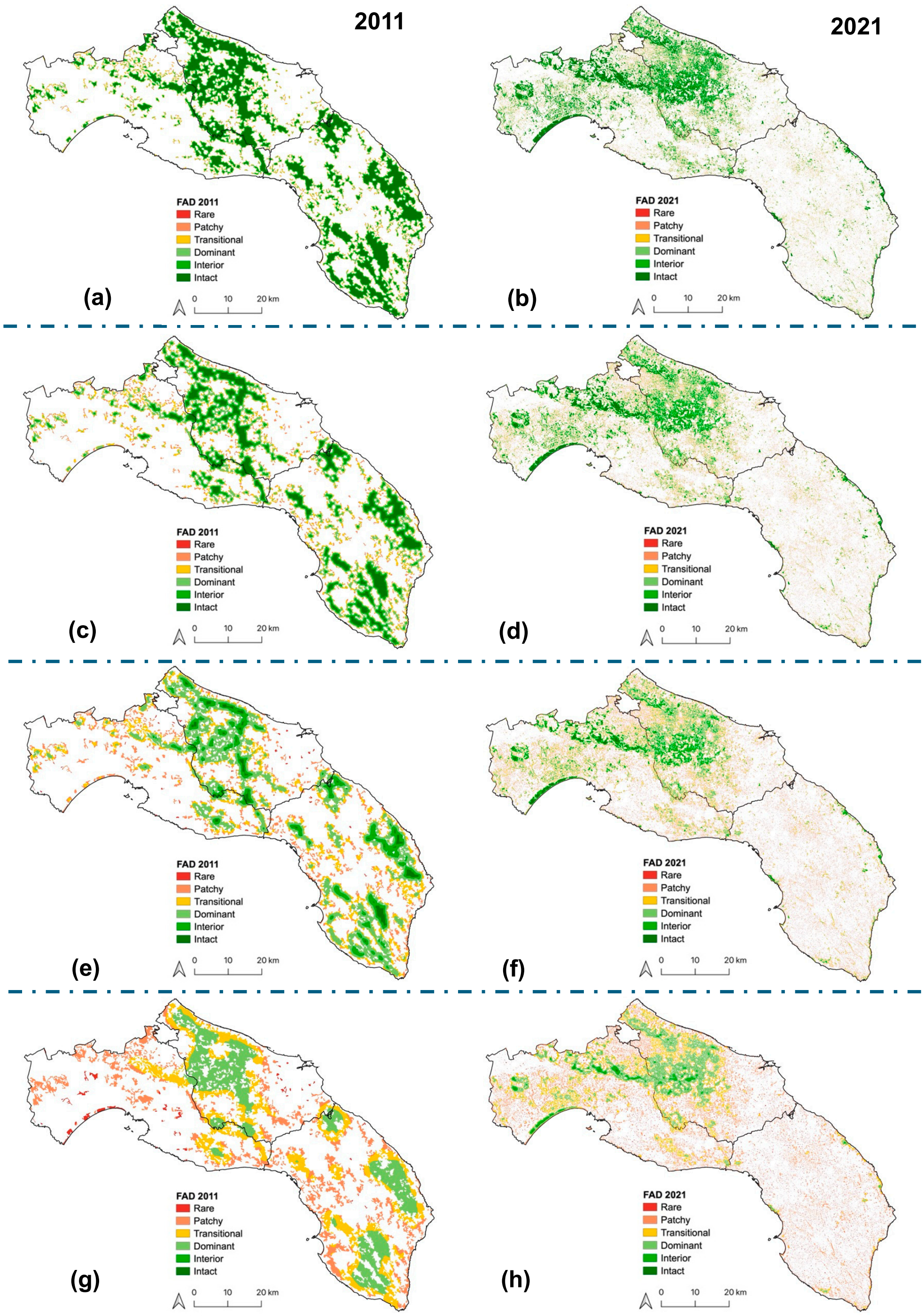

Figure 7. (**a**) Map of the foreground area density at the 7 × 7 pixels spatial scale in 2011. (**b**) Map of the foreground area density at the 7 × 7 pixels spatial scale in 2021. (**c**) Map of the foreground area density at the 13 × 13 pixels spatial scale in 2011. (**d**) Map of the foreground area density at the 13 × 13 pixels spatial scale in 2021. (**e**) Map of the foreground area density at the 27 × 27 pixels spatial scale in 2011. (**f**) Map of the foreground area density at the 27 × 27 pixels spatial scale in 2021. (**g**) Map of the foreground area density at the 81 × 81 pixels spatial scale in 2011. (**h**) Map of the foreground area density at the 81 × 81 pixels spatial scale in 2021.

