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Vegetation-based Ecological Functions Sustainability Index (VEFSI) for optimizing ecosystem services in orchards

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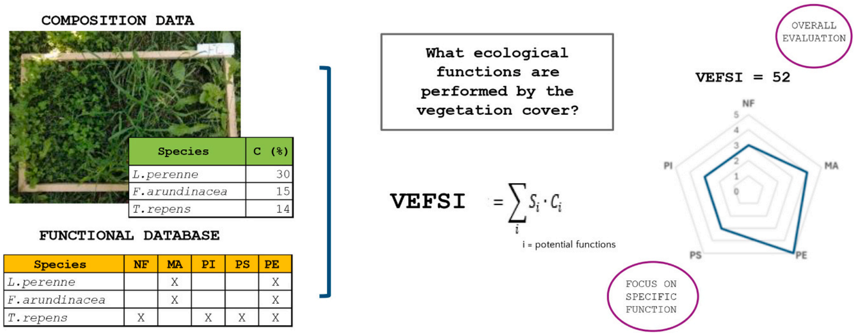
HIGHLIGHTS

- VEFSI estimates the functional potential of vegetation covers in orchards.
- 5 ecological functions evaluated based on plant diversity and abundance.
- Positive linear relationship between VEFSI, vegetation cover and species richness.
- Highlighted functional strengths and weaknesses of vegetation cover in inter-rows.
- VEFSI setting the base for corrective management interventions.

GRAPHICAL ABSTRACT



Species	C (%)
L.perenne	30
F.arundinacea	15
T.repens	14

Species	NF	MA	PI	PS	PE
L.perenne		X			X
F.arundinacea		X			X
T.repens	X		X	X	X

$$\text{VEFSI} = \sum_i S_i \cdot C_i$$

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ABSTRACT

CONTEXT: The need to quantify sustainability in agriculture and the ecosystem services it provides is increasingly felt by the sector. Indicators and indices are useful tools for this purpose, but are currently scarce in the specialized fruit-growing sector. In addition, there is a need for a more holistic view of the orchard system, which also considers unproductive spaces, such as the inter-row, where techniques can be implemented to improve adaptation to climate change.
OBJECTIVES: To help filling this gap, we developed VEFSI (Vegetation-based Ecological Functions Sustainability Index), a multifunctional index that can be used by technicians, researchers and farmers to establish the quality of grass cover in the orchard's inter-row in order to increase the ecosystem services performed by this.
METHODS: A dataset of field observation was collected during the year 2022–2023 in orchards located in South-West Piedmont (Northern Italy). Each record included observations on species richness, total vegetation cover and relative cover of each detected species. VEFSI was designed to include different ecological functions, such as nitrogen fixation, mechanical action performed by fascicled roots, soil cover performed by perennial organs, pollination service of the fruit crop and melliferous species for pollinator attraction. The index was calculated as a sum of scores attributed to single functions on the basis of the relative abundance of plants characterized by the corresponding functional traits.
RESULTS AND CONCLUSION: A positive relation has been found among VEFSI, vegetation cover ($R^2 = 0.419$; $P < 0.001$) and number of species ($R^2 = 0.53$; $P < 0.001$). Within the tested dataset the maximum theoretical value

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of 125 has not been reached, indicating trade-offs presence among functions. Despite this, the validation showed that VEFSI point out functional weaknesses and strengths of the vegetation covers, coherently with the real field situation. VEFSI proved to be a simple and reliable tool for estimating and evaluating ecological functions performed by orchard grassing.

1. Introduction

The concept of sustainability in agriculture has acquired significant prominence over time. Researchers have devoted the past three decades to exploring the possibility of quantifying it.

As early as 1991, Senanayake emphasized the need to translate theoretical concepts into practical applications for effective sustainability implementation. Due to the complex interplay of physical, chemical, and biological processes impacting environmental effects, environmental sustainability assessment cannot be deterministic. Moreover, the challenge of quantitatively assessing environmental quality has long posed dilemmas for scientists (Ott, 1978; Swinton et al., 2007; Seppelt et al., 2011; Logsdon and Chaubey, 2013). This challenge has led to the development of various indices designed to combine and simplify diverse information into a more practical format (Mafongoya and Sileshi, 2020).Of the various different ecosystems, the agricultural one is the most managed by humans to enable the achievement of goals (Swinton et al., 2007). Being a managed ecosystem, it plays a unique role in receiving and providing ecosystem services. As defined by the Millennium Ecosystem Assessment (2005) agriculture provides three major categories of ecosystem services (Fig. 1), provisioning, regulating and cultural services; at the same time it demands supporting services to produce (Mudare et al., 2023).

The quantification of ecosystem services has been extensively investigated in some ecosystems, such as forests, while much remains to be studied in the case of orchards. A significant difference between orchards and forests is that orchards primarily focus on producing consumable and high-quality food. However, orchards possess distinctive characteristics that make them suitable for studying ecosystem services. For instance, the perennial nature of trees, the presence of multi-layer habitats, and the plant diversity within the boundaries of orchards can contribute to a high level of biodiversity (Demestihas et al., 2018). In these systems soil cover is performed particularly in the interrow and it provides several soil-related ecosystem services and more, increases carbon sequestration (Montanaro et al., 2017; Morugán-Coronado et al., 2020; Repullo-Ruibérriz De Torres et al., 2021), improves its physico-chemical properties (Ramos et al., 2011), increases biological activity and enhances soil bearing capacity, allowing a prompt execution of the mechanical operations (Giacalone et al., 2021; Tang et al., 2022; Mudare et al., 2023). However, the effect of the cover crop can have much broader positive impacts, for example, it can act as a refuge and ecological corridor for beneficial insects (Fountain, 2022), and results in improved fruit quality and postharvest performance (Giacalone et al., 2021). In addition, the choice of species that are part of the orchard cover crop has several consequences, both on the quality and quantity of ecosystem services (Swinton et al., 2007) and on the mitigation of greenhouse gas emissions and environmental pollution (Gao et al., 2019). Indeed, increasing plant biodiversity in agroecosystems could improve multiple ecosystem services simultaneously (Loreau et al., 2001; Tilman et al., 2014).

Therefore, an appropriate interrow managing strategy can contribute to make intensive orchards multifunctional agroecosystems, as expressed in the Declaration of the Agricultural Ministers Committee (OECD) (Maier and Shobayashi, 2001) which states that “agriculture is multifunctional when it performs multiple functions in addition to the production derived from the main crop”.

