



The role of agroforestry in solving the agricultural landscapes vulnerabilities in the Po Plain district

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Abstract

The current trend of biodiversity deterioration in rural systems is a complex issue that operates across multiple spatial scales. Agroforestry practices have the potential to positively contribute towards addressing these trends by shaping the structure of agricultural landscapes and their underlying ecological functions. This study aims to test a multi-scale analytical approach to understand and account for these processes. Specifically, the study seeks to assess the contributions that agroforestry practices at the farm scale can make towards supporting biodiversity, in response to the wider-scale landscape eco-mosaic structural and functional challenges and requirements (both at the local and extra-local landscape systems). To achieve this, a series of landscape ecology analyses are conducted on an agroforestry-based rice farm located in the western Po Plain region of Northern Italy. These analyses examine various landscape structural traits (such as matrix composition, patch size, shape complexity, and diversity indices) and functional traits (including connectivity and bionomic indices), with different levels of detail for each scale of analysis. This allows for the evaluation of the current ecological status of both the extra-local and local scale landscape systems (including drivers of vulnerability and resilience) and the assessment of the farm's current contributions to biodiversity support. Based on these findings, strategic agroforestry interventions are identified at the farm scale to enhance its capacity to address the wider-scale ecological gaps. Two design scenarios are assessed, wherein functional ecological traits such as landscape diversity, connectivity, and ecological stability are improved. The results confirm the role of farm scale agroforestry management as a buffering tool, demonstrating how it contributes to the restoration of broader-scale landscape vulnerabilities. The applied approach provides cost-effective assessments of biodiversity-related ecological processes, with the accuracy of the findings dependent on the comprehensive multi-scale analysis conducted.

Keywords Landscape ecology · Multi-scale approach · Agroforestry · Biodiversity · Italy

Introduction

The loss of biodiversity in agricultural systems is a widely recognised emergency (IPBES, 2019; European Commission, 2020; European Union, 2020). Agrobiodiversity, here understood in its broader sense and multi-level characteristics (Jackson et al., 2013), plays a central role in maintaining the resistance and resilience capacities of agricultural systems (Ives & Carpenter, 2007; Kremen & Miles, 2012; Quijas et al., 2010; Swift et al., 2004). This is an essential characteristic of agro-ecosystems that ensures the provision of food for humans (Chopra, 2000; Dudley & Alexander,

2017; FAO, 2011; Lenné & Wood, 2011). It also maintains an interwoven network of ecosystem functions and is linked to ecosystem services on which human communities depend (Duru et al., 2015; ELN-FAB, 2012; Swift et al., 2004; Zhang et al., 2007). Agrobiodiversity is facing declining trends with patchy spatial patterns related to the large-scale spatial configuration of land use: large, intensively managed agricultural areas, where conventional agriculture predominates, are the main cause of agrobiodiversity loss (Donald et al., 2001; Falcucci et al., 2007; Kleijn et al., 2008; Pellegrini et al., 2021; Reidsma et al., 2006). In such contexts, the structure of the agricultural landscape is depleted, resulting in highly simplified organisational patterns. Such patterns can be identified at different spatial scales. At the field scale, the agro-ecosystem is kept at a low level of structural and functional organisation and is completely dependent on external energy and material inputs to maintain its status

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and its dominant anthropic functions (food production) (Gliessman, 2007). At the farm scale, land use is generally highly homogeneous (Fahrig et al., 2011). The agro-ecosystem components which are not directly intended to fulfil the food production goal are generally excluded from the system or are kept marginal. Spontaneous phytocoenoses are often simplified and lowly structured (Taffetani et al., 2011). Their compositional and structural traits are mostly related to high disturbance conditions: initial successional stages are predominant, and their evolution towards higher maturity degrees is hardly attainable (Taffetani et al., 2011). Consequently, habitat diversification is undermined, and the ecological niches availability is highly constrained (Morelli, 2013; Stoate et al., 2001). At local scale, spatial fragmentation dynamics occur, and dichotomous spatial configurations of land use can be easily identified (spatial separation into forest and seminatural, agricultural, and artificial components and functions) (Postek et al., 2019). Core areas and source areas function (Chen et al., 2008) are often residual and weakened, confined to few relict woody areas (Dramstad et al., 1996; Holland & Fahrig, 2000). They are generally related to river linear systems that maintain the most important, and often the only, ecological connectivity functions. At extra-local scale, this simplified and dichotomic spatial configuration implies wide scale unbalances and shortcomings, also entailing hydro-geo-chemical implications (Ingegnoli, 2015). Across these different spatial scales, multiple knock-on effects occur (Gonthier et al., 2014). Field scale biodiversity is a direct and indirect consequence to the diachronic evolution of all these spatial scale patterns (Clergue et al., 2005; Duelli & Obrist, 2003). The current disclosure of invasive alien species impacts is striking evidence of this (O'Reilly-Nugent et al., 2016; Pellegrini et al., 2021; With, 2002). Thus, agrobiodiversity degradation is an issue at multiple spatial scales, and over-simplification of agricultural landscapes is a core process that is currently significantly influencing agrobiodiversity trends.

The above processes and impacts are related to conventionally managed agricultural landscapes. Today, there are multiple and diverse agricultural management options that focus on different strategies to address such impacts and agri-environmental emergencies at different spatial scales. Among them, agroforestry is a recognised, viable, multi-purpose rehabilitating strategy (Lovell et al., 2021; Montagnini & del Fierro, 2022; Montagnini et al., 2011; Udawatta & Jose, 2021). We here intend with agroforestry practices in both the linear and areal landscape featured management between fields and the in-field productive agroforestry practices (Santiago-Freijanes et al., 2018). In particular, the agroforestry approach has the specificity to address in parallel the field and landscape scale rebalancing effects, as it directly shapes the agricultural landscape structure and its underlying functions (Franco, 2000; Gliessman, 2007; Montagnini

& Del Fierro, 2022). Specifically, the landscape agroforestry management can directly shape the effectiveness of landscape multifunctionality (Boinot et al., 2023). It can therefore be considered as a primary strategy to address the multiple problems associated with the over-simplification of the agricultural landscape. To be effective, agroforestry implementation needs to be strategically targeted to the specific context needs, in relation to the vulnerability and resilience drivers of the landscape system (Peterson, 2002; Peterson et al., 1998). In addition, agroforestry interventions should be closely aligned with the floristic-vegetation-ecological characteristics of the landscape context (current and potential status).

The landscape ecology approach provides viable tools for analysing and accounting for such multi-scale processes and also enables synthetic yet ecologically consistent assessments of biodiversity-related structural and functional attributes (Dover & Bunce, 1998; Dramstad et al., 1996; Forman, 1995; Forman & Godron, 1986; Turner & Gardner, 2015). Furthermore, it provides viable knowledge tools for strategically guiding land use change rehabilitating interventions (Manning et al., 2019; Opdam et al., 2001). Several metrics are worldwide being used and validated through interdisciplinary multi-scale assessments (landscape scale metrics; field scale biodiversity measures). The landscape ecology theory and pre-existing literature experiences linking biodiversity to the landscape scale parameters allow us to use some of these metrics, and in particular their mutual behaviour, as tools for interpreting the overall ecological functioning of a landscape (Turner, 1989). This means that they can be used as surrogates for biodiversity values (Duelli, 1997). In this case, precautions should be taken to avoid misleading interpretations (Turner & Gardner, 2015). Comparison of multiple metric values, at different spatial scales, is required for organic interpretation of their mutual redundancies and context-specific information load. Interpretations can be generalised to non-specific taxa groups (e.g. sensitive behaviours—interior habitat species—and generalist behaviours—edge or synanthropic habitat species), provided that: context-specific knowledge on the structural, functional, and dynamic traits of the main biological communities is available; extensive literature experiences already exist, validating the theoretical functional interpretations on comparable landscape contexts. Such an approach provides synthetic, cost-effective assessments whose accuracy depends on the multi-scale depth of analysis of ecological processes. In contrast, the use of landscape metrics correlated with biodiversity values still requires context-specific validation (e.g. by field scale floristic-vegetative or faunal data), as no generalised patterns are currently recognised due to the variety of context-specific peculiarities (Clergue et al., 2005).

Given these premises, our study tests a set of multi-scale landscape ecological analyses on an agricultural landscape

system. The aim is to present the contributions that can be made by implementing agroforestry practices at the farm scale, in response to the structural and functional issues and needs of the wider landscape eco-mosaic (vulnerability and resilience drivers). Indeed, the applied multi-scale analyses are parallelly addressed to the diagnosis on the current landscape ecological status and to the consequent identification of strategic interventions to solve the current ecological gaps at the different scales. Therefore, the aim of our study is to test a methodology that allows the following parallel assessments: evaluating the current ecological status of the landscape, synthesising multi-scale vulnerability and resilience drivers, guiding the implementation of agroforestry practices at the farm scale based on wider-scale landscape traits, and assessing the impact of different farm scale design scenarios on landscape ecological functions.

Material and methods

The applied multi-scale methodology

To achieve the objective stated in the Introduction paragraph, we have developed an assessment methodology that adopts an action-oriented approach, integrating insights from previous similar studies into a comprehensive landscape ecology analytical framework (Dal Borgo et al., 2023; Vagge & Chiaffarelli, 2023a). The methodology is applied to a study area located in the western side of the Po Plain district (North of Italy), an iconic example of agricultural landscape widespread over-simplification and agrobiodiversity diffused detriment (Celesti-Grapow et al., 2010; Domina, 2021; Falcucci et al., 2007; Pellegrini et al., 2021). Here, we recently led a study on rice fields floristic-vegetational qualitative and quantitative changes from the mid-20th century to current time, which highlighted a significant floristic impoverishment, the current positive influence of organic, extensive agricultural management if compared to the conventional one but also a great increase in alien species occurrence (Vagge & Chiaffarelli, 2023b). Such changes were related to landscape scale change drivers, highlighting the need for multi-scale biodiversity assessment and management also through landscape scale intervention strategies (Vagge & Chiaffarelli, 2023b). In the here-presented study, we started from the hypothesis that farm scale agroforestry implementation could be a viable tool for recovering landscape complexity and diversification levels (Benton et al., 2003) and consequently support higher field scale biodiversity qualitative and quantitative traits (Boinot et al., 2023; Fahrig et al., 2011; Montagnini, 2017; Montagnini & del Fierro, 2022). We considered that such contributions, and their accounting, are tightly linked to the local and extra-local landscape system traits, its shortcomings (vulnerability drivers), and

potential capabilities (resilience drivers). That is, the same agroforestry-based agricultural system can bring different contributions, depending on the surrounding landscape context ecological traits. To this aim, we identified a farm scale agroforestry managed context, and the surrounding local scale and extra-local scale related landscape systems. All of them went under a structural and functional characterisation, based on the landscape ecology quantitative approach. To coherently interpret the landscape analyses results, we preliminarily built a synthetic framework on the local environmental and ecological traits. These first steps brought to the building of synthetic analyses on the vulnerability and resilience drivers of the extra-local and local landscape systems, which both oriented the identification of some context-specific intervention strategies at farm scale, based on further agroforestry practices implementation. The design of these interventions allowed for different design scenarios. Finally, the landscape ecology indicators were recalculated for the different scenarios, allowing the contribution of the design strategies to the ecological improvement of the landscape to be assessed. The methodology applied is shown in Fig. 1.

