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FunBies, a model for integrated assessment of functional biodiversity of weed communities in agro-ecosystem

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ABSTRACT

Agrobiodiversity, by producing beneficial ecosystem services (ESs), could improve the sustainability of cropping systems. There is a number of studies reporting the use of indicators for quantifying ESs. However, there are no indicators which might be applied at local scale and allowing an integrated assessment of a wide range of ESs in agro-ecosystems. The objectives of the present research were: (i) to describe a model for integrated assessment of functional biodiversity in agro-ecosystems, denominated FunBies, (ii) to show how it was validated, and (iii) to present results of its application. FunBies is featured by an empiric model component, a conceptual component that takes into account the whole range of ESs identified by the Millennium Ecosystems Assessment and by a multi-criteria linear additive model including the whole set of functional traits potentially supplied by herbaceous plant communities. The model was validated by a panel of experts. Results at cropping system level indicated that organic systems have the potential to supply considerably higher ESs than conventional systems. ES provision increases in time together with the evolution of the phytocoenosis. FunBies potential applications include: (i) design of biodiversity components within agro-ecosystems, and (ii) justification and sizing of organic payments.

1. Introduction

The concept of functional biodiversity has been introduced to acknowledge the fact that the components of biological diversity are not only important per se but also for the ecosystem functions (EFs) they supply. The importance of ecosystem functions was streamlined in the mid-sixties, has been progressively acknowledged during the nineties and gained global attention after the publication of the Millennium Ecosystem Assessment (MA) Reports (2005).

De Groot (1992) defined ecosystems functions as “the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly”. Coherently, ecosystem services (ESs) were later defined as the benefits that people derive from ecological functions of ecosystems (Costanza and Folke, 1997; Millennium Ecosystem Assessment, 2005). The link between ecosystems functions and biodiversity in agro-ecosystems was explicated by the definition of functional biodiversity given by Moonen and Barberi (2008), i.e. “that part of the total biodiversity composed of clusters of elements (at the gene, species or habitat level) providing the same (agro) ecosystem service, that is driven by within-cluster diversity”.

Costanzo and Barberi (2014) stated that agrobiodiversity, by producing beneficial services, could improve the sustainability of cropping systems in a context of low external inputs and unpredictable climate change. In the MA (2005) ESs were listed and the importance of considering ESs in agroecosystems analysis was stressed. More recently, Costanza et al. (2017) further confirmed the importance of ESs and estimated the value of ESs as 33 trillion (10^{12}) $/year. In addition, they stressed the crucial importance of giving a value for understanding, comparing and quantifying the economic contribution of ES provision.

In this scenario the scientific community plays a fundamental role. It can provide tools and models to evaluate the whole range of ESs (Millennium Ecosystem Assessment, 2005) provided by an (agro)ecosystem. Furthermore, tools and models provided by scientific community are crucial to be integrated in an ecological-economical approach; policy measures should be developed including ES provision by using modeling as a tool to develop a full cost accounting which considers negative and positive impacts on ESs and disservices. In this regard, integrated

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List of acronyms

FunBies	functional biodiversity of agro-ecosystems
OO	old organic
NO	new organic
CO	conventional
RC	row crop
WC	winter cereal
LF	legume crop for forage
LG	legume crop for grain
ES	ecosystem service
EF	ecosystem function
FT	functional trait
MVA	multivariate analysis
FBI	functional biodiversity index
MoLTE	Montepaldi long term experiment
MA	Millennium Ecosystem Assessment
TEEB	The Economics of Ecosystems and Biodiversity

modeling becomes essential to manage economic development in line with the ecological economics approach (Costanza et al., 2017).

This concept is further confirmed on farm and lower scales by Pacini et al. (2015) who developed a model to quantify the impact of organic and conventional farming practices on a number of ecosystem services and disservices ranging from biodiversity provision, to soil erosion, nitrogen and pesticide pollution. The model was then used to evaluate and size agri-environmental measures under the shape of organic payments to remunerate farmers for actual provision of ESs or decrease of impacts on disservices, later adopted by Tuscany Government for the implementation of the Regional Rural Development Plan (2015).

There is a number of studies reporting the use of indicators for quantifying ESs (Egoh et al., 2012; Canali et al., 2019). According to The Economics of Ecosystems and Biodiversity (TEEB) initiative (Ring et al., 2010), an indicator serves to indicate or give a suggestion of something of interest and is derived from measures. Oikonomou et al. (2011) proposed a conceptual framework that combines ecosystem function analysis, multi-criteria evaluation and social research methodologies for introducing an ecosystem, function-based planning and management approach.

Egoh et al. (2007) made a literature review about existing ES indicators. In his review, he found that there are several studies which evaluated the ES provision of systems on different scales but not enough research on site scales and in particular on productive farming systems. Bagstad et al. (2013) showed 17 tools to evaluate and quantify ESs. 15 out of 17 can be used at landscape scale and only 2 (EcoMetrix and LUCI) on site scale. EcoMEtrix (Parametrix, 2010) can be applied to estimate the environmental credits for market-based trading under restoration scenarios, proving that ecosystem functional performance changes depending on changes in attributes. While LUCI (formerly Polyscape; Jackson et al., 2013) can be applied to evaluate land cover change on flood risk, habitat connectivity, erosion, carbon sequestration and agricultural productivity. Therefore, they do not include a wide range of ESs. Egoh et al. (2012) made a review of indicators for mapping ESs from worldwide but in the review, there are no indicators which might be applied at local scale and including a wide range of ESs. In addition, no ES indicators were applied in Italy.

The demand for ecosystem services is increasing in many European countries, yet there is still a scarcity of data on values on regional scale (Gatto et al., 2013). As a result, proxy indicators are often used as surrogates. Proxy methods are especially used for cultural services, as these services are difficult to directly measure and model (Chatzinikolaou et al., 2015). Our concern was to assess the ability of different agro-ecosystem management options to supply ESs, while considering site-specific production and pedo-climatic conditions in a detailed fashion. For this exercise to be effective a measure unit of functional biodiversity is needed that can evaluate the combined impacts of farming practices and the environment on ES provision.