This aspect plays a fundamental role in managing the orchard as a whole and utilizing those areas that may not be productive in terms of

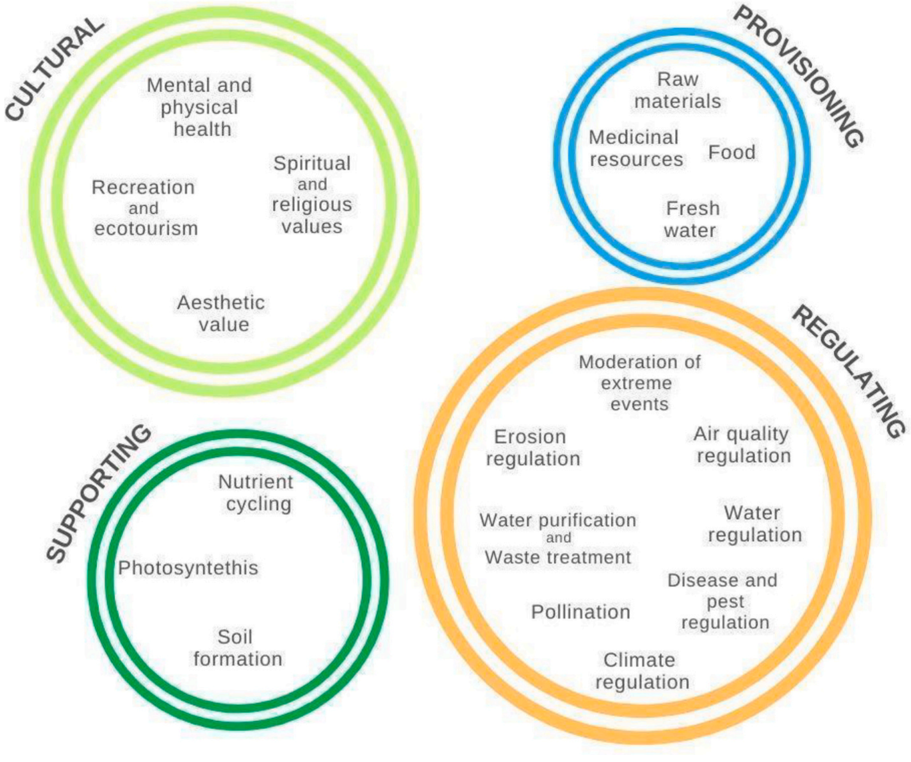

Fig. 1. Ecosystem services (adapted from the Millennium Ecosystem Assessment, 2005).

production per hectare but have a significant impact on the internal production dynamics of the farm and, consequently, at the territorial level, bringing forth positive outcomes. This step is crucial for rethinking the orchard system in all its components, and it requires to understand how and to what extent the services provided by the agroecosystem could enhance fruit cultivation. Additionally, European policy is increasing its demand for greater sustainability. Indeed, two of the 10 objectives of the 2023–2027 Common Agricultural Policy (CAP) are dedicated to mitigate climate change, particularly by improving carbon sequestration through sustainable agricultural practices, and contrasting and reversing the loss of biodiversity and associated ecosystem services losses (Regulation EU, 2021). One possible approach to achieve this is to provide farmers and technicians with user-friendly tools to determine the quality of the production system in the field, *e.g.* through the use of indicators and indices.

Today, the available works dealing with indices are more related to grasslands and wetlands (DeKeyser et al., 2003; Tangen et al., 2022) and they often focus on vegetation indices such as the biomass (Bai et al., 2024) and the Normalized Difference Vegetation Index (NDVI) (Huang et al., 2021), indices targeting soil health (Taguas et al., 2015) or estimating the pollination service based on the botanical characteristics of the species present at the field edge (Ricou et al., 2014). Multiple works are then related to the use of remote sensing for the evaluation of soil management and specific vegetation recognition (Qian et al., 2020; Assefa et al., 2021). In the context of fruit trees, there is a great lack of tools that can be used to quantify the ecological functions potentially performed by vegetal species occurring within the main crop and thus enable the transition from qualitative to quantitative analysis. In this study, we propose that a partially quantitative index can provide a realistic assessment of the current conditions in the field regarding the functional potential of the grass cover, as well as distinguish between the different situations present in the reference area (Wickham, 2016).

Therefore, the purpose of this study is to introduce the use of a multifunctional index, called VEFSI (Vegetation-based Ecological Functions Sustainability Index), to assess the potential of a vegetation cover present in the interrow of the orchards to perform five ecological functions that help increase agroecosystem efficiency. The ecological functions were selected based on the demands of intensive orchard systems in temperate areas but can be easily integrated and modified to fulfil the requirements of other cultural systems and geographical contexts, as the following study is seen as a first step towards achieving greater understanding in sustainable orchard management.

2. Materials and methods

2.1. Geographical context

VEFSI has been applied on different case studies to test its response to real scenarios, and to evaluate its ability to discriminate situations that are expected to differ in terms of potential functionality offered by the vegetation cover. The data used for this purpose were collected in three of the main fruit-growing areas in the north-west of Piedmont, Italy (Figs. 2–3).

The indicated area has a strong inclination towards fruit cultivation, encompassing the territories bordering the province of Turin and extending to Cuneo, with Saluzzo being the heart of this area. The soils have a loose texture, and there is a significant temperature difference between night and day. Due to its pedo-climatic characteristics, the area is perfectly suited for growing various types of fruit. This specific adaptation has allowed for the development of highly specialized fruit cultivation, often involving the use of narrow planting distances, approximately 1 m on the rows × 4 m between rows, dwarfing

