



Condition of linear landscape elements improves with contiguity to protected habitats: Empirical evidence useful for agroecosystem accounting and restoration

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ABSTRACT

In Mediterranean Europe, both intensification and abandonment of traditional cultural practices represent main drivers for the loss of natural and semi-natural elements in agricultural settings. Once common in rural landscapes, these habitats have to be conserved or restored to ensure resilience and resistance of agroecosystems against biodiversity loss and socio-ecological changes. In particular, linear landscape elements (LE) fall among the high-biodiversity landscape features that require to be increased in agricultural lands to facilitate species mobility and provide a wide range of ecosystem services. However, within the framework of environmental accounting procedures, there is still a need for a thorough methodology to assess conditions of LE and, subsequently, of the hosting agroecosystems. The present research is therefore aimed at (i) proposing a method for a thorough assessment of LE conditions, with a special focus on biodiversity support capacity, (ii) investigating the potential effect of extrinsic determinants on LE conditions, such as contiguity to protected habitats and governance framework, and (iii) identifying useful parameters to guide LE ecological restoration actions. Based on different structural, compositional and landscape indicators, the proposed assessment method was tested in eight administrative units of two Mediterranean Europe countries. In the study sites, favorable LE conditions were found to be strongly associated with contiguity to protected habitats, by showing marked structural continuity, dominance of trees, active dynamics, and good quality of the surrounding landscape mosaic. Potential applications of the results have been finally explored in both ecosystem accounting and ecological restoration processes.

1. Introduction

Along with urbanization processes, intensification of agriculture and abandonment of traditional agricultural practices represent the main drivers of conversion and fragmentation of natural and semi-natural ecosystems (Brondizio et al., 2019, Habel et al., 2019, Donald et al., 2006, Plieninger et al., 2006). The progressive intensification of cultural practices has resulted in increased landscape homogenization in the European Union (EU) (Caraveli, 2000, Estreguil et al., 2013), where agricultural areas already occupy nearly 40 % of the total land (Eurostat, 2023). This is reflected in the loss of natural and semi-natural elements that were once common in traditional rural landscapes (Arnáiz-Schmitz et al., 2018, Vannucci et al., 2022), as well as in the widespread erosion

of biological diversity and impairment of ecosystem services provided by arable lands (Garbach et al., 2014, Swinton et al., 2007, Tilman et al., 2001). Overall, the decrease in ecological connectivity (Bolliger and Silbernagel, 2020, Fischer and Lindenmayer, 2007), due to habitat fragmentation and disappearance of connecting elements, increases the risk of species extinction more than habitat loss alone (Anderson et al., 2022, Brook et al., 2008, Lindenmayer and Fischer, 2006, Van Geert et al., 2010). In terms of ecological processes and species dispersal, connectivity is a crucial landscape property to maintain for the improvement of biodiversity and ability to provide ecosystem services in the face of habitat fragmentation (Baguette et al., 2013, Honeck et al., 2020, Zeller et al., 2020, Zhang et al., 2019).

Recently, in both green infrastructure and ecological network

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planning, there has been a growing interest in the remaining natural and semi-natural components, such as linear landscape elements (LE), which can effectively assist species mobility, especially in highly fragmented contexts (Ahmed et al., 2021, Chardon et al., 2003, Thiele et al., 2018, Valeri et al., 2021). Defined as “linear features composed of shrubs and/or trees that form part of a management unit” (Baudry et al., 2000), LE historically served primarily as shelter, field fence, source of firewood and protection from wind and erosion (Van Der Zanden et al., 2013). In addition to the provision of a wide range of ecosystem services (García de León et al., 2021, Montgomery et al., 2020, Verhagen et al., 2018), LE networks today are known to enhance structural and functional connectivity (Valeri et al., 2021), provide a suitable habitat for pollinators and multiple small mammals (Capotorti et al., 2023, Dainese et al., 2016, Gelling et al., 2007, Morandin and Kremen, 2013), improve crop productivity and sustainability (Holland, 2019, Marshall and Moonen, 2002, Morandin et al., 2016) and enhance the ability of agriculture systems to mitigate and adapt to climate change (Hernández-Morcillo et al., 2018). Given their multifunctionality, these woody elements have thus been considered key points of the European strategies and guidelines aimed at protecting biodiversity (EC, 2020, EC, 2023a), improving coherence of the EU Natura2000 (N2K) network (EC, 2022a), enhancing sustainability of agriculture (Batáry et al., 2015) and assessing/restoring agroecosystem structural status (EC, 2022b, Vallecillo et al., 2022, Valeri and Capotorti, 2023). Nevertheless, despite the recognized high ecological and cultural values (Burel and Baudry, 1995, Schmitz et al., 2007, Schmitz et al., 2017a), LE are currently threatened by abandonment and removal (Arnaiz-Schmitz et al., 2018, Vannucci et al., 2022), with subsequent impairment of agricultural systems resilience (Bommarco et al., 2013, Sanchez et al., 2010), loss of habitats, and cultural heritage degradation (Schmitz et al., 2017a and 2017b).

Thus, in the framework of restoration ecology, LE (e.g. hedgerows, tree rows, buffer strips, ditches, etc.) fall among the high-biodiversity landscape features that are required to be increased in agricultural lands (EC, 2020, EC, 2022b). However, especially in the Mediterranean EU, there is still a need for a thorough fine-scale methodology to assess LE conditions, suitable to effectively improve the conservation status of the hosting agroecosystems and support environmental accounting processes (Grondard et al., 2021).

In addition, it is unclear which attributes of the existing LE should be especially assessed in order to steer their recovery towards favorable structural and functional states. As a matter of fact, it is challenging to pinpoint a reference status to be reached by means of restoration actions for these landscape components (Palmer et al., 2016). A feasible approach could be to refer LE conditions to an increased capacity to support key wild species as hosting habitats and dispersal corridors (Wehling and Diekmann, 2009, Valeri et al., 2021, Carlier and Moran, 2019, Closset-Kopp et al., 2016, Graham et al., 2018).

Key species to be considered should at least comprehend those that are coherent with local Potential Natural Vegetation (PNV) (Farris et al., 2010, Capotorti et al., 2019, Valeri et al., 2021), that is the vegetation that would develop in a specific habitat if human impact on the site suddenly ceased and the mature stage was attained (Tüxen, 1958). Actually, plants that are characteristic of the local PNV are crucial to landscape resilience, as they can actively contribute to boost native biodiversity, prevent biological invasions, facilitate ecological coherence of management measures and improve restoration success (Capotorti et al., 2020).

Concomitantly, pollinators must also be given special consideration in agricultural contexts. They represent key ecosystem components that, notwithstanding the fundamental role in agricultural production and ecosystem functions (Bartholomé and Lavorel, 2019), are facing a worldwide alarming decline (EC, 2023a) due to intensive agricultural practices, pollution and reduced availability of wild plants (Garratt et al., 2017, Kral-O'Brien et al., 2021, Phillips et al., 2019, Schubert et al., 2022).

Overall, it has already been shown that the potential of LE to support

biodiversity increases with woodland proximity and contiguity (Castle et al., 2019, Gelling et al., 2007, Lenoir et al., 2019, Mony et al., 2022), but there is still little evidence about the eventual effect of both contiguity to protected habitats and different governance frameworks.

Considering these knowledge gaps, the present research is aimed at (i) proposing a thorough and replicable methodology for assessing LE conditions, with an emphasis on their capacity to support PNV-characteristic species and pollinators, (ii) testing the influence of extrinsic determinants on LE conditions, such as the contiguity to protected habitats (namely, N2K sites designated under the EU Habitats 92/43/EEC and Birds 2009/147/EC Directives; EC, 1992 and 2009) and the governance framework (country effect), and (iii) identifying useful parameters to guide LE ecological restoration actions.

2. Methods

2.1. Study area

The research was conducted in the Mediterranean EU, in eight level 3 Territorial Units for Statistics (NUTS3) belonging to Italy and Spain (Eurostat, 2021). Four NUTS3 per country were selected according to latitudinal and phytoclimatic gradients, ranging from subxeric temperate to subhumid temperate in Italy, and from subxeric temperate to semiarid temperate in Spain (Botti, 2018) (Fig. 1).

The selected NUTS3 (Table S1) are quite representative of varied land cover mosaics (EEA, 2019a), with different densities of small and additional woody features in agricultural settings (EEA, 2019b) and respective structural status of arable lands (Valeri and Capotorti, 2023, Vallecillo et al., 2022). The latter ranges between unfavorable in Palencia and Segovia, to adequate in Rome, Latina and Madrid, and to favorable in Jaén.