We propose plant functional traits (FTs) as indicators to quantify ESs in agro-ecosystems at a very local scale and under different management options. There are existing studies on the response of functional traits of plant communities to changes caused by external (biotic or abiotic) factors. Lavorel and Garnier (2002) proposed a conceptual framework that links traits associated with responses to those pressures that determine effects on ecosystems. The aim was to integrate analyses of response traits in relation to environmental and/or biotic factors with analyses of functional effects of species, and hence trait composition, in order to analyze the effects of environmental changes on ecosystem processes. Diaz et al. (2004) stated that FTs can be used as predictors of resource capture and utilization which are key-factors for ecosystem functions as a response to climate change and land use. "Through investigations in various parts of the world (Ackerly, 2003; Chapin III et al., 1996; Craine et al., 2001; Cunningham et al., 1999; Diaz and Cabido, 1997; Grime et al., 1997; Reich et al., 1997; Wardle, 1998; Wright et al., 2002) evidence is growing that such predictors do exist, and can be found in the form of single traits or sets of co-occurring traits of plants".

The concept of plant functional type proposes that species can be grouped according to common responses to the environment and/or common effects on ecosystem processes. However, the knowledge of relationships between traits associated with the response of plants to environmental factors such as resources and disturbances (response traits), and traits that determine effects of plants on ecosystem functions (effect traits), such as biogeochemical cycling or propensity to disturbance, remains rudimentary (Lavorel and Garnier, 2002). Concerning this last point, we imagine that a modeling tool developed to carry out integrated assessment of a broad range of plant responses and effects can be able to support more refined analyses of functional biodiversity in agro-ecosystems.

The trait-based approach shows promising results, especially for plant trait effects on primary production and some processes associated with carbon and nitrogen cycling in grasslands. However, there is a need to extend the proof of concept for a wider range of ecosystems and ecosystem services and to incorporate not only the functional characteristics of plants but those of other organisms with which plants interact for the provision of ecosystem services Lavorel (2013).

More specifically, based on a review of a number of studies, Lavorel (2013) identified a set of key conceptual and methodological, cross-cutting issues that should be considered for optimizing trait-based assessment of functional biodiversity. Among those, we isolate three issues that we consider particularly important for integrated assessment in agro-ecosystems:

1. The relevance of the 'plant economics spectrum' (Freschet et al., 2010) rather than just the leaf economics spectrum (Wright et al., 2004), to ecosystem service provision
2. Although carbon and nutrient cycling processes are primarily driven by traits of the most abundant (dominant) species (i.e. "the biomass ratio hypothesis" by Grime (1998)), there is new evidence for more complex effects of heterogeneous trait values between species (i.e. "functional divergence hypothesis" or "niche complementarity hypothesis")
3. There is also new evidence for the relevance of trait-based analyses of ecosystem services that are underpinned by interactions between plants and, for instance, soil microorganisms or insects (Lavorel et al., 2009).

Weeds have an important role in maintaining farmland biodiversity. This needs to be balanced with their potential negative impact on crop yield and quality (Esposito et al., 2023). Models of crop–weed competition are an important tool in striking this balance (Storkey, 2006). As indicated by Moonen and Barberi (2008), we need to consider all the elements composing the productive sub-system in its heterogeneity and not only the semi-natural sub-system where biodiversity conservation is usually focused.

As previously mentioned, Oikonomou et al. (2011) proposed a conceptual, multi-criteria evaluation framework for introducing an ecosystem function-based planning and management approach. However, to our knowledge nobody has applied a multi-criteria approach to assess the impact of alternative farming practices on the capacity of weed communities to produce ESs in agro-ecosystems.

The objectives of the present research were three-fold: (i) to describe a model for integrated assessment of functional biodiversity of weed communities in agroecosystems, henceforward denominated FunBies (i.e., FUNctional BIodiversity of agro-EcoSystems) model, (ii) to show how it was validated, and (iii) to present results of its application for the quantification of ESs delivered by weed communities of organic vs conventional systems.

Because mechanistic models of weed community are not developed to the extent needed for our purpose, we built the FunBies model based on empiric evidence from databases of weed communities of cultivated field and semi-natural habitats belonging to Montepaldi long term experiment (MoLTE) were organic and conventional agro-ecosystem management options are compared since 1991.

FunBies is featured by a conceptual component that takes into account the whole range of ESs identified by the MA and by a multi-criteria linear additive model including the whole set of functional traits potentially supplied by herbaceous plant communities representative of cereal, row crop, grain and forage legume fields and semi-natural habitats of Tuscany inland hill, arable land. The model was validated by a panel of experts with reference to pedo-climatic conditions of the area.

2. Material and methods

2.1. Experimental site: the montepaldi long term experiment

The research took place in the context of MoLTE experimental fields (MoLTE), which are part of an ongoing project started in 1991 at the Department of Agricultural, Food, Environmental and Forestry Sciences, University of Florence (UNIFI-DAGRI). MoLTE fields take place in the experimental farm of Florence University, which is located in Montepaldi, San Casciano Val-di Pesa, Tuscany, Central Italy, and cover an area of about 15 ha, in a lightly sloped area. MoLTE can be considered as a model of a representative agro-ecosystem of the Chianti area and more in general of internal hill arable land of Tuscany.

The experimental site is composed by three differently managed systems, designed with the purpose of comparing organic and conventional management. There are two organically managed systems called “Old Organic” (OO) and “New Organic” (NO) of 5,2 hectares each, composed by 4 fields each, and one “Conventional” system (CO) of 2.6 ha, composed by 2 fields. The two organic systems differ between each other in the time they were converted into organic agriculture. The OO micro-agroecosystem has been converted into organic in 1991 (EC reg. 2092/91 and following regulations), while the NO has been managed under the integrated agriculture method in the period 1991–2000, since 1994 following integrated production rules as indicated by Tuscany Regional implementation program of EC regulation 2078/92, and converted into organic management in 2001. The conventional micro-agroecosystem has been conducted according to ordinary, region-specific, conventional operations, including weeding, fertilization and tillage interventions as illustrated in Appendix A, Table A.1. Organic and conventional micro-agroecosystems include semi-natural habitats composed by an artificial hedgerow composed by autochthonous species (OO boundary), a spontaneous hedgerow (OO-NO) and a spontaneous grass stripe (NO-CO).