Case study

The case study is located in Western Po Plain, Piedmont region, North of Italy (Fig. 2a) and is characterised by a temperate continental (steppic), upper mesotemperate, and upper subhumid bioclimate, with average annual rainfall of 872 mm (Albano Vercellese weather station, 1990–2022 data—Regione Piemonte, Arpa Piemonte, 2024) (Rivas-Martínez, 2004; Globalbioclimatics; Pesaresi et al., 2017). This area embeds different geomorphological features as shown in Fig. 3. Hence, we are in a territory that shows a discreet pedological diversity, if compared to the mostly spread pedological traits of Po Plain: predominant plain inceptisols developed on Wurm alluvial deposits, with some sparse plain alfisols lenses and plain entisols along the Holocene deposits of the fluvial beds (Geoportale Regione Lombardia). These geomorphological peculiarities influenced the vegetational traits and land use patterns through time, bringing to a composite presence of areas of conservation interest, which are quite uncommon in the Po Plain context. As for the actual potential vegetation (Blasi 2010), the Riss and Wurm terraces show acidophilic forests dominated by *Quercus robur* L. as mature vegetation, the earlier evolutionary stages are represented by preforest in *Betula pendula* Roth. and *Corylus avellana* L., shrub formation in *Cytisus scoparius* (L.) Link, *Frangula alnus* Mill., and *Juniperus communis* L., heathland in *Calluna vulgaris* (L.) Hull, and grassland in *Molinia arundinacea* Schrank. Recent terraces are potentially colonised by lowland forest in *Quercus robur* L., *Carpinus*, *betulus* L., and *Fraxinus excelsior* L.. Along the rivers, the potential vegetation is that of riparian

Fig. 1 Flow-chart representing the applied multi-scale methodology

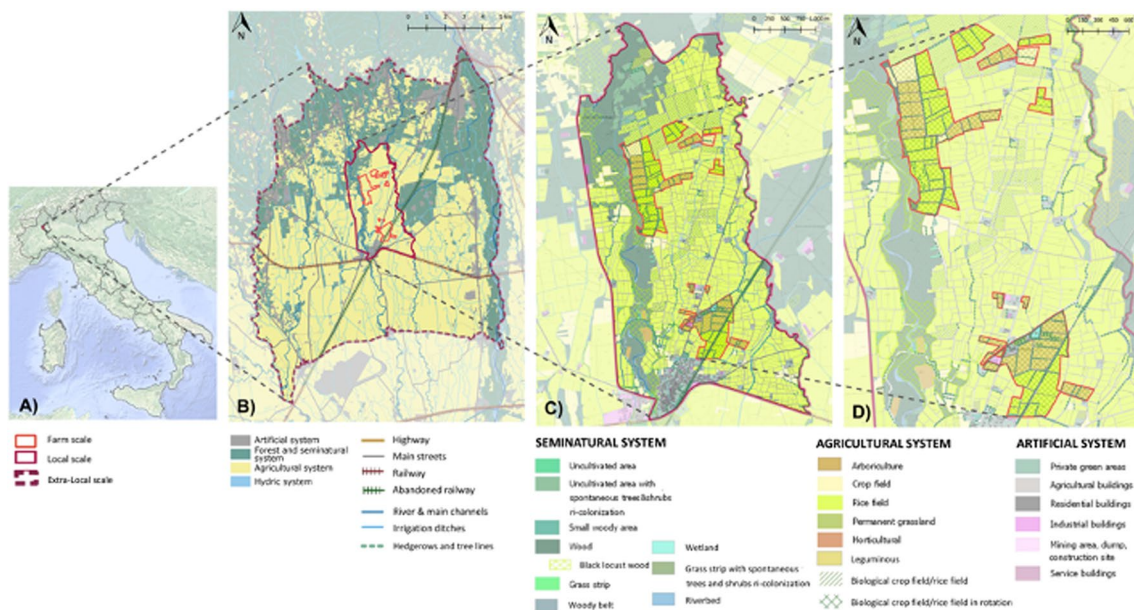
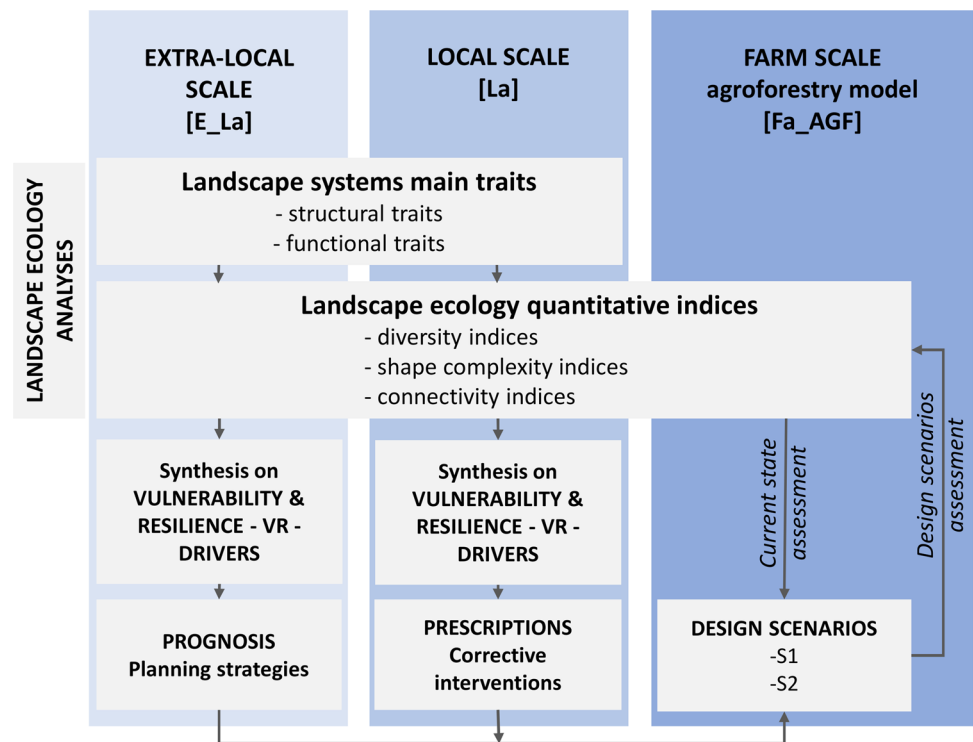
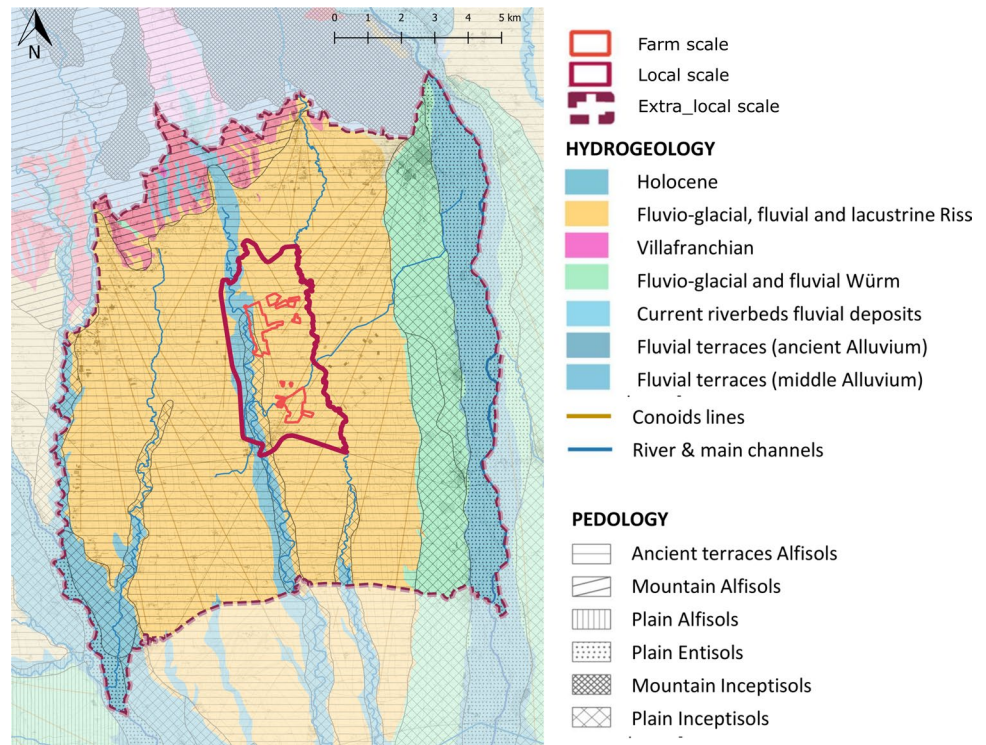


Fig. 2 a The study area location; b extra-local (E_La), local (La), and farm (Fa_AGF) scale landscape systems under analysis; c detail on the La land use; and d detail on the Fa_AGF land use

woodlands in *Salix alba* L., *Populus alba* L., and *Populus nigra* L. or *Alnus glutinosa* (L.) Gaertn. woodlands on the more developed substrates. Anthropization and secular land use have resulted in a current situation where natural coenoses are often degraded and dominated by invasive exotic species such as *Robinia pseudoacacia* L. and *Prunus*

serotina Ehrh.. Larger patches of naturalness remain on the Riss and Wurm terraces where less fertile soils and, more importantly, the establishment of regional parks has allowed conservation policies to be implemented. Agricultural land use is predominant, with rice cultivation being traditionally the most spread crop. Within the extra-local landscape

Fig. 3 Main geomorphological features of the study area



system (Fig. 2b), the natural and seminatural land uses (mainly woodlands) are mostly concentrated in the northern areas and along the North–South axes of rivers, while in the central and southern areas natural and seminatural areas are highly depleted, with a progressive gradient going N–S.

Multi-scale analyses (see Section "The applied multi-scale methodology") were applied to: extra-local scale landscape system (E_La—total surface: 17755 ha—Fig. 2b); local scale landscape system, mainly conventionally managed agricultural areas and seminatural areas, (La—total surface: 1467 ha Fig. 2c); farm scale agroforestry model (Fa_AGF—total surface: 144 ha—Fig. 2d). Extra-local and local scale areas boundaries were identified according to the landscape unit and ecotope concepts (Ingegnoli, 2002, 2015; Ingegnoli & Giglio, 2005). The farm scale agroforestry model boundaries were set coincident to the total surface of the selected agroforestry farm. The farm scale agroforestry model is focused on rice production and is based on: the maintenance and insertion of linear landscape features between fields (hedgerows and treelines with different ages, trees and shrubs species, and phytocoenoses structuring degrees); the maintenance and insertion of areal landscape features (woody areas, wetlands); the insertion of in-field linear trees and shrubs lines, which are located on linear embankments raised from rice fields ground level. Crop management is based on low-impact organic and traditional agriculture principles: crop rotations; land races cultivation; continuous flooding conditions in rice fields; diversified cover crops; green manuring; mechanical weed control; no

pesticides, herbicides, and fertilisers external inputs; lowered disturbance on habitats relevant to local fauna (continuously flooded trenches along field margins, reduced frequency of field margins mowing, and optimised machineries employment). The Farm scale agroforestry model represents a peculiarity, as the majority of the agricultural land in the studied context is managed through conventional rice production practices, based on: rice monoculture (modern cultivars); absence of crop rotations; field margins periodical chemical weeding; scarce maintenance and no new insertion of linear and areal landscape features; and diffused employment of chemicals and external inputs (herbicides, pesticides, and fertilisers).

Landscape ecology multi-scale analyses

Data collection

For the extra-local and local contexts featuring, we collected and analysed through GIS software (QGIS Desktop 3.26.0) the following data: geomorphology (Carta dei complessi idrogeologici 1:100.000), pedology (Carta dei suoli 1:50000; Carta dei suoli 1:250000), hydrology (Reticolo idrografico WFD 60/2000/CE), phyto-climate (Carta fitoclimatica d'Italia), regional land cover (Land cover Piemonte), historical land use (Ortofoto 1980–1990; Igmi aerial photos), vegetation (Carta forestale), protected areas (Aree protette e Rete Natura 2000), regional ecological network (PPR tav.P5), and other in-force land-planning tools (Geoportale

Piemonte). Spatial data layers mainly come from regional scale geodatabases (except for phyto-climate and vegetation national data bases), with a spatial data resolution coherent to our extra-local scale and local scale featuring purpose. Then, we conducted quantitative landscape ecology analyses, based on vector GIS-based representation of the landscape eco-mosaic patches (QGIS Desktop 3.26.0 software).

For extra-local scale analyses, single patches land use types categorisation was based on land cover maps (Geoportale Piemonte), which were validated through satellite images in doubtful cases (Google, 2023). Minimum patch size was set to 0.04 ha, in coherence with extra-local scale land cover maps resolution. Eighteen land use categories were identified as representative at this scale of analysis. For local scale and farm scale agroforestry model, patches boundaries were based on satellite images, regional land cover maps, and quick field checks, which were led in 2022. We used a higher detail in land use categories classification: 22 land use categories were identified as representative. Minimum patch size was set to 0.007 ha, in coherence to the higher level of detail in land use classification. Both for extra-local scale, local scale, and farm scale agroforestry model, patches surfaces and perimeters were cumulated for each land use category, which were clustered in three main landscape subsystems [forest and seminatural (FSN), agricultural (AGR), and artificial (ART)], according to Corine Land Cover classification (European Environment Agency, 2019). Each land use type clustering is reported in Fig. 2 legend.