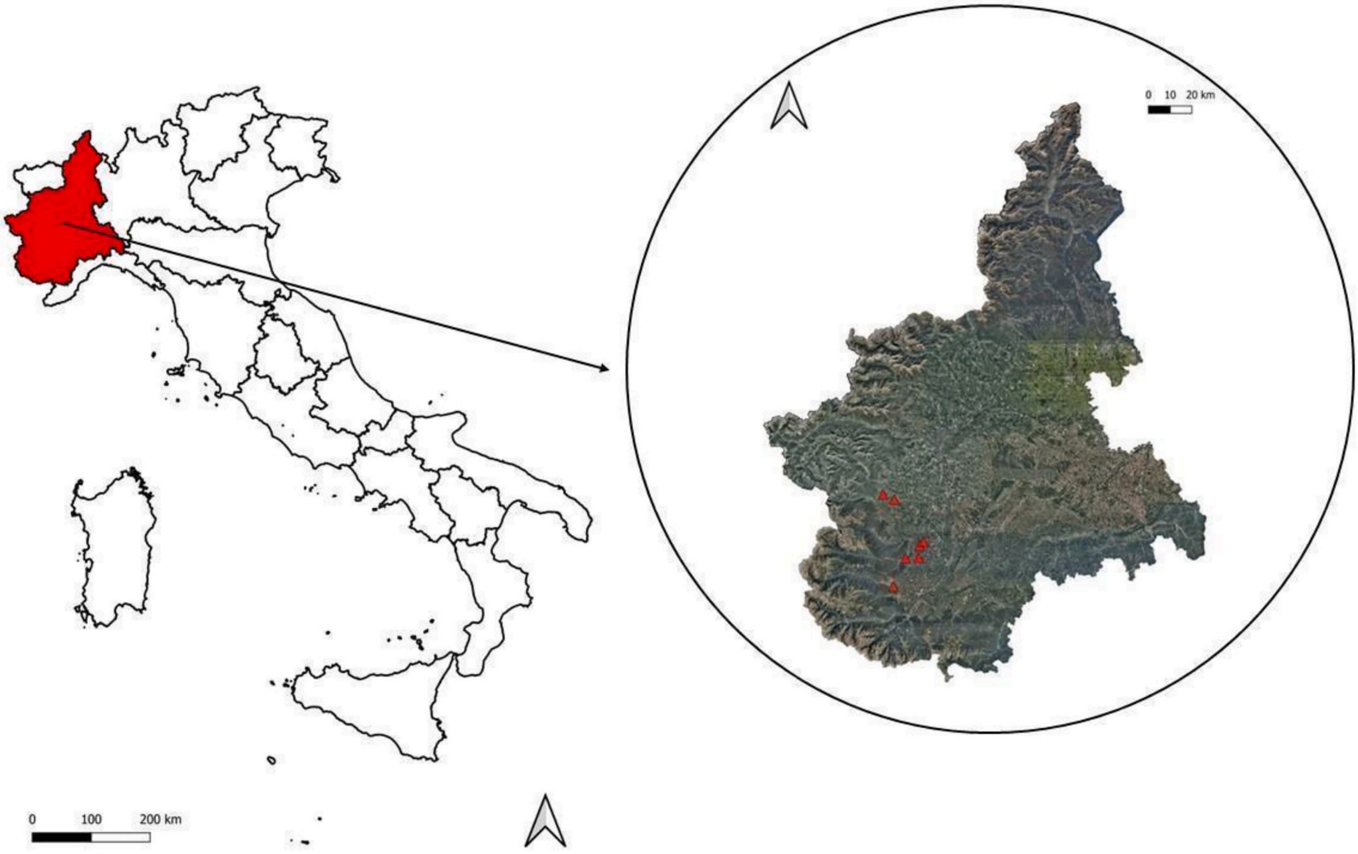

Fig. 2. Piedmont region, N—W Italy. Red triangle represents the farms involved. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

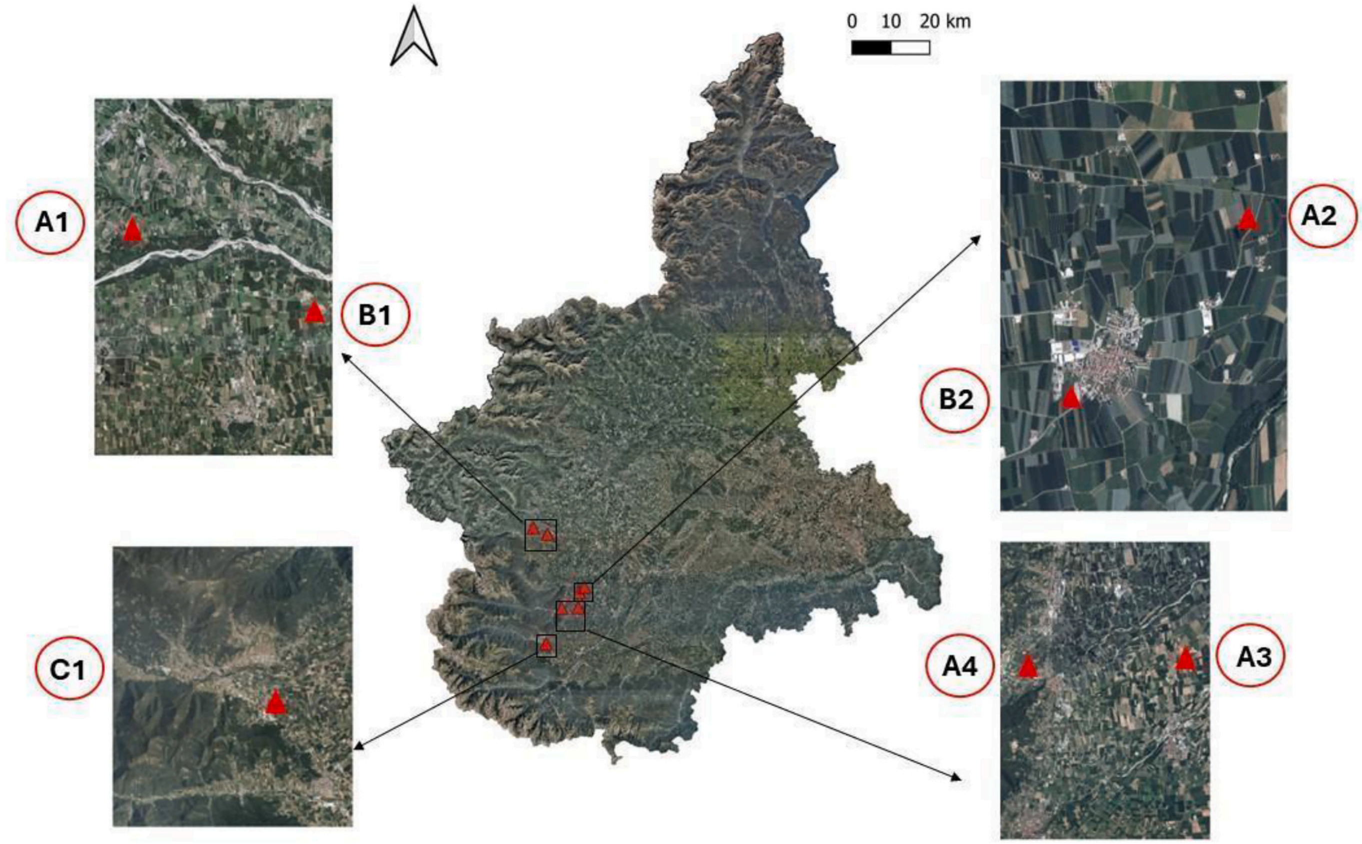

Fig. 3. Map showing the position of the fruit farms including the experimental plots on which the field observations were collected. Codes A, B and C refers respectively to apple, blueberry and cherry farms.

rootstocks, and the implementation of hail nets. This high predisposition in the sector has led to a significant increase in fruit farming enterprises, resulting in a heavily anthropized landscape, with orchards continuously expanding throughout the area.