2.2. Database: observation over 25 years

Spontaneous species data of abundance and biomass has been recorded for MoLTE from 1993. Therefore, a 25-year-old database has been created including 223 records of the spontaneous species collected within the organic and conventional fields with the same method. Further records are available for FunBies concerning biodiversity of semi-natural habitats, which are not considered for the present article devoted to crop-weed communities. In-field weed measurements were based on sampling field portions of 0.25 m^2 following the throwing of a square metal sampling frame across the 50 x 260 m fields. Depending on the target number of repeated measurements for each crop in that year, the field was partitioned into equal segments and then the frame was thrown randomly within that segment. All weeds found within the perimeter of the frame were carefully removed, if possible with the root intact, and placed inside a plastic bag. Samples were then transported to the lab where weeds were grouped according to species, and the number of individuals for each species was recorded. The samples were then dried (if fresh weight at species level >0.5 g) and the dry weight per species was recorded. Timing of weed sampling was primarily driven by the combination of three conditions: (i) potential presence of flowering plants to facilitate weed species identification, which mostly happens under local climatic conditions in April-June; (ii) crop-specific phenological phase facilitating weed species identification, which is April-May for winter crops and May-June for summer crops; and (iii) distance from agronomic operations damaging weed species such as mowing of alfalfa or mechanical maize hoeing. Crops are sampled once a year following the calendar reported above, while semi-natural habitats are sampled twice in April and June (Appendix A Table A.2).

2.3. Selection of most representative crop-weed communities

In order to quantify ES provision through a functional trait-based approach and to support the assumption that the FunBies model would be able to measure functional biodiversity of alternative management options in Tuscany inland hill arable land, we needed to consider typical community compositions of a broad range of crops under organic and conventional management systems. This was carried out by elaborating sample records of crop-weed communities collected over the last 25 years from OO, NO and CO fields of MOLTE with statistical, non-parametric multivariate analysis (MVA) techniques. Note that MVA was performed on a sub-set of the overall 223-record database, representing parcels subject to ordinary farm interventions under organic and conventional methods tested at MoLTE, excluding those other parcels of experimental designs that were subject to specific experimental weeding, fertilizing and tillage treatments.

MVA statistics allow analyzing correlations between more than one statistical variable at a time, aiming at analyzing the differences between and within groups of samples (Schervish, 1987). Each sample was labeled in such a way that it included information of the sampling period, the field and crop in which it was collected and the position within the transect. MVA variables were given by herbaceous plant species collected in the experimental field at each sampling event.

The aim of MVA in our modeling approach was to develop virtual, representative weed communities for both organic and conventional rotations typical of Tuscany inland hill arable land; the species composition of virtual, representative communities would form the database on which subsequently develop a multi-criteria linear additive model for a trait-based, integrated assessment of functional biodiversity.

Typical rotations in our reference period differ between conventional and organic systems, mainly due to the need to include legume crops in organic rotations. Typical conventional rotations last two years and are featured by a row crop followed by a winter cereal. Typical organic rotations last 4 years and include, in addition to row crops and cereals, also legume crops for grain and for forage. In our experiment, row crops (RC) were sunflower (*Helianthus annuus* L.) and maize (*Zea mays* L.);

winter cereals (WC) were durum wheat (*Triticum durum* L.), common wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.); legumes for grain (LG) were broad bean (*Vicia faba minor* L.), lentil (*Vicia lens* (L.) Coss. and Germ.)], chickpea (*Cicer arietinum* L.); legumes for forage (LF) were Lucerne (*Medicago sativa* L.) and Clover (*Trifolium squarrosum* L., *T. pratense* L., *T. alexandrinum* L.).

The final aim of this step was then to identify virtual, representative crop-weed communities for RC, WC, LG and LF crop categories of typical organic and conventional rotations of the reference area. These was achieved by analyzing within the OO, NO and CO sample sets the degree of similarity among corresponding herbaceous plant species, by grouping RC, WC, LG and LF crop samples according to similarity degree, and then by selecting the within-group most representative sets of species. These sets are the ones that we reasonably suppose supporting the provision of ecosystems services from agro-ecosystems of the area. To obtain the composition of OO, NO and CO representative crop weed communities non-parametric MVA procedures were performed with the software PRIMER 6 (Gorley and Clarke, 2006).

First, a similarity matrix which shows the degree of resemblance between each pair of OO, NO and CO sample individuals was calculated using the Bray–Curtis distance (a non-metric coefficient particularly common in ecology, (Bray and Curtis, 1957)). The resemblance matrix was used as a basis to create a two-dimensional multi-dimensional scaling (MDS) plot for each system (OO, NO and CO), where relative distances of one sample to another represented between-sample (dis) similarities. There is normally some distortion in the plot that is minimized by the MDS algorithm, which is captured by the stress value. The stress value is a goodness-of-fit measure depending on the difference between the distances of each couple of sample points on the MDS plot and the distance predicted from the fitted regression line corresponding to coefficients of dissimilarities. If such difference is equal to zero, the stress is zero. Instead, widely scattered points clearly lead to a large stress and this can be interpreted as measuring the difficulty involved in compressing the sample relationships into two dimensions. Groups of sample individuals were further distinguished by superimposing on the MDS plots graphical representations of cluster analysis (CA) at a chosen similarity level, which is a graphical facility of PRIMER (Clarke and Warwick, 2001). Such choice was handled with a heuristic procedure through a subjective inspection of the CA dendrogram (Köbrich et al., 2003).