Extra-local scale (E_La) landscape system analysis

Firstly, we detected the main landscape traits of the extra-local landscape system (E_La). We analysed the basic structural traits (Table 7), including the landscape eco-mosaic matrix (MTX) (percentage surface) (Turner & Gardner, 2015) and medium patch size (MPS) for the FSN and AGR subsystems (hectares) (Turner & Gardner, 2015), based on mean data for each land use category. We then analysed the biological territorial capacity (BTC), a synthetic indicator that evaluates the metastability degree of the landscape eco-mosaic. BTC unitary values for each land use type were taken from literature (Ingegnoli, 2002, 2006; Ingegnoli & Giglio, 1999), then multiplied by the surface of each land use category (BTC index), to then calculate the percentage contribution of each BTC unitary value to total BTC value (BTC% index) (Table 7). BTC unitary values spatial configuration were also represented through a BTC map. In consequence to these diagnostic analyses, we built a spatialized synthesis on the vulnerability and resilience drivers (VR analysis) of the extra-local scale landscape system (Adger, 2006; Gallopin, 2006; Gibelli et al., 2021; Janssen et al., 2006; Westman, 1978). VR maps are built by graphically

synthesizing the ecological functional traits of the landscape system under analysis. Land use components and planning tools constraints are classed according to their role as vulnerability and/or resilience drivers. For instance, linear infrastructures are classed as ecological barriers and habitat fragmentation drivers; whereas wide and mature woody areas are classed as biodiversity source areas (according to the analytical results interpretation). The ecological functional interpretation derived from land use components, planning tools constraints, and their relative spatial configuration is also graphically explicated. VR maps were used to identify a “prognosis” for extra-local scale, that is some specific planning strategies to reinforce the ecological functionality and balance of the extra-local scale landscape system.

Local scale (La) landscape system analysis

At local scale (La), we carried out more detailed analyses. We analysed the landscape apparatuses relative occurrence (percentage surface) (Table 7) and their spatial configuration (landscape apparatuses map), representing the physiological traits of the landscape system (eco-tissue model) (Brandt et al., 2000; Ingegnoli, 2002, 2015). As for extra-local scale, we evaluated the biological territorial capacity (BTC) values and their spatial configuration, to synthesise the ecological functional traits of the local scale landscape system. We then selected 16 landscape ecology indices, belonging to four different categories: basic structural traits, shape complexity indices, diversity indices, and connectivity indices (Ingegnoli, 2015; Ingegnoli & Giglio, 2005; Moser et al., 2002; Pielou, 1975; Turner & Gardner, 2015). Table 7 resumes, for each index, the scale of application, the applied formula, and references. Indices were selected referring to previous similar experiences (Vagge & Chiaffarelli, 2023a). Basic structural traits [landscape eco-mosaic matrix (MTX); medium patch size (MPS)] and shape complexity indices [Mean perimeter area ratio (MPAR), shape index (SI), patch fractal dimension (PFD)] were computed on each single patch surface value (Table 7); mean values were then computed for the FSN, AGR, and ART subsystems. Diversity indices were directly computed on total surface values of each land use category (Table 7): diversity_1a on TOT area (DIV1a); diversity_1b on each landscape subsystem area (DIV1b); diversity_2 proportionate to maximum diversity (DIV2); landscape structural diversity computed on diversity_1a (LSD1); landscape structural diversity computed on diversity_2 (LSD2). In connectivity analyses, the ecological quality of the linear connectivity components (links) was considered, by evaluating the ecological quality classes (EQC) of links (five possible classes, ranging [1–5]). This is a synthetic evaluation of four components of the ecological quality of links: stratification, development, continuity, and autochthonous degree; with values ranging [1–5] for

each of them). It is used for weighting the connectivity and circuitry indices values on the effective ecological quality of links (Connectivity (CON); weighted connectivity (WCON); circuitry (CIR); and weighted circuitry (WCIR); Table 7) (Vagge & Chiaffarelli, 2023a). The ratio between links and nodes (L/N) (Ingegnoli, 2015; Ingegnoli & Giglio, 2005) is also evaluated on their weighted variant (WL/N), where the number of links (L) is weighted on the EQC that they belong to (WL) (Table 7). The La analyses results were then synthesized, as for extra-local scale, in a map representing the main drivers of landscape vulnerability and resilience (VR) (Adger, 2006; Gallopin, 2006; Gibelli et al., 2021; Janssen et al., 2006; Westman, 1978), which was a useful tool to identify some “prescriptions” for local scale, that is some context-specific corrective interventions for biodiversity support and recovery.

Farm scale agroforestry model (Fa_AGF) landscape analysis

At farm scale agroforestry model (Fa_AGF), we applied the same landscape ecology indices as for local scale (Section “Local scale (La) landscape system analysis”, Table 7) (Ingegnoli, 2015; Ingegnoli & Giglio, 2005; Moser et al., 2002; Pielou, 1975; Turner & Gardner, 2015). All graphs were built with Past 4.13 software.

Farm scale design scenarios building and assessment

The applied multi-scale analytical methodology is intended to provide context-specific knowledge tools which are used to orient the identification of strategic design interventions aimed at supporting and recovering biodiversity values at the different scales through agroforestry implementation. The extra-local scale and local scale VR analyses and the identified extra-local scale planning strategies and local scale context-specific prescriptions as well as the results of the farm scale landscape ecology featuring were used to orient the identification of possible agroforestry-based new interventions at farm scale (Fa_AGF), aimed at answering to the detected landscape vulnerability traits. The agroforestry-based intervention types were chosen according to Santiago-Freijanes definition (Santiago-Freijanes et al., 2018): we focused on the insertion of new linear and areal landscape features (in-field and between fields hedgerows and treelines; filtering woody strips; small woody areas; and wetlands). Their spatial allocation was based on landscape ecological design principles (Dramstad et al., 1996; Forman & Godron, 1986), according to our analytical results (highlighted presence or absence of: barriers and fragmentation effects; sink areas; source areas; buffering areas; ecological corridors; and stepping stones). We did not use models for scenarios simulation, as our main focus was to assess

and orient real-life agricultural landscape design processes. Hence, we built two design scenarios (S1; S2) for Fa_AGF through GIS software, in coherence with: the multi-scale landscape ecology analyses results (identification of an optimised spatial configuration, strategic intervention types, and structural composition); the knowledge derived from local floristic-vegetational featuring (species selection and planting patterns). The two scenarios represent different degrees of intervention, which were discussed with farmers for feasibility check: S2 integrates the first scenario (S1) with more widespread and diversified interventions. To assess the contributions that might be given by each design scenario, we reapplied the diversity and connectivity indices to S1 and S2 (Table 7). This allowed us to compare the design scenarios effects on the landscape ecological quality and functionality, with respect to Fa_AGF current state. For connectivity and biological territorial capacity analyses, the S1 and S2 links EQC and BTC unitary values were attributed referring to an estimated projection to 10 years after implementation.

Results and discussion

Extra-local scale (E_La) results and discussion

Land use, geomorphology, pedology, bioclimate, and protected areas were analysed at over-local scale. The analyses on the E_La landscape eco-mosaic showed the extra-local landscape system to be relatively well-balanced, if compared to the most common Po Plain traits, which generally show higher over-simplification patterns (Ingegnoli, 2015). The agricultural matrix is set to 60.1% (Table 1; Fig. 4a): it can be considered quite stable (no severe ongoing transformation processes) (Forman, 1995), even if it represents a boundary condition, where agricultural functions are almost interwoven with natural, seminatural, and artificial components.

Medium agricultural patch size (MPS) is relatively low but highly variable (0.42 ha; dev.st 0.51) (Table 1; Fig. 5a). This is a positive trait from an ecological point of view (lowering of sink functions in the agricultural matrix and promotion of land use diversification thanks to the higher field margins proportion) (Fahrig et al., 2011; Hološková & Reif, 2024; Morelli, 2013). The medium patch size variability reflects the peculiar agricultural management traits of the northern area (where permanent grasslands, crop fields mixed with seminatural components, vineyards, and orchards are mostly represented, showing lower MPS values), whereas typical Po Plain conventional agriculture, such as rice monocultures (1.81 MPS), are mostly represented in the southern side. The forest and seminatural MPS is low (0.64 ha; dev.st. 0.74). The high FSN MPS variability is mainly due to differences between hydric natural components (0.10 ha MPS) and the other ones (1.00 ha MPS),

Table 1 Results on extra-local scale (E_La) basic structural traits (Matrix (MTX), medium patch size (MPS)), diversity indices (Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)),

and functional indices (Biological territorial capacity (BTC)) for the forest and seminatural (FSN), agricultural (AGR), artificial (ART) subsystems, and total landscape system (TOT)

	Subsystem	Basic structural traits		Diversity indices					Functional indices BTC
		MTX	MPS	DIV1a	DIV1b	DIV2	LSD1	LSD2	
E_La	FSN	30.58	0.64	0.51	0.83	0.18	2.77	0.68	5.32
	AGR	60.14	0.42	0.80	0.83	0.28	4.09	1.03	1.14
	ART	9.28	0.84	0.38	1.71	0.13	2.09	0.51	0.78
	TOT	100.00	0.68	1.70	3.36	0.59	7.12	2.00	2.39

See Table 7 for details on the applied indices

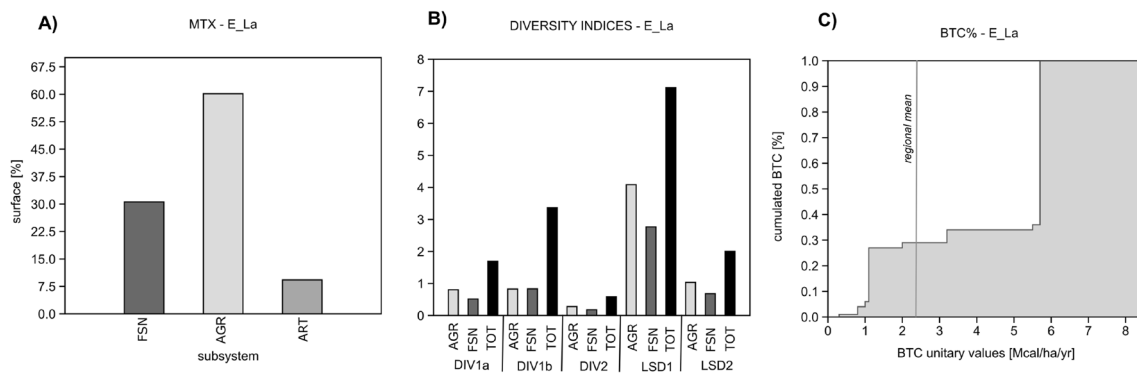


Fig. 4 Extra-local scale (E_La) landscape ecology indices values. **a** Landscape eco-mosaic matrix values (MTX); **b** diversity indices values (Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1;

LSD2)) for the AGR and FSN subsystems and for the TOT landscape system; **c** biological territorial capacity cumulated contributions (BTC%; y-axis) of each BTC unitary value (x-axis). See Table 7 for details on the applied indices

also including woodlands, which register the highest MPS values (1.71 ha). This reflects the presence of natural and seminatural patches that can be considered sufficiently wide to sustain their source functions (prevalence of edge habitats, but also interior habitats are represented) (Dramstad et al., 1996; Forman, 1995; Ingegnoli & Giglio, 2005), which might positively contribute to the other natural and not-natural components ecological quality.

Total landscape diversification values are relatively positive, for an agricultural context (Table 1; Fig. 4b). All diversity indices show the same pattern, with higher diversity values for the AGR subsystem, if compared to the FSN one. Agricultural components heterogeneity reflects the geomorphological and pedological variability between the northern and southern E_La sub-areas (Fig. 4b).

The total biological territorial capacity value (BTC) of the E_La landscape system is set to 2.39 Mcal/ha/yr (Table 1), a positive value for an agricultural landscape, which is closed to the regional BTC mean value (2.35 Mcal/ha/yr) (Ingegnoli, 2015). The biological territorial capacity cumulated contributions (BTC%) given by the

different land use categories also show a positive diversified distribution over the extra-local landscape system (step pattern line) (Fig. 4c). This reflects the discrete diversification and quite balanced distribution of the land use categories related to higher BTC values (i.e. higher homeostatic and homeorhetic capacities and higher self-maintenance capacity) (Ingegnoli, 2002, 2015). These traits reflect the potential threats that could derive from a conventional agricultural model widespread distribution, as it is also highlighted in the BTC values map (Fig. 5c), where we displayed the spatial configuration of the different BTC unitary values related to land use categories. The BTC map highlights the different behaviours of the northern, central, and southern areas of the E_La landscape system. The highest BTC values are concentrated in the northern area, where also the lowest ones are represented, linked to the East–West urbanisation axis. The southern area shows highly homogeneous BTC values, dominated by the agricultural low BTC values. The central area shows mixed patterns, with alternate lenses of higher and lower BTC.

These analyses allowed us to build a synthetic, spatial-based, interpretation on the current vulnerability, and resilience drivers of the E_La landscape system (VR analysis), which are described and synthesised in a VR map (Fig. 4d).