2.2. Selection of focal LE to be investigated

Focal LE to be investigated and assessed were selected by stratifying, in a GIS environment (Quantum GIS 3.28.2), residual woody elements retrieved from the Small Woody Features High-Resolution Layer product (SWF-HRL, EEA, 2019b), agricultural land cover (EEA, 2019a) and the N2K network (EEA, 2021). First, only SWF falling within agricultural areas were considered. Next, as the SWF-HRL raster layer embraces different types of elements (linear, patchy and additional), focal LE were further filtered according to a set of structural features, such as a minimum length of 20 m, a width between 3 and 30 m and structural gaps not exceeding 10 m (Roy and de Blois, 2006). The end points of LE were put at the intersection with other linear elements (including roads) or with areal land cover patches, or where a gap longer than 10 m was found. Finally, also considering the accessibility of the sites, a total of 80 LE was selected. In particular, 20 contiguous and 20 not contiguous LE to a protected habitat were selected both in Italy and Spain, and equally distributed among the eight NUTS3. A LE was considered contiguous to a protected habitat if completely adjoined to, or less than 10 m away from, a wooded N2K patch.

2.3. Research design

The research was performed by combining evidence from field surveys with spatial and statistical analyses in a multistep methodological process (Fig. 2).

First, a set of relevant structural, landscape and compositional indicators were collected, calculated and scored for the assessment of LE conditions by combining field surveys and GIS analyses. The assessments, useful for informing agroecosystem accounting processes, were thus validated by means of Spearman correlations with other biodiversity indicators (see Section 2.3.1).

Second, LE were functionally characterized, using bioindicators *sensu* Ellenberg (1974) weighted on the frequency of physiognomic

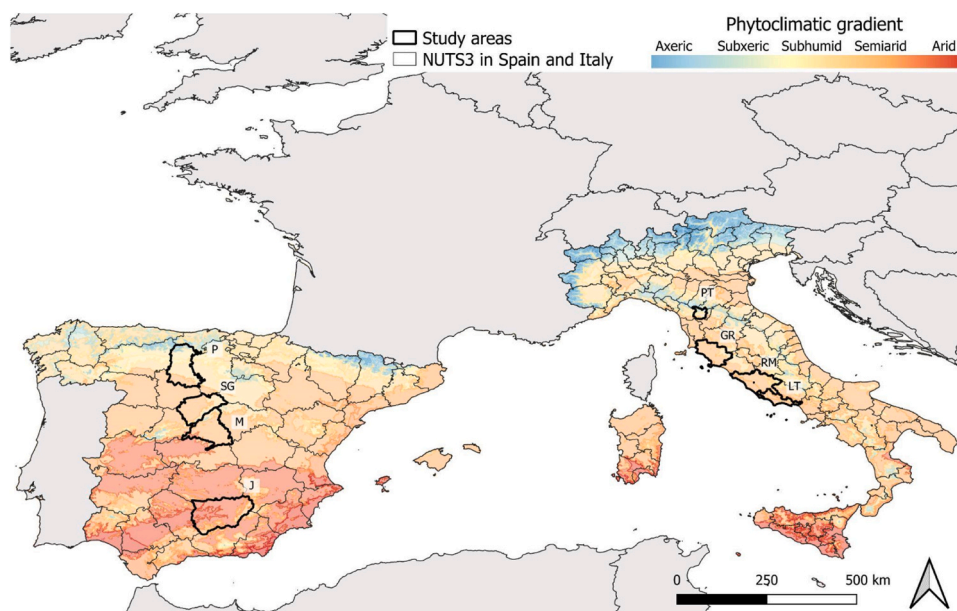


Fig. 1. Study areas selected according to latitudinal and phytoclimatic gradient. From north to south: Palencia (P) (8051 km²), Segovia (SG) (6924 km²), Madrid (M) (8029 km²) and Jaén (J) (13496 km²) NUTS3 in Spain; Pistoia (PT) (964 km²), Grosseto (GR) (4500 km²), Rome (RM) (5351 km²) and Latina (LT) (2246 km²) NUTS3 in Italy.

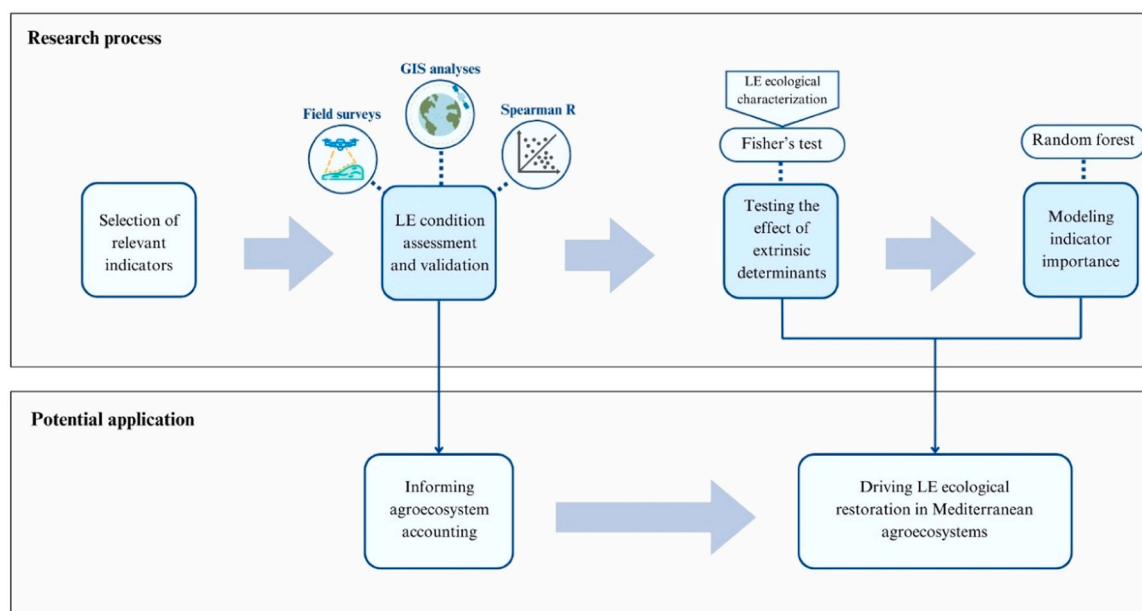


Fig. 2. Flowchart of the applied multistep methodological process.

species, to ensure that overly marked ecological differences would not confuse the subsequent tests. Once the ecological affinity among LE was verified, a Fisher's exact test was conducted to evaluate the potential effect of contiguity to a protected habitat (N2K patch) and of the governance framework (country of belonging), as extrinsic determinants for LE conditions (Section 2.3.2).

Third, only for the extrinsic determinants that resulted significant, a Random Forest classification was carried out to identify the most important condition indicators that are suitable for guiding efficient ecological LE restoration actions (Section 2.3.3).

2.3.1. Assessment of LE conditions

LE conditions were assessed according to a set of structural,

landscape and compositional indicators particularly related to the LE capacity to support local biodiversity in terms of PNV-characteristic species and pollinators. Namely, 17 indicators suitable for assessing the condition of LE under a strict ecological perspective were selected and reported to four main typologies (Table 1): i) Structure and continuity, ii) Surrounding landscape context, iii) Ecotone structures and dynamics and iv) Specific composition.

Fourteen indicators were mainly assessed through the field campaign, and the other three exclusively in a GIS environment (indicators a, b and g in Table 1).

Field surveys were conducted in 2022 and 2023, from March to October, to collect data on composition, structure, spatial contacts and dynamics of each selected LE (Fig. 3). Plant species that

Table 1

Selected 17 condition indicators and their respective rationale, calculation and scoring criteria.