2.4. Characterization of selected crop-weed communities

The similarity percentages (SIMPER) analysis of the sample groups (Clarke, 1993) was performed to highlight the species principally responsible for determining the similarities within the crop-weed community groups generated by superimposing MDS and CA.

The SIMPER algorithm first computes the average similarity between all pairs of sample units within a group based on average abundance of each single species and then disaggregates this average similarity into separate contributions from each variable (weed species in our case). The variables whose values are all equal to zero within a group, although equal, do not give any contribution to the within-group similarity. The rate between within-group similarity and each variable's standard deviation holds a strong characterization power if the variable values are relatively constant within a group, so that standard deviation of its contribution is low, and the ratio between within-group similarity and standard deviation is high.

Species which contributed most to form the groups according to SIMPER analysis were emphasized to characterize each group of samples under OO, NO and CO agro-ecosystem management options, respectively, and were considered for following attribution of ES potentials.

2.5. FunBies model

FunBies is a model for integrated assessment of functional biodiversity of weed communities in agro-ecosystems. It is composed by three parts, i.e. an empirical-statistical, crop-weed community component, which is populated by data collected in field and processed with MVA techniques as showed in previous sections, a trait-based conceptual model, which is presented in this section, and a linear additive multi-criteria (LAM) model for integrated assessment of functional biodiversity, which is reported in the next.

ESs are commonly grouped into four categories, depending on corresponding categories of the functions that provide them: provisioning, regulating, cultural and supporting (Millennium Ecosystem Assessment, 2005). In our study, we developed a conceptual model which includes all the categories of ESs, in order to quantify the overall ES value provided by crop-weed communities in agroecosystems. As the cultivated crops and corresponding spontaneous herbaceous species are typical of the reference area, the model we propose was developed to be valid for the sub-region named “Internal Hill Arable Land” of Tuscany.

For each ES category, we first selected from the MA (2005) and De Groot's (2010) lists ecosystem functions according to their ability to provide target services, relevance for our study and information availability on plant trait databases such as TRY, Ecoflora, BiolFlor and LEDA. Second, a trait-based approach was adopted for evaluating the contribution of each plant to the performance of each function (Lavorel, 2013; Pakeman et al., 2011). For this scope, plant functional traits associated with the selected EFs are shown below for each ES category together with corresponding data sources. EFs, FTs, (dis)services and corresponding descriptions are summarized for each of the Millennium Ecosystem Assessment EF categories in Appendix B. The overall conceptual model, including ES categories, specific EFs, corresponding FTs and the way in which are linked is shown in Fig. 7 combined with figures resuming the LAM model.

2.5.1. Provisioning services

For this ES category only dis-services provided by weeds are considered. Indeed, weeds compete for water, nutrients and other resources with the main crop (Zhang et al., 2007). Whether weeds are more competitive, they both enhance their biomass while reducing the performance of other plants (including the main crop, (Torner et al., 2000). Similarly, several crop parameters (height, yield, biomass) are negatively related to weed biomass (Aminpanah, 2013; Power, 2010). Therefore, competitiveness is considered to produce a disservice. According to Torner et al. (2000), plant FTs which better explain the competitive ability of weeds are directly related with plant biomass, plant height, seed weight and rate of emergence. However, after valuation of local experts this set was slightly modified and complemented with additional FTs.

2.5.1.1. Plant biomass. A higher biomass of a weed holds a negative effect on the neighbor plants in terms of nutrients stolen, the shadow caused and space competition. Data of biomass for each species were recorded over years and have been reported in the MoLTE database in terms of grams of dry matter per species.

2.5.1.2. Plant height. Similarly to the biomass, a taller plant is likely able to catch more sun light than a smaller plant next to it (Craine et al., 2013). In addition, it likely causes and increase of shadow on the nearby plant. Data of plant height for each species were collected from TRY database.

2.5.1.3. Seed weight. According to Torner et al. (2000), as well as panel experts' opinion, seed weight is sufficient to evaluate seed-related traits for competitiveness as further information might be deduced from seed weight. Indeed, a heavier seed has also more chances to emerge than a lighter seed and a higher seed weight will likely result in a higher plant biomass in the following phenological stages. In addition, a heavier seed has more chances to go deeper into the soil and therefore avoiding external disturbances (such as tillage, machinery passage, run-off etc.) that take place on superficial soil layers, further increasing seed emergence rate. Data of seed weight for each species were collected from TRY database.

2.5.1.4. Drought tolerance. A more drought tolerant plant will be more competitive in a drier soil and hence more competitive in a site featured by extreme environmental conditions such as not-irrigated and dry soils in Mediterranean semi-arid climates. Data of drought tolerance for each species were collected from TRY database.

2.5.1.5. Nitrogen demand. A plant which is well adapted to sites with a low level of nitrogen will be more competitive in soils poor of this element. Nitrogen requirements were evaluated through the Ellenberg Indicator value, ranging between 1 and 9 (Hill et al., 1999). Smaller values (1–3) are associated with plants adapted to N-infertile sites while larger values (7–9) are associated with plant species typical of N-rich sites. Ellenberg data were collected from Ecoflora database (Ecoflora, 2022).

2.5.1.6. Shade tolerance. In poor light conditions, plants that are well adapted to shade will be more competitive than species requiring lighter conditions. Shade tolerance was evaluated through the Ellenberg Indicator's Value: smaller values are associated with plant species adapted to shade while larger values correspond to light-lover plants. Ellenberg data were collected from Ecoflora database (Ecoflora, 2022).

2.5.2. Regulating services

Regulation functions are by far the ones that produce the largest share of ESs and are represented by the largest number of selected FTs (Boerema et al., 2017).