The macro-scale context-specific planning strategies were directly derived from the VR analysis results:

- Reduce the landscape ecological dichotomy between N-S, by strengthening the N-S and E-W ecological corridors and by creating a new NE-SW ecological corridor;
- Strengthen and spread buffering functions among the rural-natural interface, foster the areas with biodiversity source functions, and reduce diffused sink areas effects (specifically in the central and southern areas), by diversifying the agricultural matrix through the implementation of blue and green infrastructures and by promoting on-farm landscape features management;
- Mitigate the SW-NE and W-E infrastructure barrier effect, by equipping main roads with green bridges, wildlife tunnels, and buffering woody strips.

Local scale (La) landscape results and discussion

The local scale landscape system is in the northern-central area of extra-local scale, along the transition between the northern belt (with higher land use diversification and natural components occurrence) and the Southern one (with a predominant, more simplified, and agricultural matrix). The local context is distinguished by the presence of a stream, and its associated main ecological corridor, and the existence of regulatory constraints which preserved some northern woody areas (oriented natural reserve). Nonetheless, the spatial configuration of these components is dichotomous: agricultural and natural functions tend to be segregated.

Local scale shows a good balance between the agricultural matrix (MTX-AGR: 68.6%) and the forest and seminatural components (MTX-FSN: 26.4%) (Table 2; Fig. 6a) if compared to the Po Plain predominant traits (Ingegnoli, 2006, 2015).

Medium patch size (MPS) of forest and seminatural patches is quite high for an agricultural context (1.91 ha; dev. st 5.76) (Table 2). Nonetheless, FSN patches show high MPS variability (Fig. 6b, c), which reflects the presence of different natural and seminatural patches types: woody patches (43 patches among 185 total FSN patches) have the highest MPS (6.24 ha), with some significant outliers, representing wide woody areas along the river axis (Fig. 7d), currently supporting important source functions (Dramstad et al., 1996). Differently, the more numerous forest and seminatural patches interspersed among the agricultural matrix have lower MPS values (grass strips, small woody areas, uncultivated areas with spontaneous recolonization, wetlands, and woody belts: 0.37 ha MPS) (Fig. 7d). They contribute to

the improvement of the agricultural matrix quality (Fahrig, 2001). Agricultural patches MPS is lower than 1 ha (0.89 ha; dev.st 0.80), which should be positively interpreted (reduction of over-size related sink effects Chen et al., 2008; Dramstad et al., 1996), even though its variability is consistent (but lower than FSN MPS variability) (Fig. 5b, c). La artificial patches MPS is generally low (0.16 ha), the highest values are related to private green areas (0.26 ha) (Figs. 5b, c and 7d); this reflects the restrained impact of artificial functions among the local scale landscape system.

La landscape apparatuses are quite well-balanced (Fig. 7a): natural habitat functions are well represented, especially for what concerns stabilisation functions (19.9%), which are sustained by the high-metastability woodlands, i.e. patches with high resistance to disturbances (Ingegnoli, 2002). Protective and resilience functions are partially sustained but are limited by the predominant productive functions. Low connectivity functions values underline the current lack of interchanges and positive interactions between the natural/seminatural and agricultural components of the local landscape system.

The total biological territorial capacity (BTC) value of the local scale landscape system reaches 2.56 Mcal/ha/yr (Table 3), a higher value compared to the extra-local scale landscape system (Table 2). Biological territorial capacity cumulated contributions (BTC%) show a positive diversified distribution too (step pattern line) (Fig. 6g). The surfaces of the different land use categories (related to different BTC unitary values) are quite well-balanced. Despite this, their spatial distribution shows dichotomic patterns (Fig. 7b): the highest BTC values are all concentrated along the river axes, whereas the agricultural areas lack in medium-high BTC interspersed patches. This spatial segregation implies that current landscape homeostatic and homeorhetic capacities are only partially sustained.

Shape complexity indices are a measure of the interaction degree between patches, which is generally a consequence of the naturality/spontaneity of their evolution through space and time (Dramstad et al., 1996; Moser et al., 2002; Turner & Gardner, 2015). At local scale, the agricultural patches are quite homogeneous on their shape complexity values (Mean perimeter area ratio (MPAR), shape index (SI), and patch fractal dimension (PFD) which are generally lower than the natural/seminatural patches values (Table 2). MPAR index shows the least sensitivity to shape complexity changes, whereas SI and PFD indices are more efficient in detecting differences (see natural breaks values classification on shape complexity maps—Fig. 7e). Higher values and higher variability are registered for the FSN subsystem (Table 2; Fig. 6d–f). This is generally considered as a positive trait, as it promotes exchanges between FSN patches and the agricultural context (thanks to the fact that the overall FSN matrix components are not under-expressed) (Morelli,

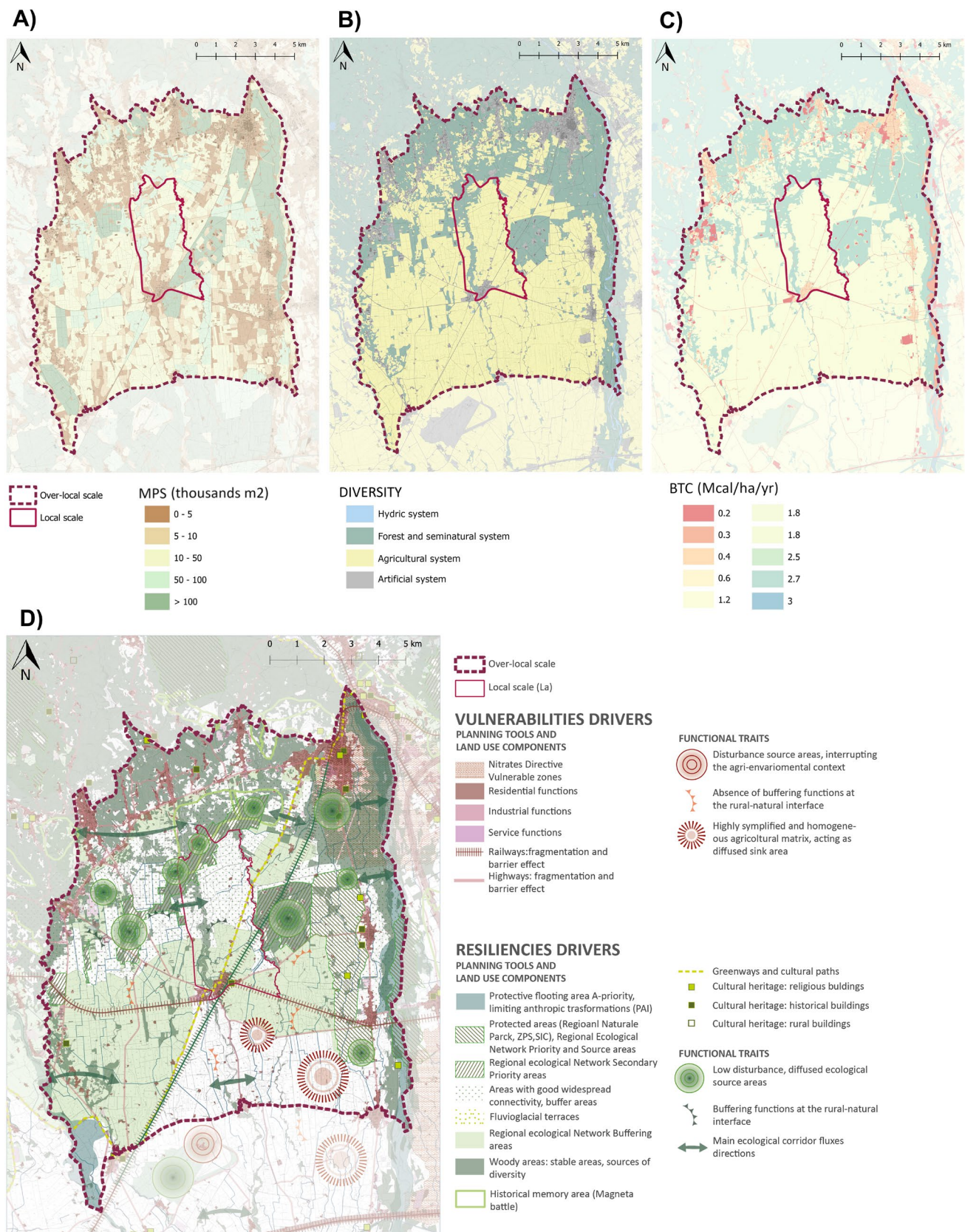


Fig. 5 Maps on extra-local scale (E_La) landscape structural and functional main traits. **a** Medium patch size (MPS) values spatial configuration; **b** spatial configuration of the single patches contributions to the landscape system diversity values; **c** biological territorial capacity (BTC) values map, highlighting the spatial configuration of the different patch types, differently contributing to BTC values; and **d** vulnerability and resilience drivers map (VR analysis). See Table 7 for details on the applied indices

2013). On the other side, their higher shape complexity can promote the exposure on FSN components to the impacts coming from the agricultural matrix (Fig. 6e). This issue can be mitigated by developing buffering functions between the two systems. This can be achieved by improving the agricultural matrix quality, its environmental heterogeneity, and connectivity, especially at the natural-agricultural interface: a recognised strategy to sustain higher biodiversity values in rural systems (Boinot et al., 2023; Donald & Evans, 2006; Fahrig, 2001; Jules & Shahani, 2003; Morelli, 2018). Artificial patches generally show the highest mean shape complexity values (except for SI), which is also due to their low medium patch size (MPS). Their variability is high; the highest values are associated to private green areas and residential buildings, which are generally clustered between each other, and which do not represent highly impacting land uses.

Locale scale landscape system diversity values show positive patterns, reflecting the medium-to-low level of landscape over-simplification, if compared to the most common Po Plain monocultural landscapes. All diversity indices variants [Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)] register the same pattern (Table 3; Fig. 6h): AGR patches show higher heterogeneity values than the FSN components, and the total diversity values are generally positive. Higher forest and seminatural components diversification might be sought, by better spreading them across the agricultural matrix (Donald & Evans, 2006; Fahrig et al., 2011; Morelli, 2013, 2018).

La connectivity and circuitry functions analysis showed medium values (Table 3; Fig. 6i), with no great differences passing from normal indices [Connectivity (CON), circuitry (CIR), links/nodes ratio (L/N)] to the ones weighted on ecological quality classes (EQCS) [Weighted connectivity (WCON), weighted circuitry (WCIR), and weighed links/nodes ratio (WL/N)]. This reflects the higher abundance of medium-to-high EQCS links, which are mostly located along the river N-S axes, which represent high quality natural and seminatural areas (the protected northern area) or medium quality areas (black-locust dominated woods, but well developed and with high continuity values) (Fig. 2c). Links/nodes ratio values show positive values, but they could be improved to at least $L/N=2$ to also increase circuitry functions. Connectivity map (Fig. 7c) highlights the

spatial segregation of connectivity functions along the two main N-S river axes, and the complete absence of E-W interconnections. The predominant agricultural matrix is currently not able to support effective connectivity functions and foster genetic, resources, and information exchanges across the existing natural and seminatural areas (Dramstad et al., 1996; Fahrig, 2003; Taylor et al., 1993; Tewksbury et al., 2002). This trait impairs the potential source functions of the forest and seminatural areas (Litza et al., 2022; Sitzia, 2007).

These analyses and evaluations brought us to the identification of the main vulnerability and resilience drivers of the local scale landscape system (VR analysis), which were synthetized in a VR map (Fig. 6f), as for E_La scale. This allowed us to identify a set of context-specific prescriptions, that is, some corrective interventions to be applied:

- Insert a diffused network of hedgerows and treelines, supporting exchanges across the rural-natural interface
- Priority to areas lacking buffering functions between the natural/seminatural and agricultural components
- Reconfigure sink areas through sparse linear and areal landscape features
- Insert small woody areas and wetlands as sparse stepping stones inside the agricultural matrix
- Improve pre-existing woods quality
- Reduce agricultural field size
- Insert small-size permanently flooded and revegetated ditches along rice field margins
- Implement in-field agroforestry
- Insert wildlife crossing tunnels and well-structured hedgerows and woody belts along main roads, going both parallel and perpendicular to road axis (*T structure*), to promote the ecological interactions with the surroundings
- Implement the SW-NE Greenway

Farm scale agroforestry model (Fa_AGF) landscape results and discussion

In the agroforestry farm system (Fa_AGF), as expected, the agricultural matrix is predominant (94.3%), but also forest and seminatural components are represented (4.6%) (Table 4; Fig. 8a), differently from conventional management typical farm models, where agricultural land use is generally completely unbalanced, at the detriment of the natural and seminatural ones. We can state that Fa_AGF represents an intermediate configuration.