Indicator (abbreviation)	Rationale, calculation and relevant references	Value	Score
Structure and continuity			
a) Width	<u>Rationale:</u> capacity to support biodiversity depends on LE width <u>Calculation:</u> average width measured at four points at least 30 m apart <u>Relevant references:</u> Deckers et al., (2004), Defra, (2007), Litza et al., (2022)	N/A < 5 m 5–15 m 15–30 m	0 1 2 3
b) Length	<u>Rationale:</u> capacity to support biodiversity depends on LE length <u>Calculation:</u> length measured from one end of the LE to the other <u>Relevant references:</u> Gelling et al., (2007), Graham et al., (2018)	N/A < 150 m 150–300 m > 300 m	0 1 2 3
c) Structural complexity (Str_comp)	<u>Rationale:</u> suitability to support plant dispersal and animal mobility increases with structural complexity of vegetation corridors <u>Calculation:</u> qualitative ranking from less suitable (relict tree lines associated with high levels of disturbance), to intermediate suitable (solitary but dense shrub corridors) and more suitable (mixed shrub-tree corridors with at least 50 % of tree cover) vegetation structures <u>Relevant references:</u> Baudry, 2000, Staley et al., (2012), Wehling and Diekmann, (2009)	N/A relict line of trees dense shrubby shrubby-tree	0 1 2 3
d) Proportion of gaps (%_gaps)	<u>Rationale:</u> structural discontinuities in woody LE negatively affect the capacity to support biodiversity <u>Calculation:</u> proportion of total gap length (minimum 1 m of shrub-tree cover lack) with respect to the total LE length <u>Relevant references:</u> Deckers et al., (2004), Dondina et al., (2018), Feber et al., (2019), Foulkes et al., (2013), Garrat et al., (2017), Gelling et al., (2007)	> 5 % 2–5 % < 2 % 0 %	0 1 2 3
e) Individual gap (Ind_gap)	<u>Rationale:</u> LE biodiversity support capacity is affected by long individual gaps in shrub-tree cover <u>Calculation:</u> length of the longest gap (in meters) <u>Relevant references:</u> Deckers et al., (2004), Dondina et al. (2018), Feber et al., (2019), Foulkes et al., (2013), Garrat et al., 2017, Gelling et al., (2007), Staley et al., (2023)	> 5 m 3–5 m < 3 m no gaps	0 1 2 3
Indicator (abbreviation)	Rationale, calculation and relevant references	Value	Score
Surrounding landscape context			
f) Contacts - sides a and b	<u>Rationale:</u> direct effects of anthropogenic disturbance on LE increase with adjacent land use intensity <u>Calculation:</u> qualitative ranking from more intense (artificial) to less intense (grassland) land use, on both sides (to be summed) <u>Relevant references:</u> Closset-Kopp et al., (2016), Deckers et al., (2004), Kremen et al., (2019), Wilson, 2019, Litza et al., (2022)	artificial permanently irrigated arable land extensive arable land or permanent crop grassland	0 1 2 3
g) Proportion of artificial cover (%_art_cover)	<u>Rationale:</u> susceptibility to pollution and alien plant invasion increases with artificial surfaces in the surrounding landscape mosaic <u>Calculation:</u> proportion of artificial surfaces within a radius of 250 m from the LE centroid <u>Relevant references:</u> Boscutti et al., (2022), Kumar et al., (2006)	> 10 % and adjacent > 10 % or < 10 % and adjacent 5–10 % < 5 %	0 1 2 3
Ecotone structures and dynamics			
h) Grassy edge occurrence (Edge)	<u>Rationale:</u> grassy edges mitigate disturbances caused by direct contact with intensive land uses <u>Calculation:</u> presence/absence and continuity of undisturbed grass margin on both sides (contact with a grassland is assimilated to a “one side continuous” edge). <u>Relevant references:</u> Defra, (2007), Foulkes et al., (2013)	absent one side (discontinuous) one side (continuous) or both side (discontinuous) both sides (continuous)	0 1 2 3
i) Grassy edge width (Edge_ext)	<u>Rationale:</u> mitigation of negative edge effect increases with the width of grassy strips along LE <u>Calculation:</u> average width measured at four points at least 30 m apart (contact with grasslands is assimilated to a 2–3 m average width). <u>Relevant references:</u> Defra, (2007), Foulkes et al., (2013)	absent or < 1 1–2 m 2–3 m > 3 m	0 1 2 3
j) Tall grassy fringe occurrence (Fringe)	<u>Rationale:</u> tall grassy fringes act as additional buffers in mitigating disturbances from adjacent intensive land uses and are indicative of a more complex structure <u>Calculation:</u> presence or absence of a more or less continuous fringe of tall herbs on both LE sides <u>Relevant references:</u> Defra, (2007), Foulkes et al., (2013), Poldini and Sbrulino, (2005)	absent one side (discontinuous) one side (continuous) or both side (discontinuous) both sides (continuous)	0 1 2 3
k) Woody plant juveniles (Juveniles)	<u>Rationale:</u> plant juveniles testify LE viability <u>Calculation:</u> presence and relative abundance (according to the Braun-Blanquet cover-abundance scale: 'low value' = 'r', 'medium value' = '+', 'high value' = '1') of juveniles for the woody species that are characteristic of local mature vegetation stages <u>Relevant references:</u> Westhoff and Van Der Maarel, 1978, Rubio-Bretón et al. (2012)	absents low medium high	0 1 2 3
l) Nucleation phenomena (Nucleation)	<u>Rationale:</u> nucleation is a progressive successional process determined by local scale dynamics, with LE potentially acting as seed sources <u>Calculation:</u> abundance (number equal or more than two individuals) of young specimens of native woody species within 2 m from the LE edge, on both sides <u>Relevant references:</u> Forget et al., (2013), Michaels et al. (2020), Rey Benayas and Bullock, (2015)	absent one side (no more than two) one side (more than two) both sides	0 1 2 3
Indicator (abbreviation)	Rationale, calculation and relevant references	Value	Score
Specific composition			
m) Cover-abundance of allochthonous species (Alien)	<u>Rationale:</u> a high proportion of allochthonous physiognomic species indicates high levels of disturbance <u>Calculation:</u> relative cover-abundance of allochthonous physiognomic species (except for non-invasive archaeophytes) <u>Relevant references:</u> Defra, (2007), Staley et al., (2023)	> 30 % 15–30 % 5–15 % < 5 %	0 1 2 3
n) Coherence with local Potential Natural Vegetation (PNV)	<u>Rationale:</u> PNV represents a reference ecological baseline, and the abundance of PNV-coherent species provides information on LE health and capacity to support local mature vegetation stages <u>Calculation:</u> relative cover-abundance of diagnostic, abundant and frequent physiognomic species of the local PNV types <u>Relevant references:</u> Capotorti et al., (2020), Farris et al., (2010)	N/A < 30 % 30–60 % > 60 %	0 1 2 3

(continued on next page)

Table 1 (continued)

Indicator (abbreviation)	Rationale, calculation and relevant references	Value	Score
o) Cover-abundance of phanerophytes scapose species (Pscap)	Rationale: a dense and dominant tree structure is associated with an overall better LE quality/significance	N/A	0
	Calculation: relative cover-abundance of physiognomic species with a phanerophyte scapose biological form (a relict tree structure is assimilated to a “< 30 %” cover-abundance)	< 30 %	1
	Relevant references: Staley et al., (2012), Wehling and Diekmann, (2009)	30–60 %	2
		> 60 %	3
p) Cover-abundance of species with apiarian interest (Apiarian)	Rationale: wild plant species with apiarian interest (i.e. providing pollen and nectar) can be considered a proxy for the LE capacity to support pollinators as foraging habitats	N/A	0
	Calculation: relative cover-abundance of physiognomic species with apiarian interest in terms of pollen and nectar importance.	< 60 %	1
		60–90 %	2
		> 90 %	3
q) Number of ruderal dominant herbs (Ruderal)	Rationale: herbaceous ruderal species represent biological indicators of anthropogenic disturbance	three or more species	0
	Calculation: number of dominant herbs (with relative cover-abundance > 50 %) that are considered ruderal according to: i) habitat type of occurrence, ii) reproduction strategy, iii) reference syntaxonomic alliance for the hosting plant communities, and iv) nitrophily (proxy for soil eutrophication).	two species	1
		one species	2
		absent	3
	Relevant references: Bartholomée and Lavorel, (2019), Garatt et al., (2017), Kallioniemi et al., (2017), Kremen et al., (2019)		
	Relevant references: Franzaring et al., (2007), Foulkes et al., (2013), Grime, (1988), Keith et al., (2020)		

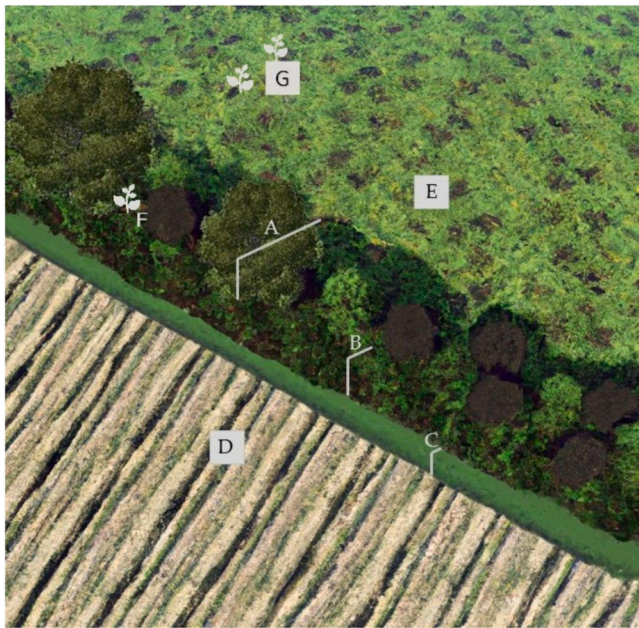


Fig. 3. Example of sampled LE features: A) Shrubby-tree structure, B) Tall grassy fringe, C) Grassy edge, D) and E) Adjacent land cover types along the two LE sides, F) and G) Dynamics in terms of juveniles and nucleation phenomena.

physiognomically characterize LE were listed, including all phanerophytes, helophytes and pteridophytes. Dominant herbaceous species along the edge between the LE and adjoining land cover patches were annotated as well (Foulkes et al., 2013).