2.5.2.1. Pollination. Pollinators' presence might be affected by herbaceous species growing within the fields as well as by the plant community in the field margins. These species can provide habitat and food for pollinators (Balzan and Moonen, 2014; Gabriel and Tscharntke, 2007; Gibson et al., 2006; Zhang et al., 2007). Flower morphology is one of the main factors that drives pollinators in flower selection (Fenster et al., 2004). Flower with large perianths, the nonreproductive part of the flower consisting of the calyx and the corolla, triggers high attractiveness to pollinators (Ivey and Carr, 2005; Mitchell et al., 2004; Molina-Montenegro and Cavieres, 2006). Therefore, Müller classes were used to evaluate the support to pollinators for each weed species. Müller (1883) classified the flowers pollinated by insects into 9 classes, depending on the depth of the nectar source (that is the floral tube length) along with the pollinator proboscis length (Durka, 2002). For each weed species found in our survey we gathered information about Müller classification from the BiolFlor database (Version 1.1). The larger the range of typical pollinators associated with a Müller class, the higher was the resulting Müller class score. Müller class scores attributed by an expert entomologist were reported in Appendix C together with Müller class characteristics and corresponding, typical pollinators (online).

In addition, flowering period was considered for the ecosystem function of pollination support since longer flowering periods likely result in pollen provisioning over a longer period with a consequent more important service. Flowering period was calculated with BiolFlor data and standardized between 0.0 and 1.0. The final score was calculated as Müller class score weighed by the flowering period value using the following formula:

$$\text{Pollinator attractiveness} = \text{Müller class score} * 0.7 * \text{Flowering period score} * 0.3 \tag{1}$$

Resulting Pollination scores were grouped in ranges of values from 0.0 to 1.0 (e.g., $0.0 < x < 0.1 = 0.1$, $0.6 < x < 0.7 = 0.7$, etc.).

2.5.2.2. Biological control. In general, there is a direct correlation between the abundance of phytophagous insects and natural enemies. Indeed, it is likely that a higher number of natural enemies, which are carnivorous insects, visits more frequently plants where a wider variety of phytophagous insects feed, regardless whether they are their primary or alternative hosts or preys (Altieri, 1999; Price, 2011). For each plant species, the number of phytophagous insect species known to feed on it was retrieved from Ecoflora database. The figure of phytophagous insects accounted in the database was expunged from species not recorded for Italy and adjusted on the basis of field surveys conducted in the studied area for years. Moreover, the possible contribution of each plant species as source of non-prey food (nectar, pollen, honeydew) to polyphagous natural enemies was approximately evaluated (Lundgren, 2009). On the basis of these overall assessments, a biocontrol supporting score was assigned. The larger the range of herbivorous insect species usually visiting the weed species, and the non-prey food production, the higher is the resulting biocontrol service score ranging from 0.1 to 1. The resulting biological control score was the result of a combination of the number of phytophagous insects retrieved from Ecoflora and the arbitrary considerations of an expert, comparing all the other values from the list. For instance, plants with similar number of visiting phytophagous insects might have different values of biological control score if one attracts only the larvae of the phytophagous and the other one also the adults or depending on the attractiveness of phytophagous (the more attractive for natural enemies, the higher the score).

2.5.2.3. Erosion regulation. For an evaluation of the function of controlling erosion processes, the root architecture, canopy width and the drought tolerance were considered. Root morphology considerably influences soil retention, stabilization and erosion control from run-off processes (Reubens et al., 2007). Anchoring effect of roots depends on their depth and spatial distribution. It has been proved that fibrous and shallower roots are more efficient than tap and deeper roots, respectively, in controlling soil erosion and water regulation (De Baets et al., 2011; Gyssels and Poesen, 2003; Zhang et al., 2013). Fibrous roots may potentially control erosion effect 1000 times more than tap roots (De Baets et al., 2007). In addition, a larger coverage of soil, as expressed by canopy width, leads to a lower soil erosion. This phenomenon is crucial especially when extreme climatic events happen (typically in summer) and hence superficial run-off is typically more pronounced. For this reason, also drought tolerance of these species was considered.

2.5.2.4. Water regulation. For studying water regulation service, water infiltration and water storage into the soil were taken into account. Root depth was considered as a FT to evaluate water infiltration. Deeper roots generally lead to a better water infiltration into the soil, as they help to reach deeper soil layers. Leaf dry matter content (LDMC) was considered for evaluating soil water storage capacity, since it is considered as an indicator of soil fertility (Hodgson et al., 2011). Smart et al. (2017) report that LDMC is the best predictor of above-ground net primary production and is a fundamental ecosystem function supporting food production and soil formation. Hence, we assumed for the FunBies model that LDMC is important for evaluating the organic matter that spontaneous species can supply also to soil, improving its structure and therefore increasing water storage capacity. Furthermore, a larger ground coverage reduces the impact of raindrops on the ground and hence lead to higher water infiltration. Data of root depth, LDMC and canopy width were gathered from the TRY database.

2.5.2.5. Climate regulation. Taylor et al. (1989) reported that for substrates low in lignin the C/N ratio is the best predictor of decomposition rate. Although more recent results suggest caution when using certain chemistry ratios to predict decomposition rate in Mediterranean ecosystems, they still confirm C/N correlates negatively with early-stage decomposition rate, which is the most common option in agroecosystems (Bonanomi et al., 2023). It was selected the C/N ratio of leaves – and not the C/N of other parts of the plant – because of the data availability on TRY. This trait gives an idea about the attitude of organic matter of each species to be stocked into the soil and not to be released into the atmosphere (in form of CO_2). Instead, small values of leaf C/N ratio reflect a faster decomposition of the plant organic matter with higher rates of CO_2 produced. Data of leaf C/N ratio were gathered from the TRY database.

2.5.2.6. Natural hazard regulation. Fire-related plant traits can be used to understand vegetation responses to disturbances from fire regime. In addition, in Mediterranean ecosystems, changes in fire regime might be more relevant than direct changes due to climate changes, making information about fire-related traits crucial (Paula et al., 2009). By fire-related traits we considered traits relevant for plant persistence and regeneration after fire (i.e., post-fire seeding emergence and mortality). Traits information was gathered from the TRY database, which reports on traits ranging between 0.03 and 1.