Climatically, the study area is characterized by an average annual temperature of 11.1 °C and annual precipitation of 994 mm (Perosino and Zaccara, 2006).

2.2. Index construction

2.2.1. Index formulation

The idea lying under VEFSI formulation was that, given a vegetal community for which the composing species and their relative abundance are known, and given a set of ecological functions of interest, an estimation of the total community functionality can be obtained by summing up the contribution that each vegetal species is expected to give for each function.

VEFSI consider the number of species detected in the field and the percentage of coverage provided by them. It then assigns to the species a score for each of the selected ecological functions, based on the presence of functional traits that are considered as proxies for the different functions. Functional traits refer to measurable characteristics of individual organisms, including their morphology, physiology, chemistry, and phenology, which are influenced by environmental variations and impact growth, reproduction, organism survival, as well as ecosystem processes. This approach, which is not based on taxonomy, enables the quantification of the effects of traits on ecosystem processes and services, while also accounting for intraspecific variation (Faucon et al., 2017).

The VEFSI construction started then from the single functions, by considering that, to estimate the potential of a plant community for the provision of a certain ecological function, the presence of plants able to perform such function is essential, but the entity of their action is strictly linked to their abundance. Therefore, the overall value of each function was obtained by multiplying two components: the number of the species able to perform the function (S) and the percentage coverage determined by such plants (C). However, while percentage cover ranges from 0 to 100, the number of species can assume potentially any value, leading to the impossibility to set a maximum threshold for the final function. To overcome this issue, the S and C values were converted into classes. For C, the scale proposed by Braun-Blanquet (1928), and commonly used to assign classes of coverage during phytosociological surveys was adopted, while for S a specific scale was set up, with the objective of valorizing even small differences (Table 1).

Once defined the value of each single function, the final index was obtained as their sum:

$\text{Index} = \sum S_i \text{ x } C_i$.

i = potential functions.

VEFSI can theoretically range between 0 (no functions provided) and 125 (all the five functions are provided by plant species that represent 100 % of the vegetation cover).

Five different ecological functions were selected and included in

Table 1
Conversion of the number of species and % coverage into classes.

Class	N° species	% Coverage
0	0	0
1	1	<5
2	2–3	5–25
3	4–5	25–50
4	6–7	50–75
5	>8	75–100

VEFSI for their added value in the health of the orchard agroecosystem and for the special needs of orchards located in temperate areas: Nitrogen fixation (NF), Mechanical action (MA), Pollinating insects (PI), Pollination service (PS) and Persistence (PE). For each function a discriminating parameter, consisting on a plant functional trait or a taxonomic affiliation, was defined in order to assess the potential of the vegetation cover to perform it, based on information on species composition, as discussed by Storkey et al. (2015).

The functions and the parameters used for their assessment are summarized in Table 2.

NF was included in the desirable functions that a vegetation cover can absolve in orchards, although the root systems of many rootstocks used in intensive fruticulture have limited ability to expand in alleys and gather N (Ma et al., 2013), and its supply must be limited to minimize excessive vegetative growth in the crops (Demestihas et al., 2018). However, the presence of sufficient N levels in the soil is fundamental to ensure a correct nutrient balance, allowing biogeochemical cycles to unfold optimally and maintaining soil fertility in the long term (Ge et al., 2020). Herbaceous plants can have a major role in the accumulation of N in soil, in particular those species able to interact with bacterial symbionts to fix atmospheric N in their roots, releasing it in soil when tissue lysis occurs (Vats et al., 2021). Therefore, NF was included in the desirable functions that a vegetation cover can absolve and integrated in VEFSI. Since the majority of N fixing herbaceous plants for these areas, are part of the *Fabaceae* family (Vats et al., 2021), the belonging to this family was set as the condition for the function assignment.

MA is carried out by the roots of plants, particularly those with a fascicled root system (Loades et al., 2015; Bodner et al., 2010). Thanks to the production of root exudates and biomass, soil exploration is facilitated and promoted, allowing for greater aeration and increasing the stability of aggregates resulting in improved soil structure. This type of root system is mostly present in plants of the *Graminaceae* family.

The PI function takes into account the potential ability of the vegetation cover to attract and support pollinating insects, acting in the long term as a reservoir of these insect species for the whole agroecosystem in which the orchard is embedded. Since melliferous species are considered attractive for pollinators, their presence in the vegetation cover was selected as a proxy to estimate its PI potential (Nicholls and Altieri, 2013).

PS function was included to valorise the role that herbaceous plants may play in terms of pollination support for the culture. Thanks to the provision of nectar, pollen and nest, wildflower species can enhance the presence of local pollinator communities helping address pollination deficits in modern apple orchards. As reported by Blaauw and Isaacs (2014) the presence of natural pollinators during the blooming in highbush blueberry enhances pollination and crop yields. To identify the species potentially contributing to this function, we considered both that blooming period of the crop and the wildflower concur, and that the species relies on insect pollination.

Persistence (PE) plays a key role in ensuring coverage throughout the year against erosion of soil organic matter but also over the years, without the need for reseeding which represents a cost for the farmer. The function is attributed to the perennial species of different families.

2.2.2. Data aggregation and representation

The final value of the index, obtained through the summation of the individual functions, returns the overall capacity of the spontaneous vegetation as a single numeric value. This data makes it possible to give an overall judgement with respect to the vegetation cover taken into consideration, allowing it to be compared with other ground covers. It is indeed from the formulation of the index that more specific information may be investigated later, considering the individual ecological function of interest.

Individual functions can be easily represented on radar plots after scaling the function score (potentially ranging from 0 to 25) on a 1 to 5 scale through a square root transformation.

This kind of representation allows to see graphically if the analysed vegetal assembly has the potential to specifically perform certain functions rather than others. Based on these observations is possible to plan actions aimed at improving the functional potential of the vegetation cover, such as adding species that can fulfil particular roles that are considered to be missing and fundamental in a specific farm or area.

Moreover, the individual functions can be broken down into the S and C components, that can be simultaneously represented on the radar plot. On the one hand, the species number class gives information on the level of biodiversity in the field for each ecological function, providing more qualitative data on the stability and potential of the functional category; on the other hand, the coverage class of a specific functional category is potentially more related to the real effects that plants may have on the orchard.