This multiscale assessment of the "Olive groves" density can help in better analyzing the effect of its spatial configuration on the provision of landscape services and in identifying the right spatial scale for the provision of each landscape service. This is because these services are not provided homogeneously across a landscape, and they evolve naturally or are human-driven across space and time [123]. For instance, pollination service and food provision are local proximal landscape services; therefore, the most suitable spatial scales are 7 × 7 pixels and 13 × 13 pixels (Figure 7a–d). Carbon sequestration is a global service that should be analyzed at the highest spatial scale (81 × 81 pixels) (Figure 7g,h), while water regulation is a directional flow-related service with a suitable spatial scale given by 27 × 27 pixels (Figure 7e,f). Finally, there are services like recreation and aesthetic values that can be independent of the scale of the users. This means that in the analysis of LS provision, it is critical to study the landscape configuration at the right spatial scale for each specific service. Unfortunately, *Xylella fastidiosa* seems to have affected both local services like pollination and food production at small spatial scales and those based on processes at higher spatial scales like carbon sequestration and water regulation, with an across-scale effect. Finally, the evident landscape degradation has affected recreational services at all spatial scales.

5. Discussion

Landscapes have a certain capacity to provide services [124], based on the potentiality of specific land covers, but also depending on the landscape configuration. In this sense, analyzing the potentiality of different land-cover classes to provide landscape services without investigating their spatial configuration could give a partial vision of their real ecological role. The analysis of the landscape services provided by different land-cover classes in the provinces of Brindisi, Lecce, and Taranto shows that wetlands, tree cover, and olive groves are the land covers with the highest potentiality of providing pollination, water regulation, climate regulation, and recreation. On the other side, food provision can be mainly attributed to croplands and olive groves. The results of LS supply (Figure 5) is based on data derived from the recent literature review and show that all land-cover classes, both natural (tree cover, wetlands, grasslands, etc.) and semi-natural (some types of agricultural areas), have shown high capacities in supporting LSs supply.

In general, olive groves have played a very important role in the supply of all five analyzed LSs. Although olive tree flowers do not require insect pollination, their loss has indirectly impacted the provision of pollination services for other plant species that contribute to the overall landscape biodiversity. In a previous study, it has been estimated that pollination service has decreased by approximately 21% and 12% in the short and long term, respectively, since the *Xylella fastidiosa* outbreak [53]. The areas with tree cover, mostly represented in Salento by woodland ecosystems, provide a high supply of landscape services such as, for example, nesting habitats and floral resources for pollinators. In particular, forest and woodland margins and small plots adjacent to more open terrain are particularly important for insect activity in providing pollination service, especially in early spring months when alternative foraging resources are scarce [125]. Therefore, the presence of large-scale tree cover should be suitable for increasing the abundance of wild bees and improving pollination service for any nearby crops [126]. In the context of regulation services, forests also provide multiple water-related landscape services, including water supply, regulation of water flows, support of aquatic ecosystem function, and the provision of recreation [127].

The most recognized effect of *Xylella fastidiosa* is economical and focused on food production. However, it is possible to underline its crucial effect on the regulation of water, given the role played by olive groves against desertification. The landscape carbon sequestration capacity has seen a strong decrease from 2011 to 2021, and the reduced role played by olive groves in sustaining pollinators has affected the support of other landscape services, given that most part of agricultural products depend on pollinators [128]. Finally, olive groves have been part of the cultural process for a long period, thanks to their millennian presence in the landscape. This means that people and olive groves have shared the landscape for a long time, but this value has decreased after *Xylella fastidiosa*.

Land abandonment has been the most evident consequence of post-*Xylella fastidiosa*, resulting in the increase in grasslands, which are semi-natural habitats hosting high plant biodiversity [129,130]. As important habitats for wild bees, grasslands can contribute to supporting pollination in adjacent agricultural landscapes [67,131]. Within the agricultural landscape, asymptomatic olive trees can be considered as the remnants of the traditional Mediterranean olive groves, which have constituted a very traditional land use, highly recognized for its ecological, cultural, social, and economic values [132]. In particular, olive groves have shaped the rural landscape of the study area and given rise to cultivation techniques and products that have developed an important repertoire of immaterial knowledge (traditions, habits, legends) and materials (historical architectures, tools) [133]. In the study area, olive groves represent one of the main tree covers, and according to experts, the loss of these olive trees and their foliage due to the Xylella emergency has led to a series of negative effects on biodiversity. In particular, this land cover supports local diversity: up to 200 wild plant species, 90 vertebrate species, and 160 invertebrate species per hectare [134], and functional diversity when the turf under the trees is maintained [135]. Furthermore, the loss of ancient trees has led to a reduction in CO_2 sequestration, and it has also exposed the landscape to flood and fire risks because many farmers have abandoned their olive groves, and it is estimated that the capacity to regulate natural risks will decrease by around 30% in the short term and by a further 13% in the long term [136].