2.5.3. Supporting services

In the supporting service category, cycling of carbon and nitrogen that contribute to soil formation as well as the organic matter decomposition processes of weeds are considered.

2.5.3.1. Soil formation. The carbon present in weed leaves may return into the soil after leaf decomposition. Therefore, an overall higher leaf carbon content results in an increase of carbon amount of the soil as well. Leaf carbon content data were gathered from the TRY database.

2.5.3.2. Nutrient cycling. There are several indices to evaluate the attitude of organic matter to be decomposed into the soil. One of the most common indexes to evaluate it is the leaf C/N ratio, which is available in plant trait databases for most of the herbaceous species. As already mentioned before, the higher the value of plant C/N ratio, the slower the organic matter will be decomposed, the smaller the portion of nitrogen mineralized will be. Similarly to the leaf C/N ratio, the specific leaf area (SLA) index was used to consider the speed of organic matter decomposition. However, in this case, a higher SLA value indicates a thin leaf (large surface/thickness ratio) and hence a fast organic matter decomposition. Data of SLA were gathered from TRY database. N is a fundamental nutrient for plants. However, it needs to be fixed from the atmosphere into the soil to be adsorbed by plant roots. This process can happen through symbioses between plants and N-fixing bacteria, non-symbiotic N-fixing organisms and, to a minor extent, by atmospheric fixation. If a plant can establish this symbiosis (typical of leguminous species), a positive coefficient was assigned to indicate its capability to increase N content of the soil.

2.5.4. Cultural services

For this category, we considered the level of importance reached by each species in terms of cultural heritage. The cultural heritage value for each species was calculated as the knowledge score weighted by the use score

$$\text{Cultural heritage value} = \text{Knowledge score} * 0.5 + \text{Usescore} * 0.5 \tag{2}$$

The Knowledge score was calculated for each species as the frequency of citations, that is the number of ethnobotanical references where the species was mentioned over the total. To this purpose, we selected a list of ethnobotanical references concerning the traditional knowledge of plants in Tuscany region (Camangi et al., 2007; Corsi and Pagni, 1979; Frassinelli, 2008; Molines, 2018; Randellini, 2007; Signorini et al., 2007). The higher the frequency of citations, the higher the knowledge score: if a species is cited in all the six references considered, the score is the highest, if it is never cited is the lowest. Similarly to the knowledge score, we calculated the Use score of each species depending on its number of traditional uses reported in the considered bibliographic references. We took into account the following uses: cosmetic, craft, domestic, dyer, food, liquor use, magical, medicinal, ornamental, recreational, religious and veterinary. As the knowledge score, the higher the uses, the higher the resulting score. Finally, the cultural heritage values were grouped in ranges of values from 0.1 to 1, i.e. $0.0 < x < 0.2 = 0.1, 0.2 < x < 0.4 = 0.3, 0.4 < x < 0.6 = 0.5, 0.6 < x < 0.8 = 0.7, 0.8 < x < 1 = 0.9$.

2.6. Integrated assessment of functional biodiversity

2.6.1. Aggregation of ecosystem services provided by plant functional traits

Integrated assessment of functional biodiversity within the FunBies model was implemented by constructing a specific LAM model to aggregate species/trait performances at the level of ES category and for calculation of one overall functional biodiversity index (FBI).

A linear additive multi-criteria model is commonly used to combine many indicators into one overall value (Dodgson et al., 2009). It allows reducing information from many individual indicators into a single summarized index, easier to interpret and more accessible to decision makers and public. The linear additive structure of aggregation allows to give different importance to the elements composing the model: the value score on each element (FT in our model) is multiplied by the weight assigned to that element (Paracchini et al., 2011). After, the weighted scores of all indicators will be summed up to give the contribution of a given species for a number of ecosystem functions within each of the provisioning, supporting, regulating and cultural ES categories. The values obtained in such a fashion will be further weighted at the level of ES category and then summed together to obtain one overall value for each of the species of a crop weed community. If we sum up the species values we obtain an overall value, i.e. the functional biodiversity index of a given crop-weed community, as shown in the following equation:

$$FBI = \sum_{Sp=1}^{N} \sum_{ES=1}^{4} w_{ES} * \left[\sum_{EF=1}^{x} w_{EF} * \left(\sum_{FT=1}^{n} w_{FT} * A_{Sp} * S_{FT} \right) \right]$$

Where W_{ES} is the weight attributed to each of the four ecosystem service categories, W_{EF} is the weight attributed to each ecosystem function, W_{FT} is the weight attributed to each functional trait, A_{Sp} is the abundance of a species either in terms of number of individuals (nr/m^2) or of dry matter weight (g/m^2), S_{FT} is the FT score per each species unit expressed either in terms of number of individuals or grams.

One of the requirements for processing multiple indicators within an aggregation framework is that all are reduced to the same scale, with common units (Nardo and Saisana, 2005). Thus all indicators must be standardized, preferably to a continuous numerical scale, in order to allow mathematical procedures such as linear-additive aggregation to be performed (Paracchini et al., 2011). FT scores representing the potential ability of a plant to provide a given ecosystem service, or cause a disservice, vary between 0 and 1 and were standardized based on FT-specific ranges of values.

Standardization was carried out in such a manner that scores close to one represent higher benefits and scores negatively weighted represent disservices. Specific ranges are reported in Fig. 7, with relevant measure units, under corresponding FTs. The range within which FT values are standardized should include potential FT values for a large number of species and in some cases could be truncated to omit too high or too low values of outliers that would cause underestimation of differences between all other species. Seed weight values, originally ranging between 0.05 and 1531 g, were log-transformed, which reduced the range between 0.05 and 310 g.

If we suppose $A_{Sp} = 1$, by sequentially aggregating FT scores at the levels of EFs and ES categories we obtain a functional biodiversity index (FBI) at species level that ranges between 0 and 1. It has to be noticed that this specific FBI represents the contribution that each species single

Table 1
Panel of experts selected for validation of the FunBies model. For each ecosystem service (ES) category, the corresponding functional traits (FTs) are shown together with required expertise and selected experts.