Medium agricultural patch size (MPS) is over 1 ha in Fa_AGF (1.48 ha; st.dev. 0.95) (Table 4; Fig. 9a). Small agricultural MPS is generally more suitable for reducing sink effects (source-sink model) (Chen et al., 2008), and for enhancing the number of potential ecological connectivity components

Table 2 Local scale (La) results on: basic landscape eco-mosaic structural traits (Matrix (MTX), medium Pptch size (MPS)), functional indices (Biological territorial capacity (BTC)), and shape complexity indices (Mean perimeter area ratio (MPAR), shape index (SI), patch fractal dimension (PFD)) for the agricultural (AGR), forest and seminatural (FSN), artificial (ART) sub-systems, and total landscape system (TOT)

Index		Basic structural traits				Functional indices				Shape complexity indices								
		MTX		MPS		BTC		TOT	ART	FSN	AGR	MPAR		SI		PFD		
Sub-system		AGR	FSN	ART	AGR	FSN	ART					TOT	AGR	FSN	ART		TOT	AGR
La	Mean	68.6	26.4	4.9	0.89	1.91	0.15	0.80	2.56	0.06	0.12	0.11	1.28	1.95	1.42	1.34	1.45	1.40
	Min				0.04	0.01	0.01	0.01		0.02	0.02	0.02	1.07	1.07	1.03	1.25	1.27	1.25
	Max				7.86	53.54	1.12	53.54		0.25	0.44	0.64	2.35	6.43	6.43	1.55	1.74	1.82
	Dev.St				0.80	5.76	0.20	2.08		0.03	0.08	0.09	0.17	0.89	0.46	0.04	0.10	0.10

See Table 7 for details on the applied indices

(Dramstad et al., 1996; Fahrig et al., 2011; Hološková & Reif, 2024; Morelli, 2013). Generally, 1 ha is considered as boundary value for over-size issues in agricultural land uses (Ingegnoli, 2015). In this case, the medium-high MPS values in Fa_AGF do not consider the presence of the in-field agroforestry embankments, which contribute to the lowering of over-size effects such as sink functions (Dramstad et al., 1996; Morelli, 2013). Forest and seminatural patches MPS is quite low (0.34 ha; dev.st 0.50) and shows low variability (values dispersion is significantly lower than AGR patches) (Fig. 8b). The highest values are linked to the woody patches (1.47 ha MPS) (Fig. 8a). This reflects the current state of natural/seminatural components, the majority of which is made of small-size areas (grass strips, small woody areas, wetlands, and woody belts) (Fig. 8a). Higher MPS values would positively influence their source areas functions, better representing interior habitat conditions among the agricultural matrix (Dramstad et al., 1996; Forman, 1995). Nonetheless, productive functions must be kept predominant in the farming system, and the interspersed presence of small size, but well interconnected, natural/seminatural components lets them act as stepping stones, and positively contribute to the ecological exchanges and balancing effects at farm scale (Boinot et al., 2023; Donald & Evans, 2006; Dramstad et al., 1996; Fahrig, 2001).

Total biological territorial capacity (BTC) values are lower than the local scale and extra-local scale landscape systems (1.44 Mcal/ha/yr in Fa_AGF) (Table 4). This value is significantly lower than the regional mean value (2.35 Mcal/ha/yr) (Ingegnoli, 2015) and reflects the highly predominant agricultural functions among the agroforestry farming system. Biological territorial capacity cumulated contributions (BTC%) in Fa_AGF have an intermediate behaviour (Fig. 8c). Most surface has medium-to-low BTC values: the main line step is at 1.3, the BTC unitary value associated to rice fields in rotation; but other minor line steps are present, related to both lower and higher BTC unitary values, included the right-side final step related to woody areas contributions (8.1 Mcal/ha/yr BTC unitary value) (Fig. 8c). Such patterns reflect a relatively vulnerable and instable condition (low-to-medium self-maintenance capacity), which is intrinsic to agricultural dominated landscapes; but which are generally worse in highly simplified conventional farming contexts, where the BTC-cumulated contributions curve would show a single main step at low BTC values (i.e. 1.1 Mcal/ha/yr BTC unitary value associated to conventional crop fields). The BTC map (Fig. 11a) highlights: the positive role played by the already existing semi-natural components; the need for further spreading higher BTC contributions among the agricultural patches.

All shape complexity indices [Mean perimeter area ratio (MPAR), shape index (SI), and patch fractal dimension (PFD)] show higher shape complexity for the FSN

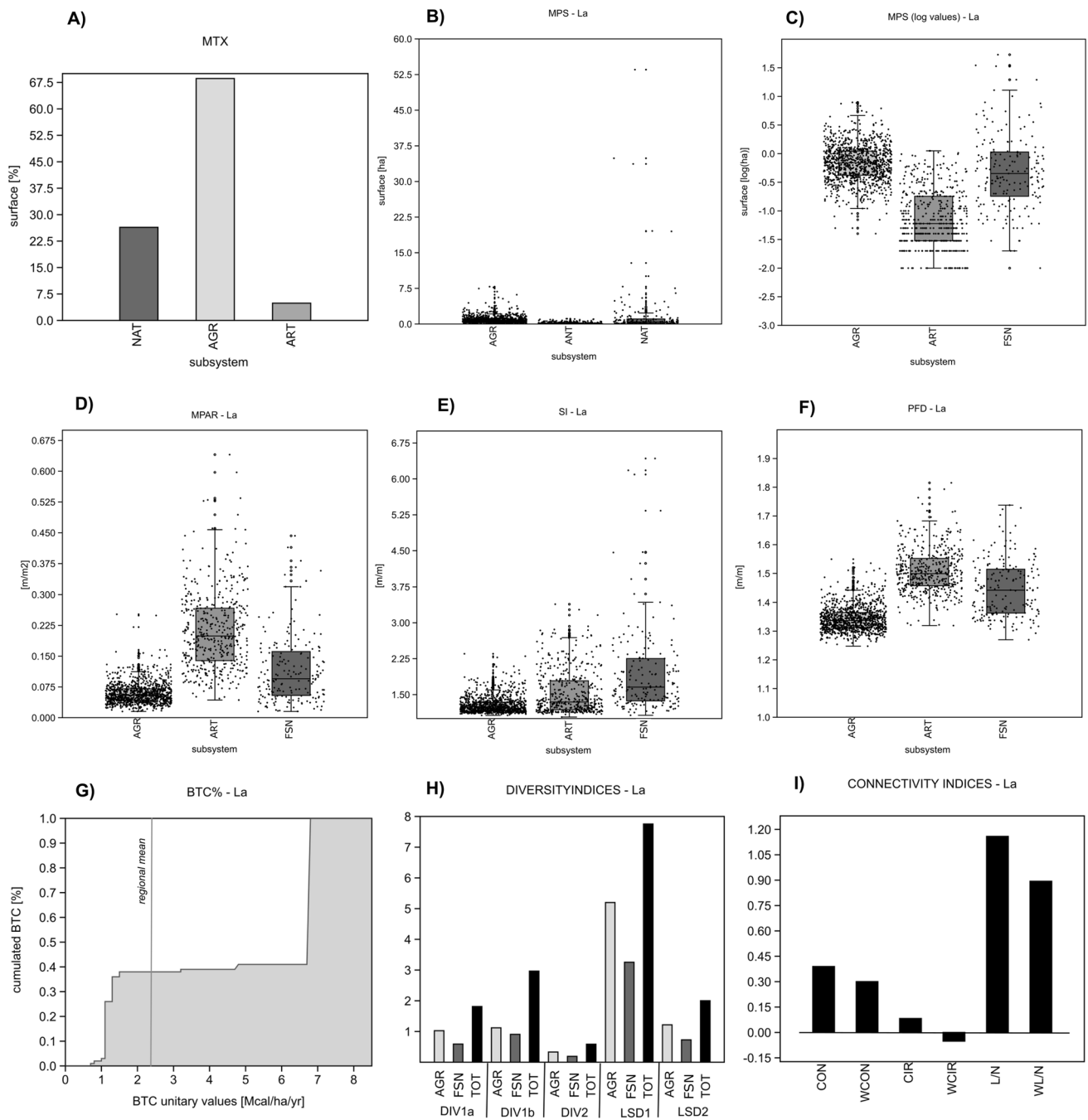


Fig. 6 Local scale (La) landscape ecology indices values. **a** Landscape eco-mosaic matrix values (MTX); **b, c** Medium patch size values (MPS), original values (**b**) and log values (**c**); **d–f** shape complexity indices values (Mean perimeter area ratio (MPAR); shape index (SI); patch fractal dimension (PFD)), for the AGR, ART, and FSN landscape subsystems; **g** Biological territorial capacity cumulated contributions (BTC%; Y-axis) of each BTC unitary value (X-axis); **h** diversity indices values (Diversity1a/total area (DIV1a); diversity1b/

landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)) for the AGR and FSN subsystems and for the TOT landscape system; **i** connectivity indices values, original values (Connectivity (CON), circuitry (CIR), links/nodes ratio (L/N)) and ecological quality classes (EQCS), weighted variants (Weighted connectivity (WCON), weighted circuitry (WCIR), weighed links/nodes ratio (WL/N)). See Table 7 for details on the applied indices

components of Fa_AGF, which also show the highest values dispersion (Table 4; Figs. 8d–f and 9b). The studied agroforestry farm represents a low-impact agricultural

management model (no chemical inputs, low machinery use, reduced soil disturbance, permanent soil cover, crop diversification, and in-field linear landscape features). In

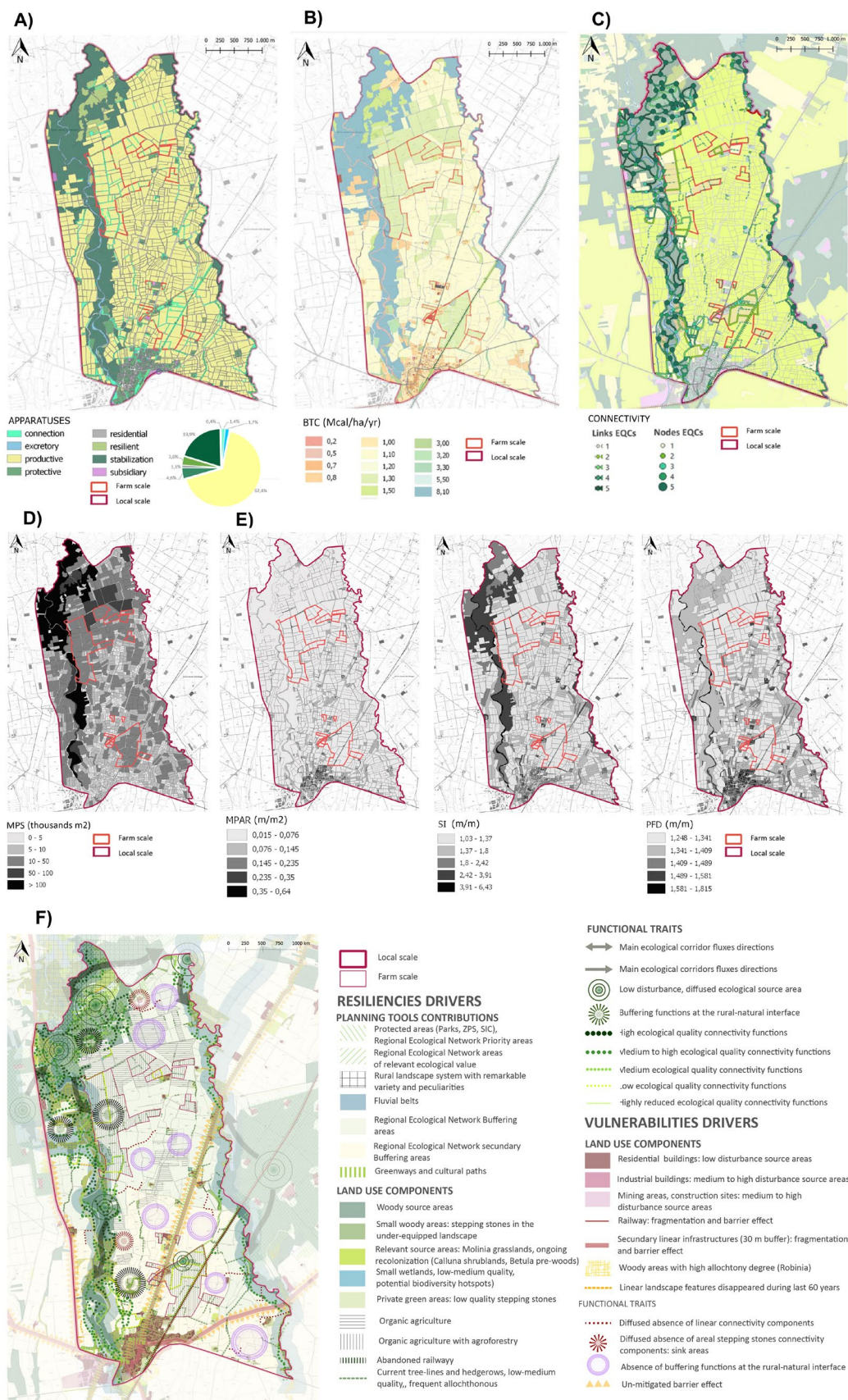


Fig. 7 Maps on local scale (La) landscape structural and functional main traits. **a** Landscape apparatuses spatial configuration and relative proportion (% surface values); **b** Biological territorial capacity (BTC) values map, highlighting the spatial configuration of the different patches types, differently contributing to BTC values; **c** the connectivity graph analysis; **d** Medium patch size (MPS) values spatial configuration; **e** spatial configuration of the shape complexity indices (Mean perimeter area ratio (MPAR), shape index (SI), patch fractal dimension (PFD)) values related to each patch (five classes clustered on natural breaks values); and **f** vulnerability and resilience drivers map (VR analysis). See Table 7 for details on the applied indices

such a context, higher natural/seminatural patches shape complexity (which reflects the presence of more convoluted patch shapes and higher available boundary surface) can positively support positive exchanges (resources, energy, genetics, and information fluxes) from the natural/seminatural patches towards the agricultural matrix (Dramstad et al., 1996); the potential impacts coming from the medium-to-high quality agricultural matrix can be considered secondary to the aforementioned processes (Fahrig, 2001). Certainly, a further increase of forest and seminatural components among Fa_AGF would further rebalance these two opposite processes (Donald & Evans, 2006).