A cover-abundance value was therefore assigned to each plant taxon according to the Braun-Blanquet scale (Dengler et al., 2008, Westhoff and van der Maarel, 1973). The nomenclature of plant taxa follows the Euro+Med PlantBase database (Euro+Med, 2006).

When a LE could not be directly accessed, samples were supplemented with photogrammetric surveys using a UAS (DJI Mini2 drone) (Bertacchi et al., 2019, Librán-Embí et al., 2020). The drone was flown at a height between 10 and 25 m and the multi-shot mode was set to an interval of 2 s. The photos (resolution: 4000 × 2250 px) were recorded on a micro-SD card and later interpreted by expert botanists for species identification. Moreover, to investigate the landscape context, the flight height was set between 25 and 60 m with 4 K video quality.

For the assessment of all indicators, direct field and GIS observations were complemented with other basic data including: land cover/land use raster product at 10×10 m spatial resolution (ISPRA, 2022), for indicator g; Spanish and Italian lists of alien vascular flora (Elorza et al., 2004, Galasso et al., 2018), for indicator m; map of the vegetation series

of Italy (Blasi, 2010) and Spain (Rivas-Martínez, 1987), for indicator n; national and regional floras of apiarian interest (e.g. Ricciardelli D’Albore and Oddo, 1978, Talavera et al., 1988), for indicator p; ecological characterization of reference vegetation communities (Biondi et al., 2014, Rivas-Martínez, 1987), strategy type according to Grime (Kattge et al., 2020), and nitrophily of occurring vascular plants (Dengler et al., 2023, Pignatti, 2005), for indicator q. Each of the 17 indicators was therefore scored, on a scale of 0–3, according to either quantitative thresholds or qualitative categories with respect to the expected impact on valuable local biodiversity, based on authors’ expertise and available scientific evidence. Subsequently, individual indicators’ scores were added up to obtain an aggregated condition value for each LE, further categorized according to natural breaks (Jenks, 1967).

In order to test differences in LE species richness between the two countries, the nonparametric Mann-Whitney U test was conducted in XLSTAT software (version 2022.2.1) (Addinsoft, 2023). The significance level was set at $p \leq 0.05$ and, as recommended for count data, species richness was preliminarily square root transformed (Mandonald and Braun, 2006).

To validate LE condition assessments, two additional features were considered: the richness of woody species, which is expected to be positively correlated with potential pollinator support (Garratt et al., 2017, Eeraerts et al., 2021, Kral-O’Brien et al., 2021), and the cover-abundance of the characteristic species of the reference PNV (Capotorti et al., 2015, Poldini and Sburlino, 2005), which is expected to aid in the dispersal of plant species that are typical of mature vegetation communities (Capotorti et al., 2020, Valeri et al., 2021). By varying according to climate, lithology and morphology, PNV allows the unique ecological characteristics and biodiversity potential of each site to be accurately reflected. Namely, different species of the genera *Populus* (poplars) and *Salix* (willows) were considered characteristic for the hygrophilous PNV type, and different species of the genus *Quercus* (oaks) for all the other PNV types. These additional features were correlated with the aggregated LE condition values by means of the Spearman correlation (Spearman, 1904). The level of significance was set at $p \leq 0.05$, and the greater the strength of the correlation the greater the validating potential was assumed (Döring and Bortz, 2016).

2.3.2. Testing the effect of protected habitat contiguity and governance framework on LE conditions

LE were functionally characterized in ecological terms by means of bioindicators (Pignatti, 2005, Dengler et al., 2023), to ensure that overly marked ecological differences would not confuse the investigation on external factor effect. Indicators for light, temperature, continentality, soil moisture, soil reaction (pH) and nutrients were weighted on the frequency of physiognomic species and graphically represented by N2K-link status (contiguous and not contiguous) and by country (Spain and Italy).

Subsequently, in order to test the potential effect of protected habitat

contiguity and governance frameworks on LE conditions, a Fisher's exact test (Fisher, 1932) was carried out on the contingency tables showing the frequencies of the condition classes by N2K-link status and by country, respectively. In detail, the null hypotheses (H_0) were: i) LE conditions and LE N2K-link status are independent, ii) LE conditions and governance framework are independent. Consequently, the alternative hypotheses (H_a) claim that there is a dependency between the variables.

The level of significance was set at $p \leq 0.05$ and the strength of the associations was assessed by means of Cramer's V statistics (Cramer, 1946).

2.3.3. Modeling indicator importance

By means of XLSTAT software, a Random Forest classification was carried out only for the extrinsic determinants significantly associated with LE conditions.

Random Forest is a machine learning-based method that inherently accounts for random variability and interactions between predictors (Breiman, 2001), making it well-suited for exploring interactions between nonlinear data, such as the ecological ones (Bardino et al., 2023, Knudby et al., 2010). It can predict both continuous and categorical dependent variables using decision trees and improved bagging and bootstrap algorithms (Yang et al., 2010). The extrinsic determinant was set as a response variable, and the categorical values (scores) of the individual condition indicators as explanatory variables (method: bagging, sampling method: random with replacement, number of trees built: 10,000).

Random Forest includes measures of variable importance that can be used to determine the most important features and their impacts (Archer and Kimes, 2008). Accordingly, the Mean Decrease Accuracy (MDA), which represents how much accuracy the model loses by removing each variable, was calculated. The greater the loss of accuracy, the more critical the variable is for an effective classification (Han et al., 2016).

Out-of-bag (OOB) predictions were used to estimate the probability that each observation belongs to a given class of the response variable (Cutler et al., 2007), and therefore adopted for evaluating the classification performance and validating the model (Breiman, 1996). For categorical datasets, the OOB score is computed as the proportions of correctly predicted observations in all the classes of the response variable. Complementarily, it defines the misclassification rate (OOB error) as the proportion of the overall misclassified observations (Bhagat et al., 2022). The dataset was split into two subsets, one serving as the training set (including 70 % of the observations) and one serving as the validation set (including 30 % of the observations) (Nguyen et al., 2021), and the OOB error was calculated for each. In both cases, the number of observations was equally balanced between the two extrinsic determinant classes in order to maximize model accuracy (Chen et al., 2004).

3. Results

3.1. LE species composition

In the 80 surveyed LE, occurring between 41 and 1300 m a.s.l., a total of 115 physiognomic species have been detected (79 in Italy and 65 in Spain). LE species richness resulted to be markedly and significantly different between the two countries (U standardized = 5.526; $p < 0.0001$) (Fig. 4), with Italian LE showing on average almost twice as many species as the Spanish ones (10.17 ± 0.63 vs 5.30 ± 0.36). In Italy, the most frequent species were *Rubus ulmifolius* Schott (found in 80 % of the LE), *Ulmus minor* Mill. subsp. *minor* (68 %) and *Prunus spinosa* L. subsp. *spinosa* (65 %), while in Spain they were *Crataegus monogyna* Jacq. (found in 45 % of the LE), *Rubus ulmifolius* Schott (45 %), *Asparagus acutifolius* L. (43 %), and *Rosa agrestis* L. (38 %) (Fig. 5).

The complete list of physiognomic species and their respective frequency in sampled LE are provided in Table S2.