Ecosystem service category	Functional trait(s)	Expertise	Name of expert(s)
Provisioning	Weeds and competition	Weed scientist, Ecologist	Argenti, Vazzana
Regulating	Roots, water/climate regulation, soil retention	Agronomist, Pedologist	Napoli, Certini
	Pollination and biocontrol	Entomologist	Sacchetti
Supporting	Soil formation and nutrient cycling	Soil scientist, Botanist	Ceccherini, Bussotti
Cultural	Cultural heritage and local memory of the use	Botanists	Selvi, Viciani

unit can supply to functional biodiversity. Of course, the more abundant is a species in a field, in a hectare or in whatever reference area, the more it can contribute to overall functional biodiversity. In the present case species abundance was measured by both number of individuals (nr/m^2) and dry matter weight (g/m^2). Each weighted FT score was multiplied either by dry matter weight or by number of individuals depending on which of these two measure units would fit better the selected FT indicator. Coherently each FT score was either referred to a single unit of number of individuals or of dry matter weight.

An example of calculation procedure for functional biodiversity index at single species level is given in Appendix D and Table D.2. By summing FBIs calculated for each single species belonging to crop-weed communities we obtain an overall FBI that can represent functional biodiversity performances at the level of OO, NO or CO micro-agroecosystem, or whatever else assemblage of species in a given agroecosystem.

2.6.2. Expert validation

The conceptual and the LAM models including plant FTs, FT scores and weights were validated by a panel of experts. Noble (2004) defined a panel of experts as a “group of informed individuals selected to assign impact assessment judgment based on experience and expertise”. Indeed, expert-based assessment is the most appropriate approach to validate indicators when no real, quantitative data based on observations are available (Paracchini et al., 2011). The panel was composed by members with different expertise so that they could validate coefficients of a wide range of ESs. In addition, gathering together experts with different scientific backgrounds ensured interactions and discussions leading to a reinforced validation.

The “Expert Panels” guidelines proposed by the JRC of European Commission (Torner et al., 2000) were followed to establish the size and composition of the panel, gathering members together and choosing a panelist chair. Following, the step-bystep guide was implemented to carry out the procedure for validation. First, the size of the panel was decided depending on the objective of the impact assessment and the available time and resources. The composition of the panel was based on criteria withdrawn from Noble (2004). Criteria were as follows:

- Experience: (i) knowledge of two or more of the specialty areas considered in the assessment, (ii) 7–10 years of combined education and professional experience in impact assessment;
- Reputation: (i) publications, (ii) participation in professional meeting and/or symposia, (iii) panelist’s involvement in similar types of projects, (iv) appropriate geographic representation;
- Heterogeneity of the panel.

A first call was sent them on the 7th of August 2017 with the description of the project including detailed background information along with the request of taking part in the panel. Finally, a panel composed by 9 experts was established, which is presented in Table 1. At this stage we gave preference to academic experts. Indeed, expert validation did not focus only on the aggregation procedure including FT scores and weights; also the overall architecture of the FunBies was scrutinized, which comprises an empirical-statistical, crop-weed community component, a trait-based conceptual model, and a linear additive multi-criteria (LAM) model. FunBies was constructed based on multi-faced scientific knowledge from MVA statistics, functional ecology, economics and mathematics, which requested, besides scientific background on single agroecosystem components and processes, a more general expertise on scientific research methods.

Information regarding background of the panelists, including previous experiences, publications, meetings and other panel contributions was collected from each member (Table 2).

Once the panelist chair was chosen, scoring systems and weights for each FT were identified by the authors based on the literature review. Then, the procedure for validation was implemented, which consisted in two phases. First, a one-to-one meeting with the panel chair and each panelist was organized. In this meeting, the panel chair presented and discussed the overall FunBies multi-criteria framework and assessed together with each expert corresponding FT scores and weights. Second, a plenary meeting was organized on the 13th of October 2017 to discuss and officially validate FT selection and corresponding scores and weights. In the course of the plenary session each FT scoring system and weight was submitted to the whole panel of experts in order to ensure a truly inter-disciplinary validation of the LAM model. Furthermore, standardization rules of FT scores were established and assessed.

3. Results

3.1. Selection of most representative crop-weed communities

In Figs. 1, 2, 3, 4, 5, 6 cluster dendrograms and MDS plots ordering sample observations of crop-weed communities of OO, NO and CO micro-agroecosystems collected at MoLTE in the period 1993–2017 are reported, respectively. Observations were ordered with the aim to model the provision of ecosystems services based on the most representative crop categories of the reference area. MVA representations proved to be reliable and useful in the FunBies model construction, considering the extreme diversity of sample individuals. Stress values of MDS plots lie between 0.19 and 0.21. According to Clarke and Warwick (2001), a stress value between 0.1 and 0.2 gives a potentially useful 2-dimensional picture, though for values at the upper end of the range a cross-check of

Table 2
Information about experts’ background. Each capital letter in the columns is referred to a member of the panel.

Experts background	A	B	C	D	E	F	G	H	I
Total years of practice/experience[1]	25	25	12	20	12	20	25	30	20
Number of publications on the topic[1]	20	20	10	10–15	12	10	20	100	15
Presentations at conventions[1]	5	5	1	2–3	2	1	5	50	2
Holds/held leadership/management positions in ecosystem service assessment	No	No	No	No	No	No	No	Yes	No
Currently active in the area of ecosystem service assessment	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes

Legend: A, Prof. G. Argenti; B, Prof. F. Bussotti; C, Dr. M.T. Ceccherini; D, Prof. G. Certini; E, Dr. M. Napoli; F, Prof. P. Sacchetti; G, Prof. F. Selvi; H, Prof. C. Vazzana; I, Prof. D. Viciani.

[1] Related to agronomical-environmental subjects.