The diversity indices values for the Fa_AGF AGR subsystem highlight positive heterogeneity values (Table 5; Fig. 8g), if considering that the most typical Po Plain conventional rice production farm model generally shows high land use homogeneity. All indices (except for DIV1b) show higher values for the AGR subsystem, compared to the natural/seminatural one (FSN), accounting for the positive contribution given by crop diversification. Parallely, this pattern suggests the opportunity for further diversifying the Fa_AGF forest and seminatural components.

Connectivity functions appear to be well represented in the farm scale landscape system. Connectivity and circuitry indices show positive values, if considering the predominant agricultural matrix (Table 5; Fig. 8h). Gaps between the normal indices [Connectivity (CON), circuitry (CIR), links/nodes ratio (L/N)] and the ones weighted on ecological quality classes (EQCS) [Weighted connectivity (WCON), weighted circuitry (WCIR) and weighed links/nodes ratio (WL/N)] are higher than at La Scale. This reflects the higher relative abundance of low-to-medium EQCS linear landscape features (generally, they show good autochthony values, but lower development, stratification, and continuity values). This pattern allows us to quantify the current positive contribution given by the already existing in-field and in-between fields hedgerows and treelines. Parallely, it highlights the need for a more widespread, interconnected linear landscape features development, also working on their EQCS improvement (Dondina et al., 2016; Tewksbury et al., 2002), to promote better balanced genetic exchanges

between the forest/seminatural and agricultural components (Litza et al., 2022; Sitzia, 2007).

Farm scale design scenarios corrective contributions

To build farm scale design scenarios, multi-scale analyses results are key knowledge tools. To synthetize, in this case study, the wider-scale (E_La; La) agricultural landscape systems represent mixed conditions, if compared to the most common Po Plain traits, which generally show higher oversimplification patterns. In E_La and La both intensively managed and highly simplified agricultural components and natural and seminatural components co-exist, even if they are often physically separated, in consequence to the geomorphological traits and the related diachronic land use evolution. At both scales of analysis, some ecological gaps and dichotomic functional organisation patterns are identified that are currently compromising a wide scale conjunction and positive coexistence of agricultural and natural functions. At farm scale, the studied agroforestry farm management model represents an alternative to the upper scale dichotomic spatial and functional configuration. If compared to a conventional management model (the most spread one among the La and E_La agricultural matrices), it can bring a positive contribution to the re-activation and spread of significant ecological functions, which depend on the agricultural matrix quality (Donald & Evans, 2006; Fahrig, 2001; Jules & Shahani, 2003), the agricultural landscape complexity, its diversification (Benton et al., 2003; Fahrig et al., 2011; Stein et al., 2014), and its connective role (Fahrig, 2003; Taylor et al., 1993; Tewksbury et al., 2002). A recent study specifically pointed out how agricultural linear landscape features multifunctionality depends on landscape features density in the landscape, as a result of greater habitat amount, connectivity, and environmental heterogeneity (Boinot et al., 2023).

According to these statements, in the studied context, the agroforestry management can have a role in mitigating the current dichotomic functional configuration of the wider-scale landscape systems, by softening the agricultural land and consequently offsetting the impacts coming from the spatial segregation of natural and seminatural habitats (Donald & Evans, 2006). Fa_AGF currently acts as a buffering belt between the western natural river axis and the eastern highly simplified agricultural matrix. The landscape ecology analyses highlighted how this role could be further sustained. The applied multi-scale landscape ecology analytical approach was found to be a suitable tool both to account for these positive contributions and to highlight the gaps between the current contributions given by agroforestry to the landscape eco-mosaic diversification and the potential ones, referring to the specific local context traits: their main vulnerability drivers, to be counterbalanced, and their

Table 3 Local scale (La) results on: diversity indices (Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)) for the forest and seminatural (FSN), agricultural (AGR) subsystems, and total landscape system (TOT); connectivity indices (Connectivity -CON-; weighted connectivity -WCON-; circuitry -CIR-; weighted circuitry -WCIR-; links/nodes ratio -L/N-; weighted links/nodes ratio -WL/N-) for the total landscape system

Index	Diversity indices						Connectivity indices					
	DIV1a			DIV1b			DIV2			LSD1		
	AGR	FSN	TOT	AGR	FSN	TOT	AGR	FSN	TOT	AGR	FSN	TOT
La	1.03	0.59	1.81	1.12	0.91	2.97	0.33	0.19	0.59	5.20	3.25	7.76
										1.22	0.73	2.00
										0.39	0.30	0.08
										-0.05	1.16	0.89

See Table 7 for details on the applied indices

Table 4 Farm scale (Fa_AGF current state and design scenarios (S1, S2)) results on: basic landscape eco-mosaic structural traits (Matrix (MTX), medium patch size (MPS)); functional indices (Biological territorial capacity (BTC)); and shape complexity indices (Mean perimeter area ratio (MPAR), shape index (SI), patch fractal dimension (PFD)) for the agricultural (AGR), forest and seminatural (FSN), artificial (ART) subsystems, and total landscape system (TOT).

Index	Basic structural traits						Functional indices						Shape complexity indices					
	MTX			MPS			BTC			MPAR			SI			PFD		
	AGR	FSN	ART	AGR	NFSN	ART	AGR	FSN	ART	AGR	FSN	TOT	AGR	FSN	TOT	AGR	FSN	TOT
Fa_AGF	Mean	94.3	4.6	1.1	1.48	0.34	0.34	1.25	1.29	4.75	0.92	1.44	0.05	0.20	0.08	1.24	2.31	1.45
	Min				0.04	0.02	0.06	0.02					0.02	0.07	0.02	1.10	1.03	1.03
	Max				4.44	2.10	0.91	4.44					0.25	0.37	0.37	1.65	5.34	5.34
	Dev.St				0.95	0.50	0.39	0.99					0.04	0.09	0.07	0.12	1.12	0.64
Fa_AGF_S1									1.29	4.75	0.92	1.44						
Fa_AGF_S2									1.29	5.07	0.92	1.61						

See Table 7 for details on the applied indices

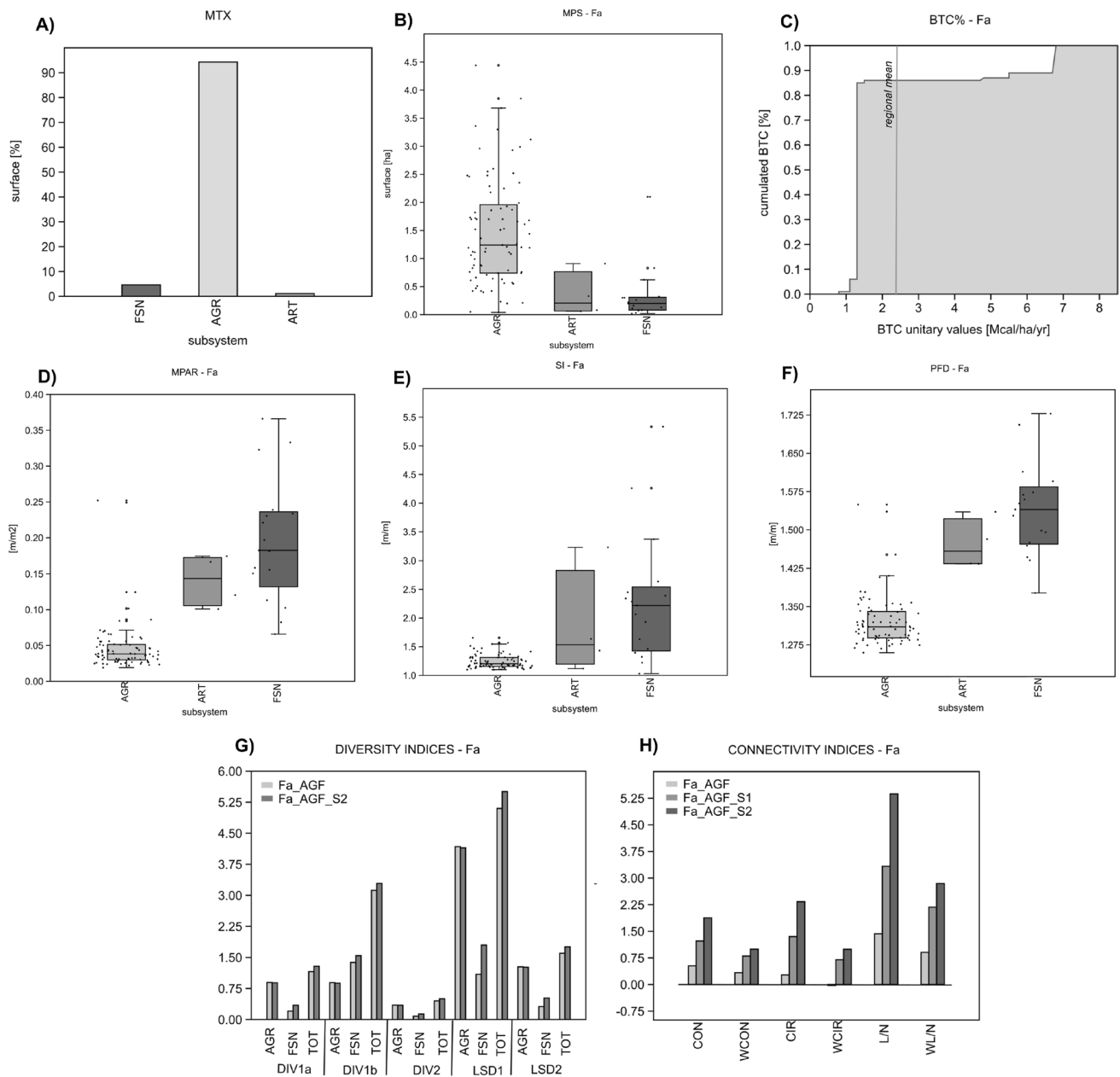


Fig. 8 Farm scale (Fa) landscape ecology indices values. **a** landscape eco-mosaic matrix values (MTX); **b** Medium patch size values (MPS); **c** Biological territorial capacity cumulated contributions (BTC%; Y-axis) of each BTC unitary value (X-axis); **d–f** shape complexity indices values (Mean perimeter area ratio (MPAR); shape index (SI); patch fractal dimension (PFD)), for the AGR, ART, and FSN landscape subsystems; **g** diversity indices values (Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)) for the AGR and FSN subsystems and for the TOT landscape system,

comparing current state to S2 design scenario (see Section 3.4 Farm scale design scenarios corrective contributions); **h** connectivity indices values: original values (Connectivity (CON), circuitry (CIR), links/nodes ratio (L/N)) and ecological quality classes (EQCS) weighted variants (Weighted connectivity (WCON), weighted circuitry (WCIR), weighed links/nodes ratio (WL/N))), comparing current state to S1 and S2 design scenarios (see Section 3.4 Farm scale design scenarios corrective contributions). See Table 7 for details on the applied indices

resilience drivers, to be supported and promoted through farm scale interventions (Fig. 5d; Fig. 7f). In coherence with the statements derived from the multi-scale landscape ecology analyses, we hypothesised to further improve the

contributions given by Fa_AGF to the landscape ecological quality, by building two design scenarios: represents a first degree of agroforestry implementation; S2 represents a more widespread agroforestry implementation (Fig. 10). In S1, we



Fig. 9 Farm scale (Fa_AGF) main landscape structural traits. **a** Medium patch size (MPS) values spatial configuration; **b** spatial configuration of the shape complexity indices (Mean perimeter area ratio

(MPAR), shape index (SI), patch fractal dimension (PFD)) values related to each patch (five classes clustered on natural breaks values). See Table 7 for details on the applied indices

only included new linear landscape features (different types of shrub hedgerows, trees and shrubs hedgerows, and tree-lines), as described in detail in Table 6. In S2, we included further linear landscape features, integrating S1, and newly inserted areal landscape features (small woody areas, wetlands, and filtering woody strips) (Table 6). The overall areal forest and seminatural components rise +4% in Fa_AGF S2, compared to current state. The linear landscape features pass from 15 total km to 26 km in S1 to 55 km in S2; that equals a mean density of 117 m/ha of linear landscape features in current state, 204 m/ha in S1, 428 m/ha in S2 (total Fa_AGF surface: 127.5 ha) (Table 6). In Po Plain, the average linear landscape features density was about 200 m/ha in the early XXth century, which collapsed to about 10 m/ha at present time; a Po Plain study identified a density of 80–120 m/ha as boundary condition to positively support higher biodiversity values (Groppali & Camerini, 2006). Hence, Fa_AGF already shows highly positive values in current state. The final S2 configuration represents a balanced compromise between the preservation of the agricultural productive functions and the concurrent support to the ecological ones. Newly inserted natural and seminatural patches were derived from the conversion of field marginal areas, sacrificing as little productive surface as possible (Fig. 10).