A total of 122 dominant herbaceous species have been detected (60 in Italy and 67 in Spain), 40 of which were found to be ruderal. The

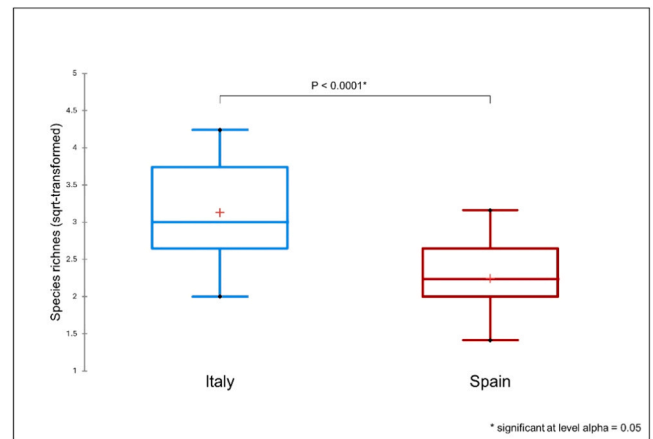


Fig. 4. Box plots showing LE species richness in Italy and Spain (red cross indicates median).

complete list of detected herbaceous species, along with respective ruderality, is provided in Table S3.

3.2. LE conditions

Scores of individual condition indicators for the assessed LE are summarized in Fig. 6.

Aggregated condition values for each LE ranged from 13 to 43 and have been assigned to four classes, according to natural breaks, spanning from very unfavorable and unfavorable to favorable and very favorable (Table 2).

Overall, 6 LE resulted in very unfavorable (7.50 %), 19 in unfavorable (23.75 %), 36 in favorable (45.00 %) and 19 in very favorable conditions (23.75 %).

As regards validation, Spearman statistics showed a significant positive correlation of the aggregated condition value with the richness of woody species (coefficient = 0.35, $p = 0.002$) and, especially, with the cover-abundance of characteristic species of the reference PNV (coefficient = 0.61, $p < 0.0001$).

3.3. Effects of protected habitat contiguity and governance framework on LE conditions

The ecological profile of LE resulted to be quite similar with respect to N2K-link status and in the two countries (Figs. 7 and 8).

In keeping with the landscape context of the analyzed LE, the ecological profiles are generally characterized by a medium-high luminosity and temperature, medium continentality and intermediate soil humidity, while slight greater differences are observed in soil pH and nutrient availability.

The frequencies of LE condition classes by N2K-link status and by country are shown in Figs. 9 and 10, respectively.

Fisher's exact test highlighted a significant dependence between LE condition classes and N2K-link status ($p < 0.0001$, H_0 has been rejected), but not with countries ($p = 0.693$, H_0 has been accepted). In the first case, the strength of association assessed by Cramer's V statistic was equal to 0.620, which indicated a large-intensity dependence between the variables and suggested a positive effect of the contiguity to a protected habitat on LE conditions. On the contrary, the governance effect seemed to be meaningless.

3.4. Indicator importance

Since only N2K-link status was found to be significantly associated with LE conditions, the Random Forest model was run using this extrinsic determinant as the response variable.

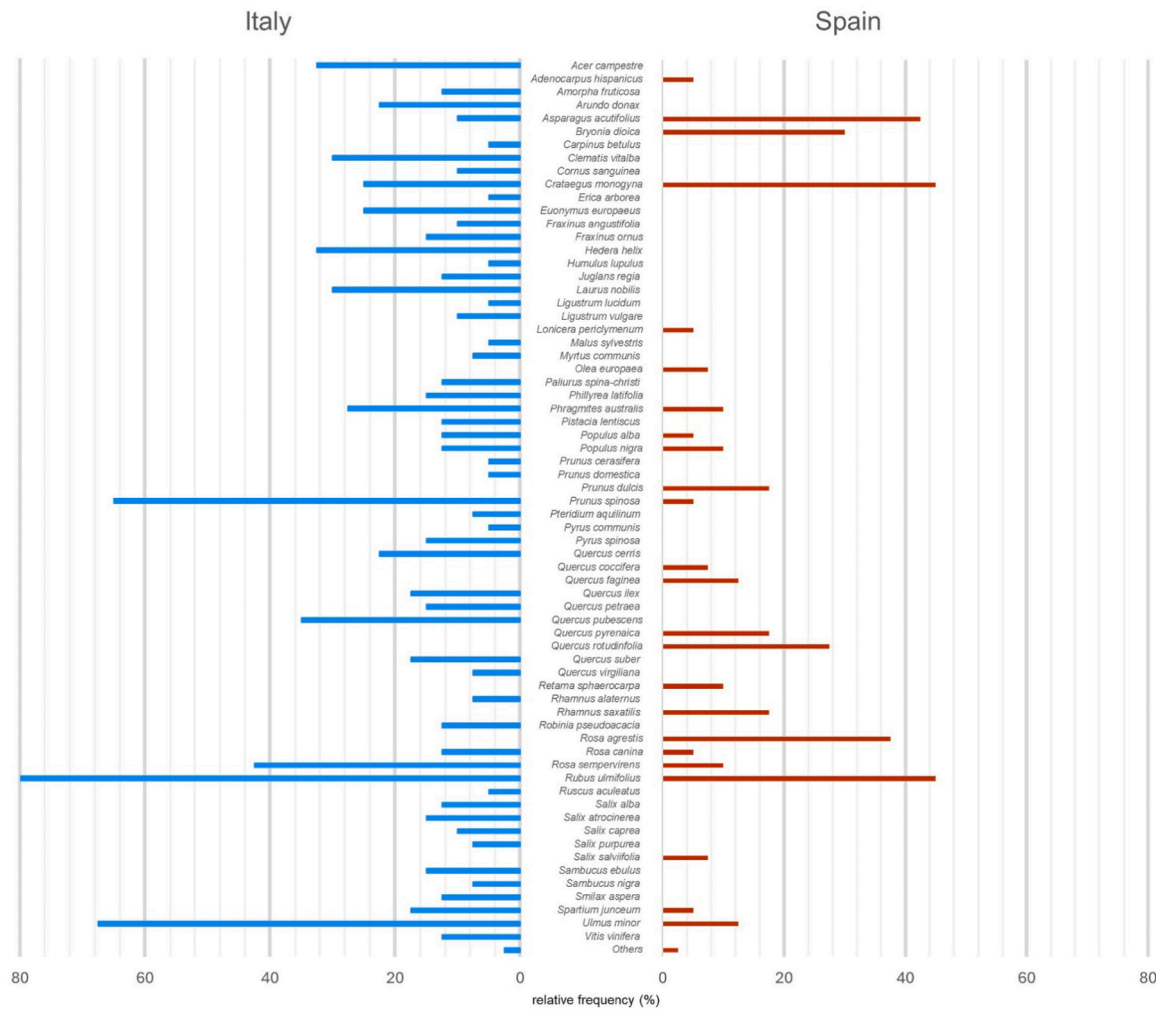


Fig. 5. Relative frequencies of the physiognomic species detected in LE of Italy and Spain with respect to the total LE sampled by country. The full name of the species is reported in [Table S2](#).

In the training set, the model found more than 82 % of the observations consistent with the classification (OOB error = 0.179), while in the validation set the percentage increased by over 83 % and the OOB error dropped to 0.167.

According to the MDA values, the top five important condition indicators in discriminating the N2K-link status included: extent of the longest gap (e), abundance of scapose phanerophytes (o), nucleation phenomena (l), abundance of juveniles of the species typical of mature vegetation communities (k) and quality of contacts (f) ([Fig. 11](#)).

Summing up, LE that are contiguous to a N2K patch, and generally with better conditions, are characterized by high structural continuity (absence of large gaps), dominance of trees, active dynamics, and good quality of the surrounding landscape mosaic ([Table 3](#)).

4. Discussion

Based on an original selection of indicators, calculated by means of combined field surveys and GIS/statistical analyses, a method to assess LE condition was proposed and tested. Since the adopted structural, compositional and landscape indicators are strictly related to LE capacity to support local biodiversity, the method can be considered suitable for addressing the challenges posed by current sustainable agriculture policies and strategies ([Rendon et al., 2022](#), [Scherer et al., 2020](#)).