Croplands is the class that shows the highest LSs demand. All agricultural activities have high requirements for regulating and supporting services to guarantee provisioning services (i.e., food). On the other side, the most natural classes of land cover, such as tree cover and shrublands or wetlands, do not require the provision of LSs. For many landscape services, such as pollination, spatial relationships are likely to occur between providers (suitable habitats for pollinators) and users represented by areas that need the benefit of pollination (plants that require pollination) [137]. Multi-spatial scaling analyses provide the opportunity to investigate the land covers that serve as sources of pollinators along with their spatial configuration, which is an extremely crucial factor in managing the landscape to support proximal local services [138]. In this sense, services like pollination are affected by local landscape configuration in terms of spatial proximity between the land covers that support pollinators (source) and those that benefit from pollination (sink) [15]. However, it must be recognized that for many landscape services, the spatial localization and the clear definition of supplier-beneficiary relationships are difficult to identify as socio-ecological systems are complex systems and, therefore, there are almost never one-to-one relationships [139].

The analysis of landscape fragmentation caused by *Xylella fastidiosa* infection applied to the "Olive groves" class has highlighted the effects played by this pathogen on the whole agricultural-natural landscape configuration. The results of the landscape metrics in 2021, several years after the first signals of the infection, have supported the quantification of the fragmentation caused by *Xylella fastidiosa* at one single spatial scale. These results, together with those coming from the multiscale analysis of the landscape configuration, are the first examples of a new way to deal with the problems of *Xylella fastidiosa*. This new perspective has allowed us to recognize that *Xylella fastidiosa* is not only a socio-economic but also an ecological problem. This new perspective, based on the landscape configuration change after Xylella, can be the basis for new restoration strategies that can be set according to the most suitable spatial scales for the landscape services analyzed in this research.

6. Conclusions

Usually, landscapes are managed and changed by humans in response to a society's demand for landscape services. The conversion of land covers or land management change for enhancing a specific landscape service can directly or indirectly alter landscape functioning and the provision of other services through the generation of trade-offs among them.

This study has highlighted some important aspects related to the synergies and trade-offs among land-cover classes:

- The demand for landscape services is higher in human-dominated land-cover types, like croplands, while in other cases, the areas of supply and those of demand can overlap.

- Each service is scale-dependent, and it is affected by landscape configuration at its specific scale of action. For instance, pollination, which is a local service, is affected by local configurations and by the local functional flows among the sink and source of pollinators. Carbon sequestration or water regulation are services affected by landscape configuration at higher scales than pollination. To better focus landscape management on landscape service restoration, it is important to consider the most suitable spatial scale where managers should intervene. Broader landscape management for supporting the flow of landscape services, therefore, requires an understanding of how landscape processes occur across the different land covers that characterize an area. In the case of *Xylella fastidiosa*, the most suitable spatial scales for managers are the broad scale, which has a general overview of the phenomenon and its possible trends, and the local scale, which identifies specific actions useful to regenerate the ecological role of the landscape.
- It is essential to analyze LS flows to understand the ways in which their supply is maintained, while taking into account a landscape regeneration oriented toward the socio-economic–ecological recovery. In the case of cultivated lands, the problem, in fact, generally arises from a compromise between the provision of LS services, such as the production of food, fiber, or bioenergy and regulatory services such as water purification, soil conservation, carbon sequestration, biodiversity conservation, pollination, and services supporting cultural values. Consequently, only an in-depth spatial analysis of landscape services can support an understanding of the synergistic or trade-off interactions among them, their suitable scales, and the dynamics of their demand and supply. The collection of all these data can allow for the formulation of a sustainable management strategy toward landscape recovery.

The future research agenda should strengthen the integration of landscape services into restoration environmental policies for resolving different landscape degradation issues (i.e., land degradation, land-take, and desertification). The mapping of land covers from the perspective of providers and users of landscape services plays a crucial role in understanding their spatial and temporal dynamics, as well as in enabling planning decisions and policies for the conservation and sustainable use of natural resources.

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