Such interventions are intended to contribute to the rising of in-farm biological territorial capacity values (BTC) and make them better spatially distributed, reducing the current dichotomic separation between annual crop fields (lowest agricultural patches BTC unitary values) and woody areas (highest BTC unitary values). Moreover, such interventions are supposed to rise the micro-habitat

diversification and their spatial interconnection (“bocage” landscape model (Boinot et al., 2023)), based on the ecological corridors and stepping stones principles (Donald & Evans, 2006; Dramstad et al., 1996; Forman, 1995; Franco, 2004). This answers to the highlighted need of strengthening the diversification values of Fa_AGF to foster its contributions as buffering belt between the rivers axes natural functions and the widespread, homogeneous agricultural functions dominating the local landscape system.

The recomputing of diversity indices on the design scenarios shows the positive contribution given by the insertion of new areal seminatural landscape features in slightly rising FSN heterogeneity values, and TOT farm heterogeneity values. No relevant changes are detected for the AGR subsystem, as the only changes only derived from the subtraction of some agricultural surfaces, converted to seminatural land uses. In S2, only 4% of the Fa_AGF current agricultural surface is “sacrificed” to natural functions, but this allows a mean +9% rise in-farm scale (TOT) diversity indices, if compared to Fa_AGF current state (mean value of the gaps registered for the DIV1a, DIV1b, DIV1, LSD1, LSD2 indices (Table 5)). The highest gaps are registered by DIV1a and DIV2 indices: respectively, +11.2% and +11.1% compared to TOT current state values. This is coupled to an increase in total biological territorial capacity value, which is computed considering the status of the designed interventions 10 years after implementation (from 1.47 Mcal/ha/yr in current state to 1.61 Mcal/ha/yr in S2) (Table 4). BTC map also shows the scattered presence of slightly higher BTC patches (Fig. 11a),

Table 5 Farm scale (Fa_AGF current state and design scenarios (S1, S2)) results on: diversity indices (Diversity1a/total area (DIV1a); diversity1b/landscape subsystem (DIV1b); diversity2 (DIV2); landscape structural diversity1/2 (LSD1; LSD2)) for the agricultural (AGR) and forest and seminatural (FSN) subsystems and total landscape system (TOT); connectivity indices (Connectivity (CON), circuitry (CIR), and links/nodes ratio (L/N)), and ecological quality classes (EQCS) weighted variants (WCON), weighted circuitry (WCIR), and weighted links/nodes ratio (WL/N)) for the total landscape system

[illegible]

See Table 7 for details on the applied indices

which partially contribute to the rebalancing of metastability properties among the agroforestry farming system.

Concerning connectivity functions, the recomputing of connectivity and circuitry indices shows a clear positive gradient, going from current state to S1 and to S2 (Table 5; Figs. 7h and 11b). The same pattern is outlined if comparing the links/nodes ratio. The overall linear landscape features length rises +266% in S2, compared to Fa_AGF current state. Parallely, connectivity index values (CON) rise +257%, Circuitry (CIR) rises +763%, links/nodes ratio (L/N) rises +276%. Weighted connectivity (WCON) and weighted links/nodes ratio (WL/N) were computed referring to the newly inserted linear landscape features expected status 10 years after plantation; their values show lower positive gaps (respectively: +199% in WCON; +215% in WL/N). Weighted circuitry values (WCIR) show the highest gap, but this is due to the anomalous WCIR negative values in current state. WCON and WL/N values reflect the fact that in S2, there is a higher amount of lower ecological quality classes (EQCs) linear elements, due to the lower development degree of the newly inserted linear landscape features (projection to 10 years after implementation), if compared to the fewer ones, but already well developed, represented in the current state scenario (Fig. 11b).

These evaluations allow us to account for the positive contributions given by the S1 and S2 insertion of hedgerows and treelines, which directly influence the ecological dynamics inside the agricultural patches (new biotic, resources, genetic and information fluxes, promoting a better balance between generalist and interior species). Besides connectivity functions, the reconstituted in-farm ecological network also supports, in a synergistic way, habitat diversification (insertion on new linear and well-structured phytocoenoses representing new evolving habitats in the agricultural landscape matrix). These components can balance the negative effects due to agricultural patches over-size. As a whole, these changes improve the agricultural matrix quality among Fa_AGF, thanks to the maintaining and insertion of a diversity of landscape features, which are coupled to low-impact agricultural practices. A higher quality agricultural matrix is recognised to reduce species habitat extension needs for populations persistence (Fahrig, 2001) and natural/seminatural habitats fragmentation impacts (Jules & Shahani, 2003). This supports the positive role that could be played by the inserted stepping stones components, which are small sized but evenly distributed across Fa_AGF (Donald & Evans, 2006; Morelli, 2013). From this point of view, the balanced insertion of areal and linear components (partly along field margins and, partly, along in-field linear embankments) represents an efficient strategy, optimising the reduction of productive agricultural surface while supporting the natural and seminatural components multifunctionality, thanks to

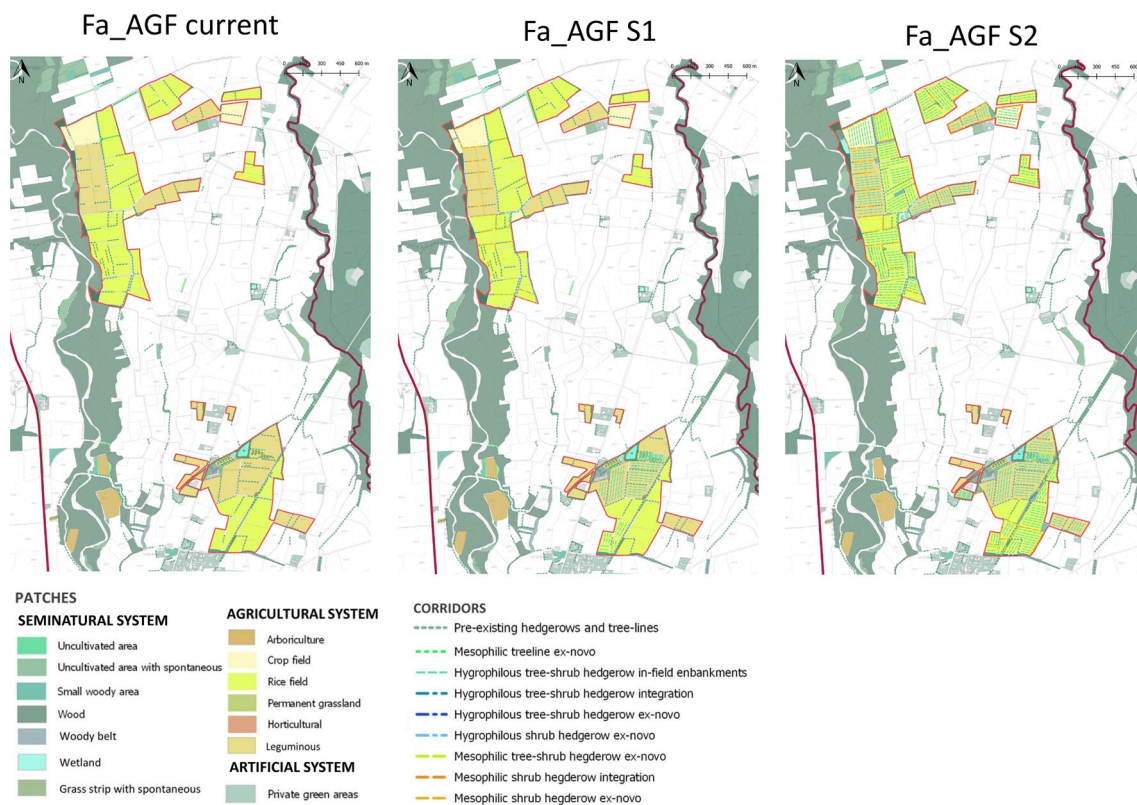


Fig. 10 The agroforestry farm model (Fa_AGF) landscape eco-mosaic composition: changes between the current state (left side) and the two design scenarios (S1, S2) (linear and areal landscape features insertion)

the implementation of a “bocage” landscape model (Boinot et al., 2023).

Conclusions

In this study, we employed a multi-scale analytical methodology to analyse and interpret the main ecological structural and functional traits of an agricultural landscape system and the contributions that can be given by a farm scale agroforestry management (Fa_AGF). The selected set of landscape ecology indicators, which were already tested on previous studies in similar contexts (Vagge & Chiaffarelli, 2023a), allowed us to outline a quick, yet ecologically consistent, diagnosis on the extra-local, local and farm scale landscape ecological status (i.e. their capacity to support biodiversity values). The first outputs were synthetic maps representing the vulnerability and resilience drivers of extra-local and local scales of analysis, which guided the identification of extra-local scale targeted planning strategies and local scale specific prescriptions. This was the starting point for identifying farm scale corrective intervention strategies, which were set up by building two design scenarios, where we forecasted different degrees of the farm agroforestry model

implementation through landscape features insertion. This allowed us to account for: 1. The current contributions of the farm scale agroforestry management model (in relation to the wider-scale vulnerability and resilience drivers); 2. Its further potential contributions, which were optimised thanks to the farm scale scenarios coherence with extra-local landscape context planning strategies and local scale prescriptions.

Indeed, the current agroforestry model showed to reasonably contribute to the agricultural landscape diversification and metastability values. The assessment of the two design scenarios accounted for their additional positive contributions. The studied farm scale agroforestry approach represents a distinct model that deviates from the prevailing conventional agricultural management, which is widespread at both the local and extra-local scales, with far-reaching impacts. Agroforestry management has been recognised as an opportunity to strategically integrate natural and agricultural functions. In the highly simplified and depleted agricultural landscape context, the farm scale agroforestry management model effectively serves as a buffering tool. This model can be strategically integrated within the natural-agricultural interface belt and, more broadly, in the simplified agricultural areas of the local and extra-local landscape systems.