2.3. Index validation

In order to explore the response of the index to real field situations, vegetation cover data were collected across the most productive fruit growing areas of Piedmont (Fig. 2), in farms hosting apples (A1, A2, A3, A4), blueberries (B1, B2) and cherries (C). The selected plots were of similar length, and three center rows were chosen for each plot. A first, wider dataset, composed of monthly observations performed from April to September in 32 different plots (16 monitored in 2022 and 16 in 2023) was built to perform a general index characterization. A second group of observations was collected in May, June and July on 9 plots (4 monitored in 2022, 5 in 2023), characterized by similar management conditions, and used to perform a first index validation.

The vegetation surveys were carried out by using a rectangle with an internal area of 0.4 m^2 (50x80cm). The frame, delimiting the area of analysis, was randomly positioned three times, each of them in a different interrow of the plot, targeting the entire width of the interrow to include in the final data the variability deriving from differences between lateral and central spaces (Fig. 4). For each field observation a list of detected species has been created. Total vegetation cover and relative cover of each species have been visually estimated. These data, with a table including information on the ecological functions of the detected species (supplementary material 1) were used to calculate

Table 2

Ecosystem services and ecological functions included in VEFSI, and parameters used for the attribution of a function to vegetal species.

Ecosystem services		Functional traits	Parameter	References	Resource for plant identification
Supporting	Nutrient cycling	Nitrogen fixation (NF)	family Fabaceae	Vats et al., 2021	Acta Plantarum, 2007
	Soil formation	Mechanical action (MA)	Fascicled root system	Loades et al., 2015 Bodner et al., 2021	Expert knowledge
Regulating	Pollination	Pollinating insects (PI)	melliferous species	Nicholls and Altieri, 2013	Expert knowledge
	Pollination	Pollination service (PS)	flowering contemporaneity with culture + insect pollination	Blaauw and Isaacs, 2014	Acta Plantarum, 2007
–	–	Persistence (PE)	perennial species	Duchini et al., 2018	Acta Plantarum, 2007

VEFSI.

Monitoring operations were carried out by the same operators throughout the period considered.

2.4. Data analysis

A first index characterization was performed on the 187 monthly observations of the wider dataset, to explore a wide range of plant assemblages differing in terms of sampling month, year and site. Summary statistics of the VEFSI values calculated, and a linear regression was applied to test the relationship between the index value, the total vegetation cover, and the species richness. These two parameters are commonly used to quantify the efficacy and biodiversity of a vegetation cover in orchards (Bodner et al., 2010; Bałuszyńska et al., 2022; Ciaccia et al., 2022) and, since each function within the index derives from the product of S and C components, a direct relationship between them and the index was expected. Moreover, for each function the distribution of the outputs across the classes was examined.

Summary statistics calculations, regression analysis and plots drawing were performed in R (version 4.3.0) using R base functions and packages ggplot2 (Wickham, 2016) and fmsb (Nakazawa, 2024).

To perform a first validation, exploring more in detail the suitability of VEFSI for vegetation cover data evaluation in real scenarios, we focused on 9 plots, homogeneous in terms of inter-row management, and consequently easily comparable.

Having multiple field observations per year, we decided to calculate for each plot an annual index obtained on the average community composition of May, June, and July. Using community data derived from observations collected across the productive season allows to obtain a better characterization of the vegetal assembly, including both spring and summer species, and thus to estimate more reliably its functional potential. Alternatively, also single observations can be used, although to make a meaningful comparison, they should be done in the same season, so as to consider the seasonal diversity between the different species constituting the vegetation.

3. Results and discussion

3.1. Index characterization

The VEFSI index proposed in this study was formulated to provide a tool for the assessment of the functional potential of herbaceous vegetation covers in orchards and was tested on a set of field records collected between 2022 and 2023 in Piedmont, Northern Italy, in areas characterized by intensive-specialized fruticulture. The dataset included situations very different in terms of total vegetation cover, ranging from 6 to 100 %, with an average of 68 % (Fig. 5), while the vegetal diversity was less heterogeneous, ranging from 2 to 19 species, with an average of 9 (Fig. 5). This range of values covers the most common conditions in mediterranean and temperate European orchards (Gago et al., 2007; Licznar-Małańczuk, 2020; Restuccia et al., 2020; Paušič et al., 2021; Ciaccia et al., 2022), suggesting the dataset as suitable for testing the behaviour of the VEFSI index in this context, although situations characterized by higher species diversity can be found (Bałuszyńska et al., 2022), and should therefore be integrated in order to better explore the higher limits of the index.

VEFSI showed an average of 31, coinciding with the median of the distribution. The lowest values, spanning from 5 to 7 (Table 3), were obtained for seasonal replications performed in plots of the same farm in the summer 2022, that was characterized by particularly harsh conditions in terms of drought and temperatures. In all the cases the number of species detected was very low (2 to 4), while the vegetation cover ranged from 6 to 73 %. However, since most of the soil cover was represented by species contributing only minimally to the functions included in the index (like *Echinochloa crus-galli*, performing only MA), the final result was similar even with very different levels of vegetation cover.

The five highest values spanned from 60 to 66 (Table 3). They were obtained in different plots of two farms and derived from measurements performed all along the productive season. In almost all cases, a high number of species correspond to high values of ground cover, although values close to 100 % are never reached. In fact, according to a study conducted by Golian et al. (2023) in an apple orchard in Poland, it is difficult for ground cover to reach near 100 % values. The study revealed that the maximum ground cover achieved in the row was 70 % represented by the control group.

A specific situation is represented by the ground cover of plot 20 that, despite being composed of only 8 species, was able to score similarly to the other four, more biodiverse communities. If this may be partially due to the slightly higher level of total soil cover (91 %), the most important difference lies in the abundant presence of multifunctional species, including vetch and three species of clover, that can simultaneously contribute to NF, PI, PS and PE functions (Scavo et al., 2020; Cole et al., 2022; Harris and Ratnieks, 2022).

A significant linear relationship (Fig. 6) was found with total vegetation cover ($F_{185} = 135.1$, $R^2 = 0.419$, $p < 0.001$), but the species number was able to explain a higher proportion of VEFSI variance ($F_{185} = 210.7$, $R^2 = 0.530$, $p < 0.001$). The stronger relationship existing between VEFSI and species richness rather than the level of soil cover is in accordance with the observation that, if greater cover crop biomass tends to quantitatively enhance ecosystem services provision (Quinton et al., 1997; Bodner et al., 2010; Schipanski et al., 2014), multifunctionality is more related to biodiversity (Smith et al., 2014; Suter et al., 2021). Moreover, the limited overall ability of vegetation cover and species richness to explain VEFSI variance is in line with the index formulation, that takes into account both the parameters, but uses them to quantify the occurrence of functional traits, adding a further level of information on the ecological functions potentially delivered by the vegetal assembly. Similar trends were described by Finney and Kaye (2017), showing that plant diversity explains only a small fraction of variance in the ecological functions provided by cover crop polycultures in an agricultural system, while functional diversity indexes, particularly those based on the distribution of traits abundance are stronger predictors of multifunctionality.