A special emphasis was placed on the capacity of LE to support PNV-characteristic species and pollinators. Actually, PNV is being adopted as

a reference system for setting ecological restoration targets ([Capotorti et al., 2020](#), [Farris et al., 2010](#)) that go beyond a narrow focus on the species of conservation concern ([Scherr and McNeely, 2008](#), [Valeri et al., 2021](#)) towards an improvement of “diffuse naturalness” and maintenance of spontaneous recovery potential ([Capotorti et al., 2023](#)). On the other hand, pollinators have been recognized as key biodiversity components, for both nature and human health, that depend on factors other than those of PNV-related species ([Garratt et al., 2017](#), [Kral-O’Brien et al., 2021](#), [Kremen et al., 2002](#), [Phillips et al., 2019](#), [Schubert et al., 2022](#)). Pollinator support capacity is therefore crucial for a thorough assessment of conditions for any ecosystem type and at any level of investigation, including overall complex agroecosystems and the small landscape elements within them ([EC, 2022b](#)).

4.1. Study limitations and future directions

Overall, despite valuable insights, the assessment procedure could be either simplified or enhanced. On the one hand, since gathering and processing data for the calculation of 17 indicators may be time-consuming, a valid alternative would be to directly measure the cover-abundance of PNV-characteristic species as a pragmatic surrogate, which resulted to be positively and strongly correlated with LE conditions. This approach still requires essential GIS competencies and, especially, botanical skills, for replicating the assessment procedure over different geographic context and at different scales. However, in that case, some restrictions concerning the effective pollinator support

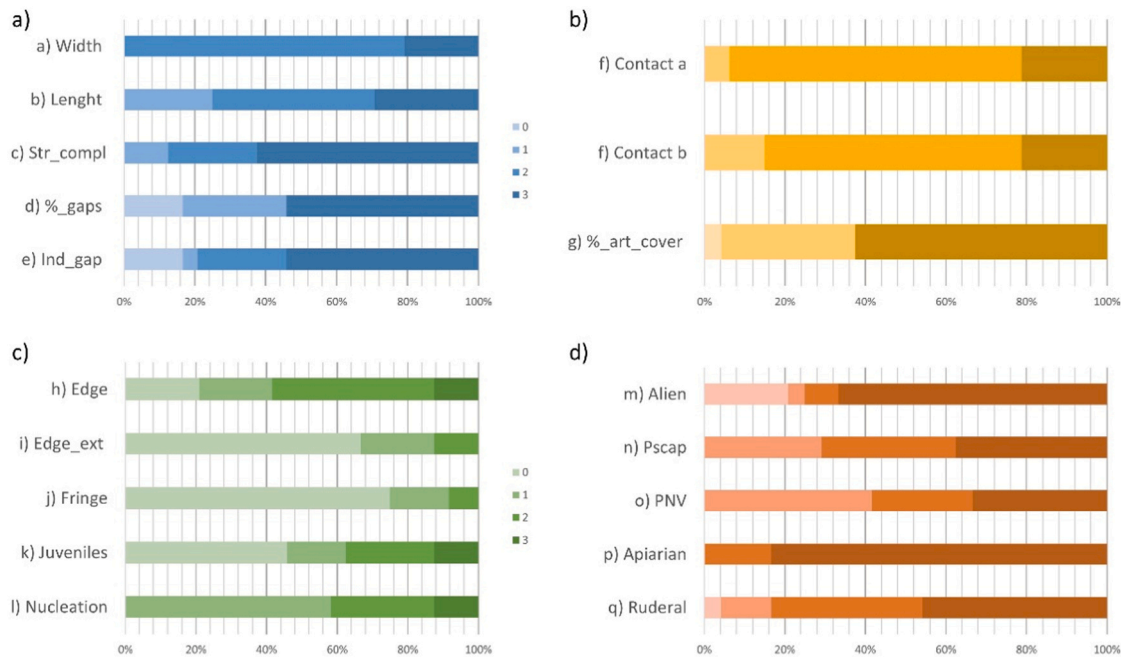


Fig. 6. Cumulative histograms showing the frequency of scores assigned to the 80 LE, grouped by condition indicator typologies: a) Structure and continuity; b) Surrounding landscape context; c) Ecotone structures and dynamics; d) Specific composition. The complete description of individual indicators is available in Table 1.

Table 2
Classes of aggregated conditions assigned to LE according to natural breaks.

Natural break	Condition class	Number of LE
13–22	Very unfavorable	6
23–30	Unfavorable	19
31–37	Favorable	36
38–43	Very favorable	19

capacity could arise (Barendregt et al., 2022; Capotorti et al., 2023), to be potentially overcome with complementary entomological skills.

On the other hand, to obtain an even more thorough picture of LE functionality, other attributes, such as water stress or the presence of diseased and decaying trees, should additionally be considered (Staley et al., 2020). Furthermore, socio-ecological indicators might enhance the applicability and comprehensiveness of the proposed method. Considering socioeconomic features relevant to biodiversity conservation could indeed provide a more insightful understanding of LE context since agricultural landscapes often embody a wealth of cultural and management practices that are integral to their ecological characteristics (Arnaiz-Schmitz et al., 2018; Tieskens et al., 2017). Consequently, since a given broad governance framework must necessarily be translated into local measures for effective land management, considering detailed socioeconomic factors would allow for a better understanding of potential indirect pressures on biodiversity. This is especially true in cultural landscapes where the respective governance structures may play a crucial role in conservation of native species (Bethwell et al., 2022; Velten et al., 2018). Since in Italy and Spain the implementation of common rural development goals varies due to different administrative structures, regional priorities, and socio-economic contexts (EC 2021a, 2021b), we assumed the country of belonging as a proxy for the wide governance framework. However, using this proxy may have underestimated the effect of local governance on LE conditions. Thus, encompassing both biophysical and detailed socio-ecological dimensions could help enhance guidance for LE ecological restoration efforts.

4.2. Interpretation of the positive effect of contiguity to protected habitats on LE conditions

Empirical testing of the assessment method showed that contiguity with a N2K wooded patch is favorable for LE biodiversity support capacity. This positive effect is probably due to enhanced forest naturalness in protected habitats, which in turn promotes the availability of seed sources for the dispersal of characteristic plants of local mature stages into adjoining LE (Sitzia, 2007; Wehling and Diekmann, 2009).

Concerning the indicators that better express this positive effect, structural continuity (absence of large gaps) emerged as a very relevant factor. This finding complements available evidence from other research, which in contrast highlighted the importance of width in determining LE quality (Deckers et al., 2004; Closset-Kopp et al., 2016; Litza and Diekmann, 2019). Continuity probably favors the rate of frequentation by small rodents (Dondina et al., 2018; Gelling et al., 2007), which are important tree seed dispersers especially for oak species (Gómez et al., 2008; Perea et al., 2011), and improves habitat suitability for some pollinators (Garratt et al., 2017). It might also indicate low-impact management regimes and, in general, landscape contexts with low levels of anthropogenic disturbance (Schmitz et al., 2007).

The quality of contacts has indeed emerged as another important indicator, confirming the complementary and adverse impact of nearby intense land uses on residual woody elements quality (de Blois et al., 2002; Smart et al., 2001; Kremen et al., 2019).

The importance of tree canopy dominance may instead be indicative of a longer historical permanence (Wehling and Diekmann, 2009; Staley et al., 2012) that favors successional maturity and strengthens plant regeneration (Baudry, 2000). Moreover, such maturity is expected to better sustain small mobile pollinator species, often nesting in wood cavities rather than in the ground (Kremen and M’Gonigle, 2015).

Finally, the relevance of active dynamics signals, in terms of nucleation and rejuvenation of woody species, complements the available evidence on the active role of contiguous LE for the maintenance and dispersal of overall forest plants across fragmented landscapes (Sarlöv-Herlin and Fry, 2000; Lenoir et al., 2019; Mony et al., 2022).