Table 6 Changes in Fa_AGF design scenarios: patch type surfaces (hectares (ha) and % surface (%) values) passing from current state to S1 (no differences in areal patches) to S2 (newly inserted areal

landscape features); linear landscape features length (hedgerows and treelines linear meters (m) and % length increase (+ %), compared to current state) passing from current state to S1 and to S2

	Fa_AGF					
	Current	S1	S2	Current	S1	S2
PATCHES	<i>ha</i>	<i>ha</i>	<i>ha</i>	<i>%</i>	<i>%</i>	<i>%</i>
Grass strip	0.62	0.62	0.08	0.5%	0.5%	0.1%
Grass strip with sparse trees and shrubs	1.20	1.20	1.10	0.9%	0.9%	0.9%
Small woody area	0.26	0.26	2.73	0.2%	0.2%	2.1%
Wetland	0.70	0.70	1.05	0.6%	0.6%	0.8%
Wood	2.93	2.93	3.34	2.3%	2.3%	2.6%
Woody belt	0.11	0.11	2.81	0.1%	0.1%	2.2%
TOT	5.83	5.83	11.11	4.6%	4.6%	8.6%
Crop field in rotation	8.68	8.68	7.79	6.8%	6.8%	6.0%
Horticultural	0.09	0.09	0.09	0.1%	0.1%	0.1%
Leguminous	44.86	44.86	43.54	35.2%	35.2%	33.8%
Rice field	0.00	0.00	0.00	0.0%	0.0%	0.0%
Rice field in rotation	66.65	66.65	64.90	52.3%	52.3%	50.4%
TOT	120.28	120.28	116.31	94.3%	94.3%	90.3%
Agricultural buildings	0.33	0.33	0.33	0.3%	0.3%	0.3%
Private green areas	0.91	0.91	0.86	0.7%	0.7%	0.7%
Residential buildings	0.14	0.14	0.14	0.1%	0.1%	0.1%
TOT	1.38	1.38	1.33	1.1%	1.1%	1.0%
LINEAR LANDSCAPE FEATURES	Current	S1	S2	Current	S1	S2
	m	m	m	+ %	+ %	+ %
	14903.3	26040.5	54579.5	0%	+ 75%	+ 266%

Bold is used to better identify the main points and the most important results

This can help mitigate and reduce the identified ecological gaps, particularly in the over-sized agricultural areas where sink functions are dominant and restore the balance of local landscape vulnerabilities by merging productive and ecological functions and services across different spatial scales. A well-balanced combination of a dense network of seminatural linear and areal landscape features, designed in accordance with the diagnostic analyses at larger scales, has been recognised as a viable and effective solution for the studied context. It promotes positive interactions between natural/seminatural and agricultural micro-habitats (as evidenced by the analysis of shape complexity, diversity, and connectivity indices at the farm scale), thereby reducing the dichotomous, hyper-specialised, structural, and functional configuration of the local landscape system. The greatest contributions given by design scenarios (positive gaps from current state) were recognised on connectivity indices values. This indicates that even with minimal changes to the areal patches (and relatively low positive changes in landscape diversity values), significant changes in ecological fluxes and exchanges

between natural/seminatural and agricultural patches can be achieved.

The applied analytical approach has the advantage of synthetically representing the impacts and benefits on biodiversity-related functions of agricultural landscapes, allowing us to account for specific farm management models contributions, such as the agroforestry one. The methodology requires low-cost and quickly-available raw data and is suitable for the application among similar contexts (agricultural landscapes). It has lower precision than field scale result-based assessments, but its accuracy relies on the multi-scale depth of the analyses. In this regard, it might positively be integrated in the implementation and assessment processes of policy-driven practices, which should encourage a coherent implementation of targeted agri-environmental practices, to be able to balance the current agricultural landscapes vulnerabilities. In our study, the agroforestry farm management showed to positively contribute in balancing such multi-scale issues, in line with the results of a similar study on comparable contexts (Vagge & Chiaffarelli, 2023a). Governance level should not only promote the implementation of such practices

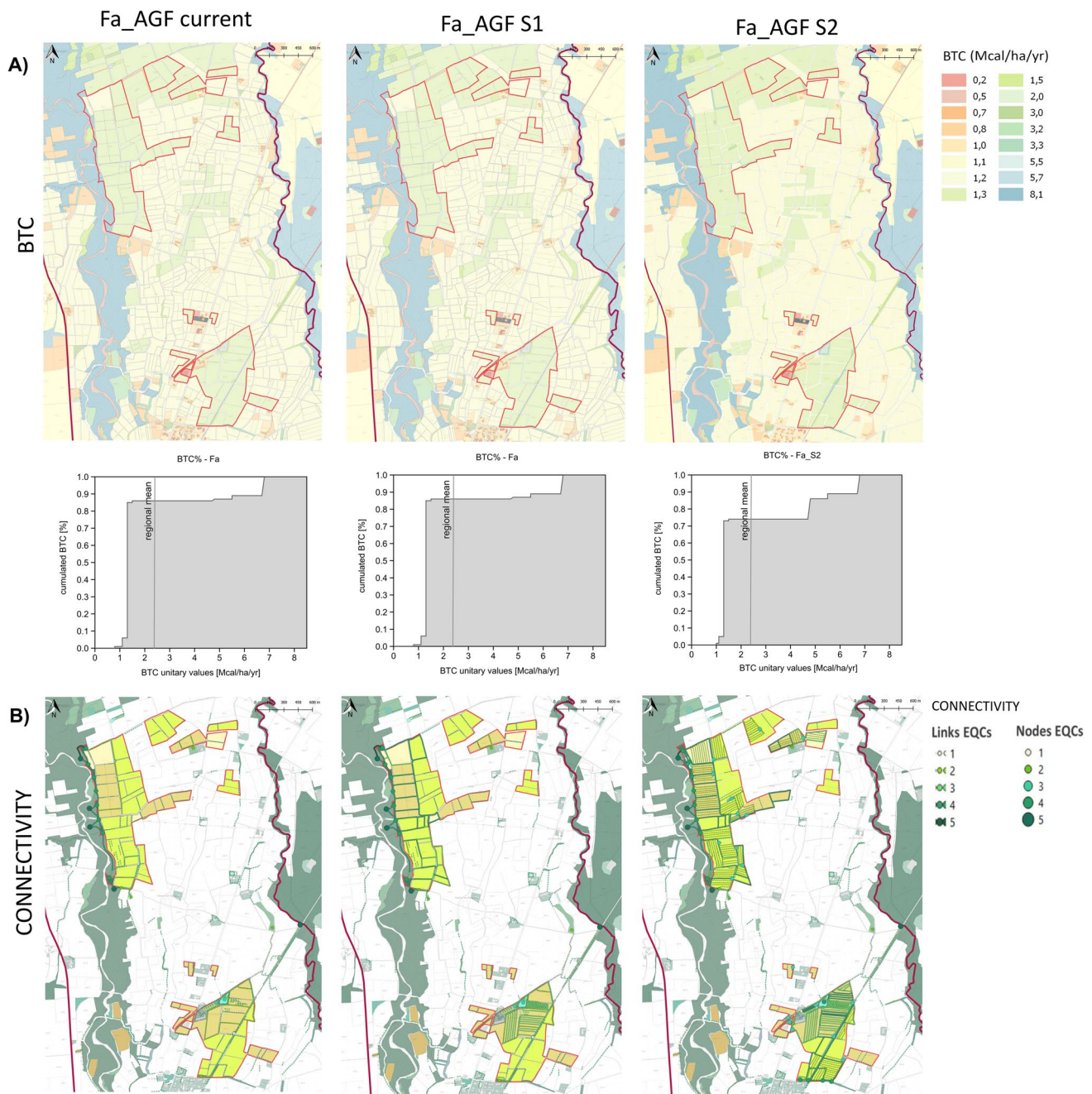


Fig. 11 The agroforestry farm model (Fa_AGF) functional main traits: changes between the current state (left side) and the two design scenarios (S1, S2) (central and right side). **a** Changes in the spatial configuration of biological territorial capacity values (BTC) and in

biological territorial capacity cumulated contributions (BTC%), passing from current state to S1 (no differences in areal patches) to S2 (newly inserted patches with higher BTC values) and **b** the connectivity graph analysis on current state, S1 and S2

but also focus on proper knowledge tools adoption for a coherent and impactful implementation. Further examinations of these issues, through wider applications and tests,

Table 7 The applied landscape ecology indices. For each index, the following information is provided: the employed acronym, the applied scale of analysis, the applied equation, and the related references

	Indicator	Scale	Equation	References
Basic structural traits	Matrix (MTX)	E_La La Fa	$MTX = \frac{\sum_{i=1}^n A_i \times 100}{A_{tot}}$ A_i = total area of each land use categories patches A_{tot} = total area	Turner and Gardner (2015)
	Medium patch size (MPS)	E_La La Fa	$MPS = \frac{\sum_{i=1}^n A_i}{N_i}$ A_i = area of each patch N_i = no. of patches	Turner and Gardner (2015)
Shape complexity indices	Mean Perimeter area ratio (MPAR)	La Fa	$MPAR = \frac{\sum_{i=1}^n PAR_i}{NP}$ $PAR_i = \frac{P_i}{A_i}$ P_i = Perimeter of each land use category patches NP = total no. of patches	Moser et al. (2002)
	Shape index (SI)	La Fa	$SI = \frac{P_i}{2 \times \sqrt{\pi \times A_i}}$	Moser et al. (2002)
	Patch fractal dimension (PFD)	La Fa	$PFD = \frac{2 \times \ln P_i}{\ln A_i}$	Moser et al. (2002), Turner and Gardner (2015)
Diversity indices	Diversity_1a/tot (DIV1a)	La Fa	$DIV_{1a} = -\sum_{i=1}^n \frac{A_i}{A_{tot}} \times \ln \frac{A_i}{A_{tot}}$	Turner and Gardner (2015)
	Diversity_1b/landscape element (DIV1b)	La Fa	$DIV_{1b} = -\sum_{i=1}^n \frac{A_i}{A_y} \times \ln \frac{A_i}{A_y}$ A_y = total area of each landscape system (FSN, AGR, ART)	Turner and Gardner (2015)
	Diversity_2 (DIV2)	La Fa	$DIV_2 = \frac{-\sum_{i=1}^n \frac{A_i}{A_{tot}} \times \ln \frac{A_i}{A_{tot}}}{\ln S}$ $\ln S = \max(DIV)$ S = no. of land use categories	Turner and Gardner (2015), Pielou (1975)
	Landscape structural diversity_1 (LSD1)	La Fa	$LSD_1 = DIV_1 \times (3 + DOM_1)$	Ingegnoli (2015), Ingegnoli and Giglio (2005)
	Landscape structural diversity_2 (LSD2)	La Fa	$LSD_2 = DIV_2 \times (3 + DOM_2)$	Ingegnoli (2015), Ingegnoli and Giglio (2005)
Connectivity indices	Connectivity (CON)	La Fa	$CON = \frac{L}{[3 \times (N-2)]}$ L = no. of links N = no. of nodes	Fabbri (2005)
	Weighted connectivity (WCON)	La Fa	$WCON = \frac{\sum_{i=1}^5 L_i \times W_i}{[3 \times (N-2)]}$ L_i = no. of links for each Ecological Quality Class ($EQC_i = [1-5]$) $W_i = EQC_i$ weight: $W_i = \frac{EQC_i}{EQC_{max}}$	Vagge and Chiaffarelli (2023a)
	Circuitry (CIR)	La Fa	$CIR = \frac{(L_{max} - N + 1)}{[2 \times (N - 5)]}$	Fabbri (2005)
	Weighted circuitry (WCIR)	La Fa	$WCIR = \frac{[(\sum_{i=1}^5 L_i \times W_i) - N + 1]}{[2 \times (N - 5)]}$ L_i = no. of links for each Ecological Quality Class ($EQC_i = [1-5]$) $W_i = EQC_i$ weight (as above)	Vagge and Chiaffarelli (2023a)
	Links/nodes ratio (L/N)	La Fa	$L/N = \frac{L}{N}$ L = n. of links N = n. of nodes	Ingegnoli and Giglio (2005), Ingegnoli (2015)
	Weighted links/nodes ratio (WL/N)	La Fa	$WL/N = \frac{WL}{N}$ $WL = \sum_{i=1}^5 L_i * (\frac{i}{5})$ WL = weighted n. of links	Ingegnoli and Giglio (2005), Ingegnoli (2015), Vagge and Chiaffarelli (2023a)

Table 7 (continued)

	Indicator	Scale	Equation	References
Indices on ecological functionality	Landscape apparatuses	La	$APP_i = \frac{\sum A_i}{A_{tot}}$ $APP_i = \text{each landscape apparatus}$ $A_i = \text{area of each patch belonging to } APP_i$	Ingegnoli and Giglio (2005), Ingegnoli (2015)
	Biological territorial capacity (BTC)		$BTC = \sum_{i=1}^m BTC_i \times A_i$	Ingegnoli and Giglio (1999), Ingegnoli (2006)
	Biological territorial capacity cumulated contributions (BTC%)	E_La La Fa	$BTC\%_y = \frac{\sum_{y=1}^n BTC_y \times A_y}{\sum_{i=1}^m BTC_i \times A_i}$ $BTC_y = \text{single y-BTC unitary value}$ $A_y = \text{area of each patch belonging to } BTC_y$ $BTC_i = \text{each i-BTC unitary value attributed to each i-land use category}$ $A_i = \text{area of each patch belonging to } BTC_i$	Ingegnoli and Giglio (1999), Ingegnoli (2006)

would improve the applicability of such recommendations and the replicability of such a methodology.

Appendix A

See Table 7.

Author contributions Conceptualization, resources, visualisation, supervision, project administration, and funding acquisition were contributed by I.V.; methodology, data curation, and writing—original draft preparation were involved by I.V., G.C., and N.S.; software and formal analysis were performed by G.C. and N.S.; validation, investigation, and writing—review and editing was done by I.V. and G.C. All authors have read and agreed to the published version of the manuscript.

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Data availability The data presented in this study are available on request from the corresponding author.

Declarations

Conflict of 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.

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