Exploring separately the index functional components across the whole dataset highlighted that only two of the selected functions (PI, PS)

Fig. 4. Square sampling method, followed by data collection, to monitor land cover and number of species.

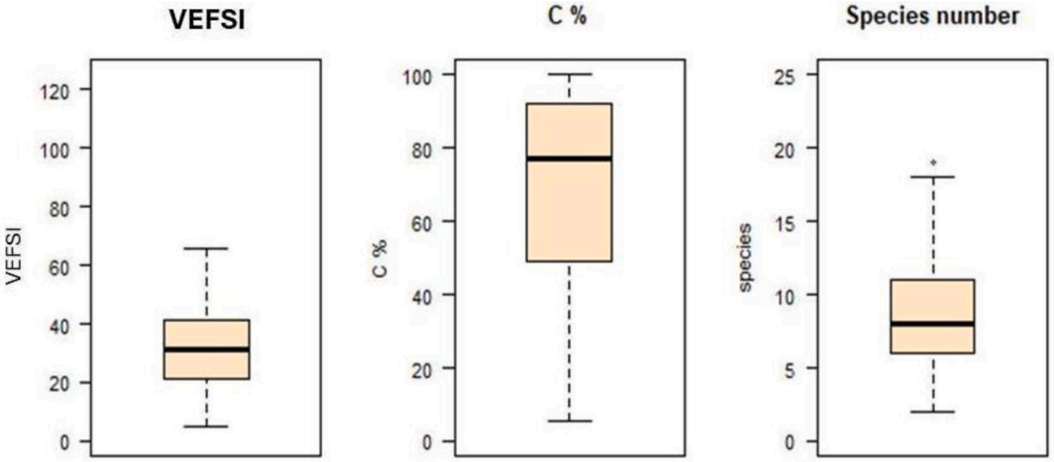

Fig. 5. Box plot representing the distribution for VEFSI, vegetation cover (C%) and number of species for all the dataset.

Table 3
Highest and lowest VEFSI values obtained across the dataset, with corresponding total vegetation cover and species number data.

Plot	Farm	Year	Month	VEFSI	C%	Species
Lowest index values						
1	B1	2022	June	5	73	2
1	B1	2022	September	5	21	4
1	B1	2022	July	6	61	2
1	B1	2022	August	7	45	3
3	B1	2022	July	7	8	4
Highest index values						
23	A1	2023	May	66	80	17
20	A4	2023	July	61	92	8
22	A1	2023	May	61	87	15
23	A1	2023	June	60	78	19
24	A1	2023	September	60	86	18

had the potential to reach the maximum expected value, and only for a very limited number of cases (Fig. 7).

This may be explained considering that melliferous capacity and entomogamous pollination are traits that can coexist with all others in the same species, although this combination can vary depending on the crop and weed species chosen. In contrast, some functions such as nitrogen fixation are linked to a small number of species, in this area phylogenetically close, and it is therefore more difficult for them to maximise both number of species and degree of cover. In fact, NF is the function that, at least for the investigated vegetation covers, shows a distribution strongly skewed towards the lower values. It should be noted that the nitrogen-fixing species in this area belong to the leguminous family, but as also reported by Tedersoo et al. (2018), nitrogen-fixing species also belong to other families.

The maximum value for MA and NF functions is only achievable in the complete absence of leguminous plants for the MA function and gramineae for NF. This situation is related to the biology of the species mentioned, as the first function is performed by species with fasciculate roots, while as reported by Chmelíková and Hejcman (2012), the majority of the nitrogen fixing species in these areas are characterized by taproot system.

Overall, the results distribution is in accordance with the impossibility to approach the highest theoretical value (125), at least within this dataset. On the one hand, this can be due to the limited number of analysed case studies, all referring to vegetation covers sampled on the same geographical area, and thus including a limited total number of species (N). Moreover, in agroecosystems where human intervention is significant, such as cultivated lands, the abundance of species is often limited (Albrecht, 2003; Beckmann et al., 2019). This limitation arises from the techniques applied to the systems (Newbold et al., 2015; Maxwell et al., 2016), which involve the selection of specific species, as well as the nature of the system itself, including its pedoclimatic characteristics. On the other hand, our results are in line with a concept emerging from recent studies on multispecific herbaceous assemblages: if increasing the number of species within a vegetal assembly theoretically gives the opportunity to enhance its multifunctionality through the expression of functional diversity (Finney and Kaye, 2017; Suter et al., 2021; Argens et al., 2023), the existence of trade-offs among functions may prevent the achievement of the maximum expected result for each function (Storkey et al., 2015; Blesh, 2018). Therefore, the best results in terms of overall multifunctionality tend to be reached with assemblages that not necessarily reach the maximum value for each considered function, but instead show a good balance among functional traits (Storkey et al., 2015; Blesh, 2018; Suter et al., 2021; Bybee-Finley et al.,

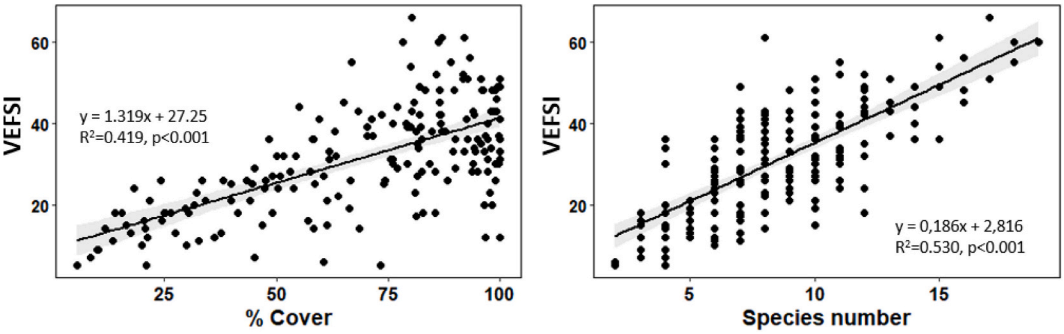

Fig. 6. Regression analysis between VEFSI and percentage vegetation cover, and VEFSI and species number.