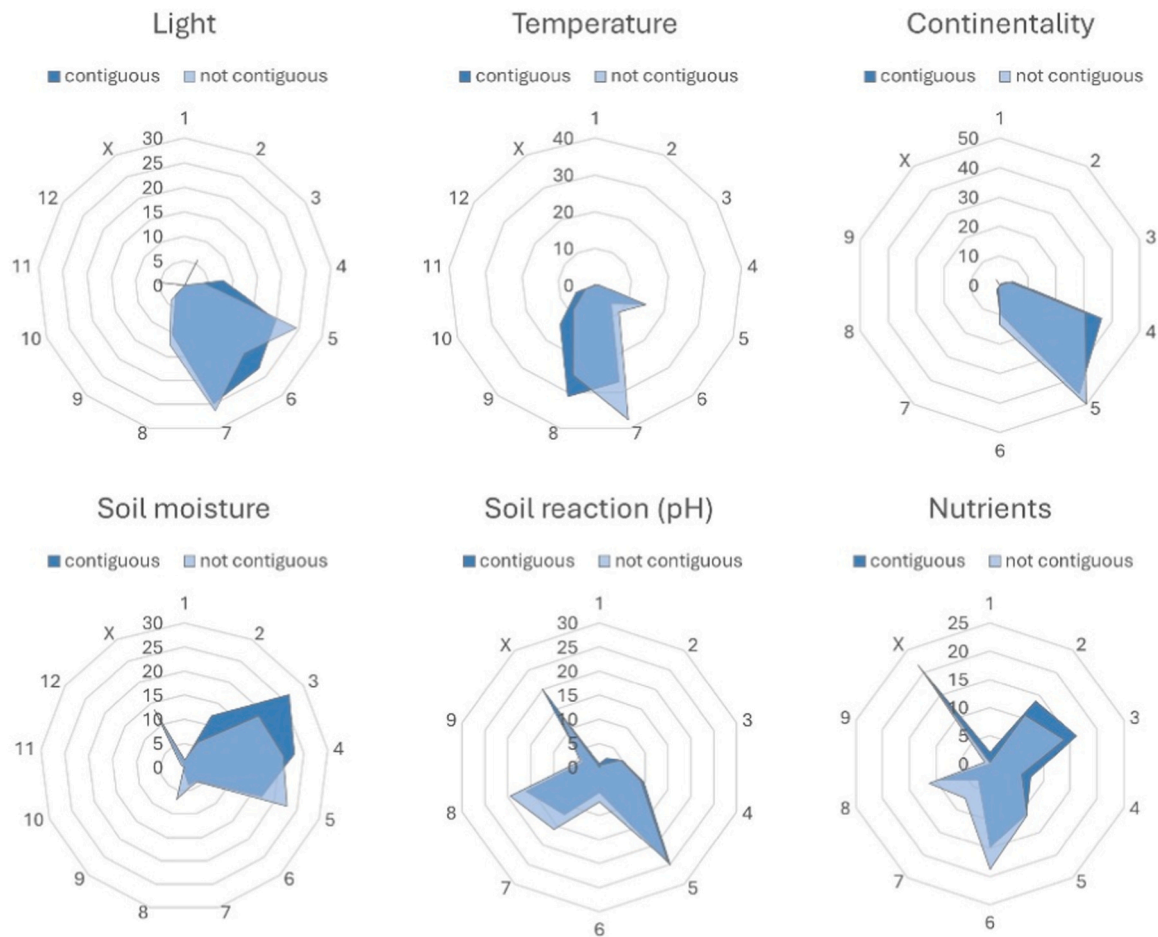


Fig. 7. Bioindicator values weighted on the relative frequency of physiognomic species (percentages in the vertical axis) by N2K-link status (contiguous and not contiguous).

4.3. Potential application of the research

In keeping with the implementation strategy for the Ecosystem Accounting of the UN System of Environmental-Economic Accounting (UN, 2022), the proposed method for the assessment of LE conditions may contribute to the development of multi-tiered agroecosystem accounts. Usually, in fact, conditions of this type of ecosystem are mainly assessed in terms of LE cover density and for accounting application at the national/international levels (Rendon et al., 2022, Valeri and Capotorti, 2023). A complementary approach that considers LE as individual ecosystem sub-types, deserving specific assessment of conditions for a finer estimation of agroecosystem assets and service capacity, would instead be more suitable to support sustainability policies and decision-making processes at the local level (EC, 2022b).

Especially at the local level indeed, LE condition assessment can guide the identification of targeted conservation/restoration actions, to be implemented for fine-scale green infrastructure and ecological network planning (Capotorti et al., 2019).

As emerged from the present case study, restoration of LE in Mediterranean agroecosystems should for example be primarily directed at improving the crucial features identified. Notably, instances featuring substantial gaps (e.g. > 5 m) could be filled by strategically planting a mix of native species that are coherent with the local vegetation potential, most of all in LE with few scapose phanerophytes. These actions have the potential to stimulate the inherent regenerative capacities of LE, boosting positive self-recovery feedback (EC, 2023b), and pushing passive reforestation dynamics when adjacent lands undergo abandonment (Forget et al., 2013, Rey Benayas and Bullock, 2015). This

recovery is expected to be faster and more effective in landscapes that host natural habitats, such as N2K sites, where propagules of target species and dispersal vectors already occur (Valkó et al., 2017).

Moreover, restoration of LE can help counteract fragmentation due to agricultural practices and promote landscape connectivity, as uncultivated LE within intensively managed agricultural landscapes are often the only corridors suitable for species dispersal between residual natural and semi-natural habitats (Jones et al., 2013, Marzi et al., 2019, Verhagen et al., 2018). Besides providing refuge habitats and pathways for the movement of species, a well-connected network of LE also facilitates overall ecological functioning in agricultural systems, improving adaptive capacity to environmental changes (Schippers et al., 2015) and long-term conservation of biodiversity (Alignier et al., 2020).

Under a wider perspective, LE restoration actions can be also considered dependent on socio-ecological systems with multiple interactions and feedback between landscape characteristics, socio-economic conditions of local populations, land use planning and management strategies (Arnaiz-Schmitz et al., 2018). Likewise, LE restoration creates opportunities for local economic development by diversifying land uses and promoting sustainable practices (Van Geert et al., 2010). Thus, land planning strategies for conservation, improvement, and restoration of LE networks within agricultural lands can effectively contribute to achieving multifunctional, biodiverse, and resilient agricultural systems (Aschi et al., 2023, Carlier and Moran, 2019). Spatial configuration and inherent socio-ecological functions of LE should be considered and integrated into the design and implementation of more effective policies to support pro-environmental agricultural practices and promote sustainable agricultural landscapes

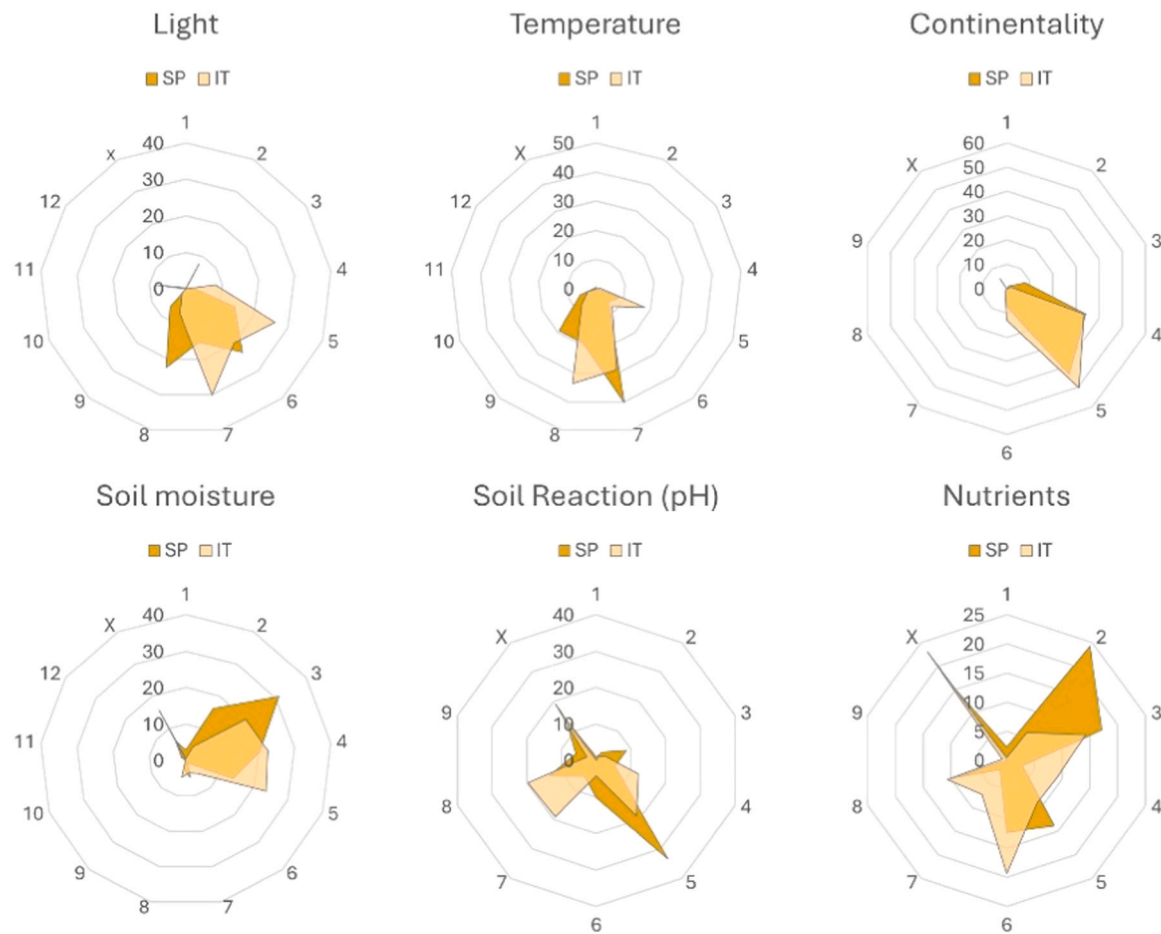


Fig. 8. Bioindicator values weighted on the relative frequency of physiognomic species (percentages in the vertical axis) by country (SP = Spain and IT = Italy).