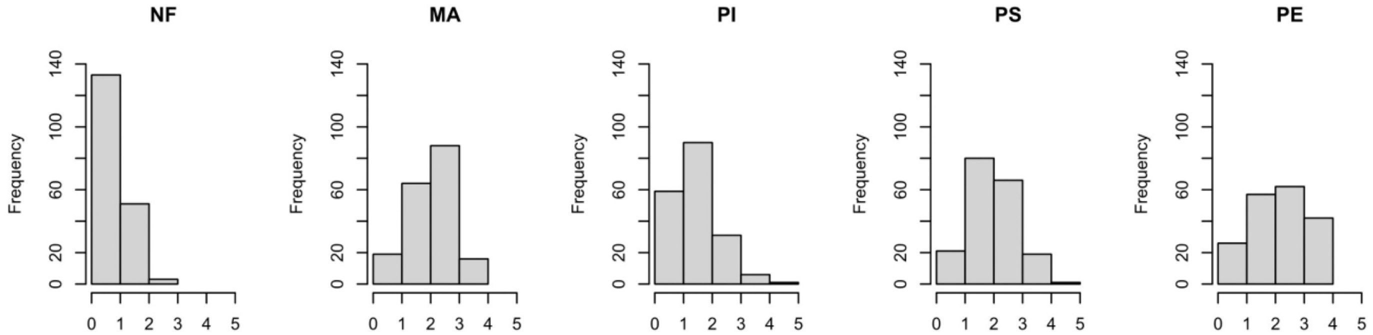

Fig. 7. Frequency of individual ecological functions calculated on the total database.

2022; Argens et al., 2023).

3.2. Index validation

The most common solution applied for orchard alley management in the studied area is spontaneous grassing, which has the potential to fulfil several ecological functions, ranging from maintaining soil fertility to supporting pollinators and natural enemies (Nicholls and Altieri, 2013; Repullo-Ruibérriz De Torres et al., 2021; Las Casas et al., 2022). However, the real contribution offered by vegetation covers to agroecosystem functioning is highly variable in relation to the composition of the vegetal community (Hanisch et al., 2020). Therefore, as a first application we tested the suitability of VEFSI for the evaluation of spontaneous vegetation covers in terms of functionality, with the objective to identify deficiencies and select appropriate species to integrate the original cover in order to improve poorly covered functions. The aim is to ensure the sustainability of the vegetation cover and better management of the entire orchard, improving the surrounding environment and enabling optimal crop growth in an agroecosystem that promotes synergy between ecological functions, as also demonstrated by Wei et al. (2024). Indeed, numerous studies have shown that these synergies occur when ecological functions are simultaneously enhanced (Daba and Dejene, 2018).

Fig. 8 shows VEFSI results calculated on the average annual vegetation covers of 9 selected plots. Subdividing the ecological functions on a radar plot allows to discriminate functional strengths and weaknesses

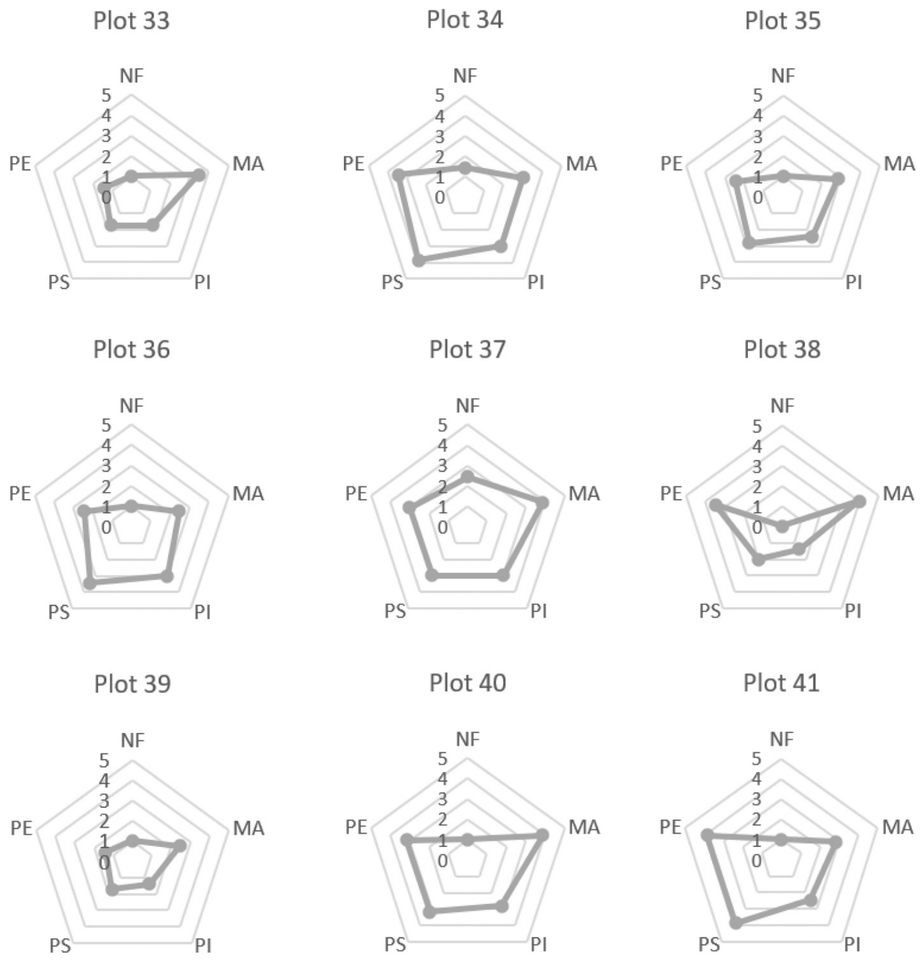

Fig. 8. Radar plots showing the scores obtained by every function in 9 plots characterized by homogeneous inter-row management. NF: Nitrogen fixation; MA: mechanical action; PI: pollinating insects; PS: pollination support; PE: persistence.

of the grassings.

From most of the graphs emerge that, as discussed in the previous section, the most deficient function is nitrogen fixation. An exception is plot 37, which has a greater incidence in this function, linked both to the presence of two legume species and to their high percentage of cover (around 26 %). On the opposite extreme, plot 38 scores 0 for NF function, due to the lack of legume species.

Observing the overall profile of the investigated farms, there are two examples of vegetal assemblages particularly poor in terms of functional potential. The first, already cited, is plot 38, showing deficiencies not only in NF but also in PI and PS functions. This combination can partially be attributed to the complete lack of leguminous species that contemporarily contribute to all the cited functions (Harris and Ratnieks, 2022), but also to the absolute prevalence of *graminaceae*, unable to provide PI and PS functions.

The second case is plot 39, scoring very low for all the functions but MA. This case corresponds to a new fruit orchard establishment, set up a few months before the start of the monitoring activity, where the vegetation cover was mostly represented by fast-growing, annual weeds able to rapidly recover after the tillage operations (Gago et al., 2007; Miñarro, 2012; Licznar-Małańczuk, 2020).

From these observations is possible to hypothesize some corrective actions, using VEFSI as a tool to identify species that enrich the vegetation cover but do not compete to perform the same ecological functions, since the correct balance among functional traits has been described as a fundamental requirement to allow a vegetation cover to optimally deliver the intended ecosystem services (Storkey et al., 2015; Blesh, 2018; Bybee-Finley et al., 2022¸ Garba et al., 2024).

For instance, in plot 38, where the community is dominated by grasses, the introduction of one or more leguminous species sown as an integration to spontaneous species would contemporarily support the NF, PI and PS functions (Cole et al., 2022; Harris and Ratnieks, 2022), preserving at the same time the mechanical support given by the resident species, and leading to a persistent and well-balanced vegetation cover. In the case of plot 39, where the vegetal population is still in phase of assembly and nearly none of the species detected is of particular interest for the establishment of a high-functionality vegetation cover, the best solution might be the complete substitution of the spontaneous cover by a seeded mixture (Jannoyer et al., 2011). An element to be considered in the mix choice would then be the presence of perennial weeds that should be competitive enough to contrast both the annual species, dominant in the first phases of orchard establishment, and the spontaneous perennials, that tend to gain prevalence in the following years (LicznarLicznar-Małańczuk, 2020).

VEFSI index also makes it possible to compare the development of the species present in the interrow following years characterized by different weather events (for more details see the supplementary material 2). By considering two different years, such as 2022 and 2023 it is possible to observe changes in the presence of the species in the field and the evolution of the individual and total cover. This data can be useful as thanks to these comparisons, the species that are best adapted to a particular agroecosystem can be selected.

This choice can increase the resilience of the orchard system as the presence of species adapted to a particular context allows the agroecosystem to actively respond to extreme phenomena, such as those of recent years. The index could then be used to assess the resilience of the orchard system. For example, if it has a greater need for rapid ground cover and no particular N requirements, then grass species will be preferred (Fiore et al., 2018).

4. Conclusion, limits and future perspectives

Despite the potentialities of VEFSI, there are some aspects potentially limiting its application that should be carefully considered when using it, and that would set the base for its future upgrades.

Above all, it is important to outline that the index evaluates only the potential of the vegetal assembly but does not consider how the management strategy impacts on it. For instance, a vegetal community can be very promising in terms of pollination support, but if the vegetation is frequently cut and never reaches the flowering stage, this function will not be fulfilled. Keeping this in mind, the index can also become a tool for researchers, technicians and farmers to reason and guide the choice of agronomic management strategies, not only in relation to the crop requirements but also considering the ecological services that the orchard may provide.

Moreover, VEFSI has been developed to face the needs of Northern Italy fruticulture, focusing on the species found in this area and on functions considered particularly important in this context. However, both these limitations are easy to overcome. The species dataset can be integrated with new plants or built *de novo* to match the vegetation cover typical of different geographical areas. This would allow to extend the use of VEFSI to new contexts, where the monitoring of plant species and their functions can be crucial for a reliable evaluation of agroecosystems sustainability and for its improvement. Considering the limited number of functions included (N fixation, mechanical action, pollinating insects, support to crop pollination and persistence), chosen on the basis of their general importance in temperate orchards, we can point out that the same formula can support both the removal of functions considered negligible in a particular context and the integration of new functions. This would lead only to a variation of the potential maximum VEFSI value (with an increase/reduction of 25 for each added/removed function). The main limit for this modification is that a functional trait database including information on the new functions for all the plants detected in the field should be available. For instance, a promising function to integrate may be the support to mycorrhization. The potential for mycorrhizal colonization is a very interesting trait since the presence of plants that support mycorrhization would allow the maintenance of mycorrhizal fungi across the orchard, with potential advantages for the culture and for the whole orchard (Trinchera and Warren Raffa, 2023). In this case, a dedicated database is already available (FungalRoot, Soudzilovskaia et al., 2020), although not covering all the species found in the current dataset. However, the inclusion of the novel function would require the definition of thresholds to define which is the level of fungi-plant association required to define a mycorrhization-supporting plant. The same issue would apply for all the currently supported functions, since different plants have the potential to fulfil the same ecological function with different efficiency. However, the implementation of a weighting system to switch from a dichotomous classification of the single functions to a quantitative or categorical one would allow to increase the final accuracy of the model only if associated with a plant detection system compatible with the identification of plants at the species level.

A final consideration concerns, indeed, the source of vegetation cover data used as input for VEFSI calculation. Certainly, the most accurate estimation of the functional potential of an orchard permanent herbaceous cover can be obtained from punctual vegetation surveys performed by trained operators, able to discriminate also among similar species. The surveys should include multiple time points along the year, in order to allow the accurate recognition of species with staggered blooming periods, and the detection of species with different seasonality. However, such an approach would require an investment of time and resources that is often not available. An alternative approach to make the information acquisition process more user friendly also by non-experts would be the application of recognition systems based on artificial intelligence and neural-network image analysis procedures to be applied to pictures collected in the field. Some analogous system is already available for the recognition of single plant species (Aitkenhead et al., 2003; Affouard et al., 2017), but a future, fascinating challenge is to extend this capability to the analysis of complex plant associations. As a matter of fact, the visual interpretation of a tridimensional plant canopy from bidimensional pictures would lead to a loss of sensitivity in plant detection and prevent the identification of some species for which the concurrent observation of different plant organs is required. However, with a proper simplification of the functional attribution, based for instance of trait association to taxonomic categories wider than the species, and with the definition of reliable default values to be applied when single functional traits cannot be assigned, an acceptable balance between VEFSI practical applicability and informativeness could be achieved.

An appropriate management of the vegetation in orchard alleys may result in productive and environmental advantages, linked to the provision of ecosystem services by plants. The present work proposes an index that allows a synthetic functional evaluation of herbaceous vegetation covers in orchards, based on plant community composition and percent cover data. VEFSI index can be used both to highlight strengths and weaknesses of vegetation covers, describing their actual functional potential in the field, and to suggest corrective actions to improve their performance in terms of deliverable ecosystem services. It may therefore represent a simple, informative and flexible tool to assist technicians and farmers in orchard management decisions.

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CRediT authorship contribution statement

Ilaria Bruno: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation. **Ilaria Mania:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Matteo Lovera:** Methodology, Investigation. **Luca Brondino:** Resources, Investigation. **Cristiana Peano:** Supervision, Project administration, Funding acquisition, Conceptualization.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104186.

Data availability

Data will be made available on request.

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