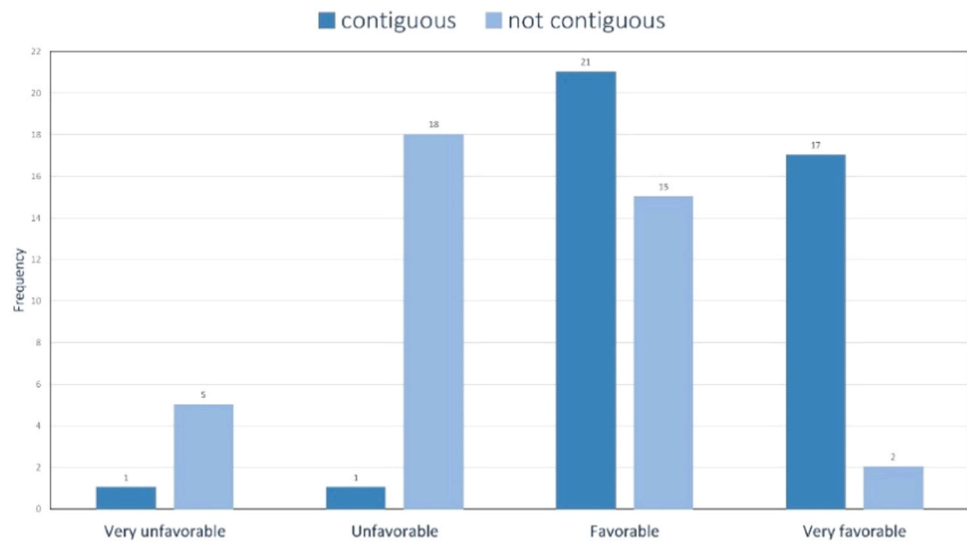


Fig. 9. Frequencies of LE condition classes by N2K-link status (contiguous and not contiguous).

(Batary et al., 2015; Pe’er et al., 2020).

5. Conclusions

This work presents a potentially replicable method for a detailed assessment of LE conditions, especially in terms of support capacity for PNV-characteristic species and pollinators. The method was tested in

part of the Mediterranean Europe, where such a thorough appraisal was lacking.

The strong and positive association between LE conditions and contiguity to a protected habitat was also highlighted, and respective discriminant LE features were identified. Namely, LE that are contiguous to a N2K patch resulted to be characterized by high structural continuity (absence of large gaps), dominance of trees, active dynamics, and good

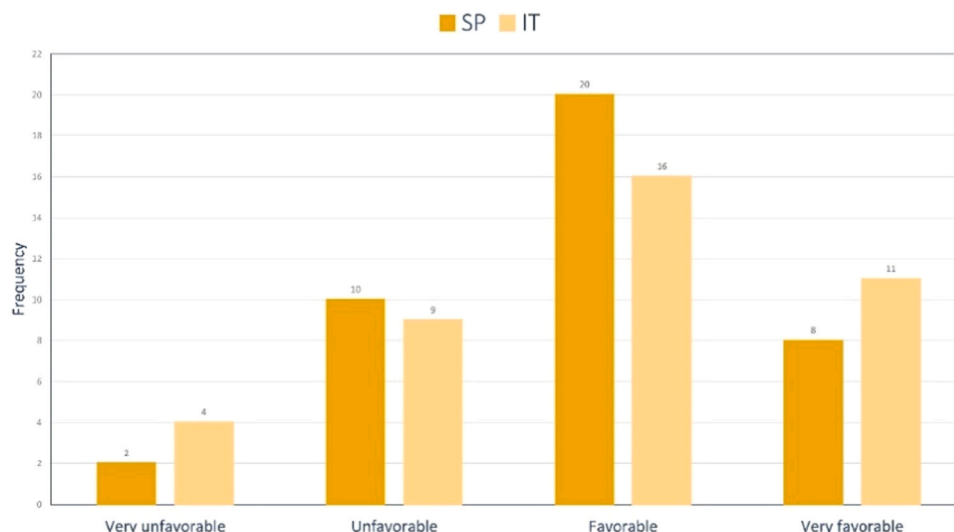


Fig. 10. Frequencies of LE condition classes by country (SP = Spain and IT = Italy).

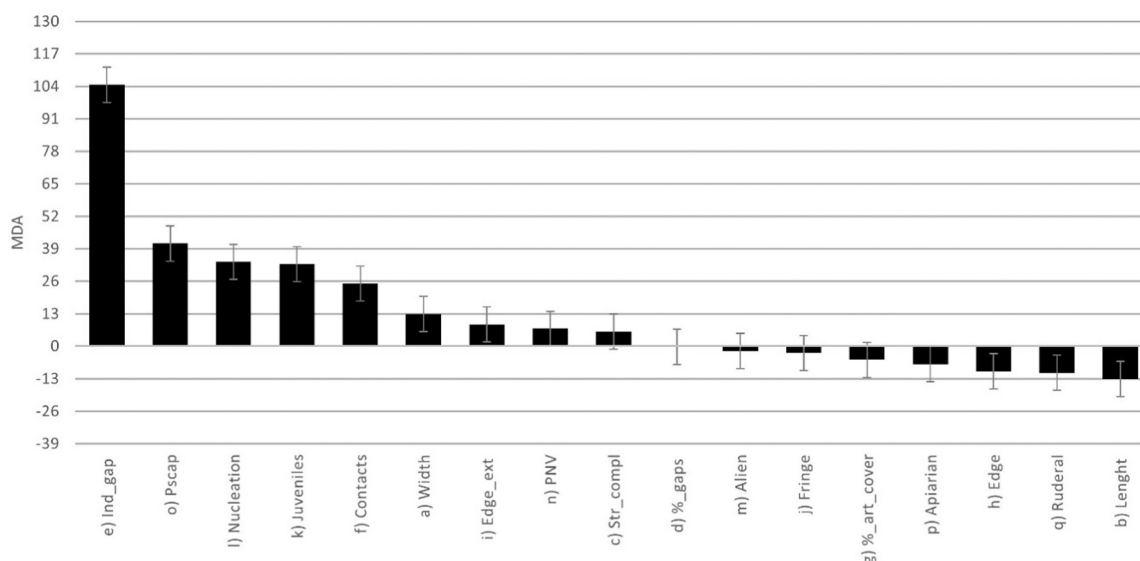


Fig. 11. Indicator importance according to the Mean Decrease Accuracy (MDA) values. The top five important indicators are the variables that exceed the MDA average (12.93).

Table 3

Mean scores of the top five important indicators assigned to the sampled LE by N2K-link status.

Indicator	Mean score (contiguous)	Mean score (not contiguous)
Ind_gap	2.2	1.0
Pscap	2.3	1.8
Nucleation	2.0	1.5
Juveniles	1.8	0.7
Contacts (a + b)	4.5	3.8

quality of the surrounding landscape mosaic.

Overall, the proposed assessment approach shows promising potential applications in both ecosystem accounting and ecological restoration processes, and more in general, may effectively contribute to addressing current challenges for sustainable agriculture.

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Ethical statement

No specific permissions applied to this study according to the national legislation.

CRediT authorship contribution statement

Giulia Capotorti: Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **SIMONE VALERI:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Methodology, Investigation, Funding acquisition,

Formal analysis, Data curation, Conceptualization. **María F. Schmitz**: Writing – review & editing, Writing – original draft, Resources, Investigation, Data curation. **Belén Acosta-Gallo**: Writing – review & editing, Resources, Investigation, Data curation. **Duilio Iamónico**: Writing – review & editing, Resources, Data curation. **María Villodre**: Visualization, Data curation. **Cecilia Arnáiz-Schmitz**: Visualization, Data curation.

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.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agee.2024.109199](https://doi.org/10.1016/j.agee.2024.109199).

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