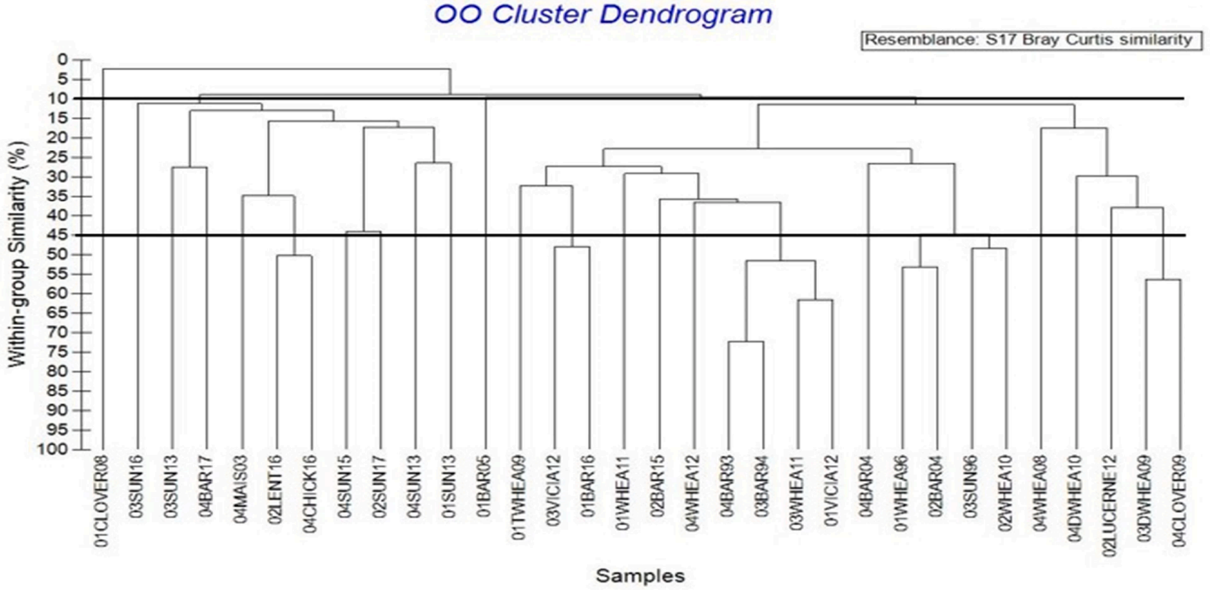

Fig. 1. Cluster dendrogram grouping sample crop-weed sample individuals of the old organic (OO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the species variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. Two major groupings were identified at 10 % of within-group similarity. Cluster composition at 45 % of within-group similarity was used to complement multi-dimensional scaling ordination considering four categories of crops, i.e. winter cereals, row crops, legume crops for forage and for grain.

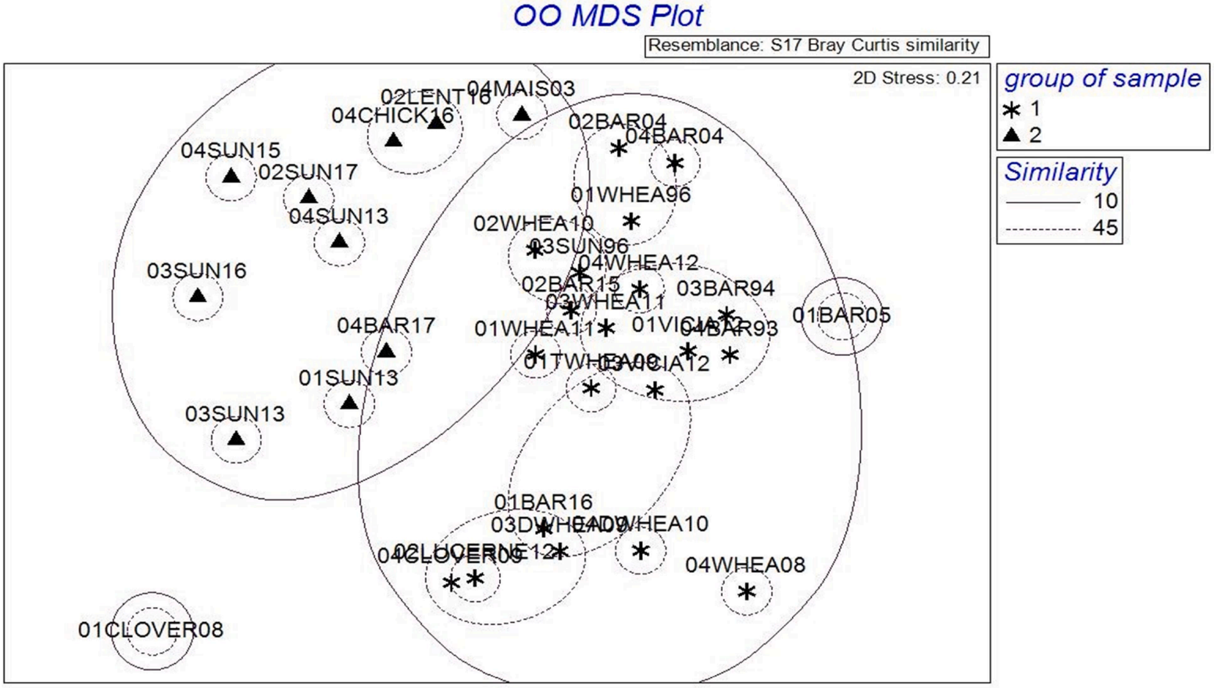

Fig. 2. Superimposition of cluster groupings on the multi-dimensional scaling plot representing crop-weed communities of the old organic (OO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. The stress value of the representation is 0.21. Two major groups were identified at 10 % of within-group similarity, i.e. Group 1 including winter cereals (WC) and legume crops for fodder (LF) (labelled with a star, named OO-WC+LF), and Group 2 including mainly row crops and legume crops for grain (labelled with a triangle, named crop-weed community OO-RC+LG). Crop-weed communities' composition in terms of species identity and abundance is reported in Table 3.

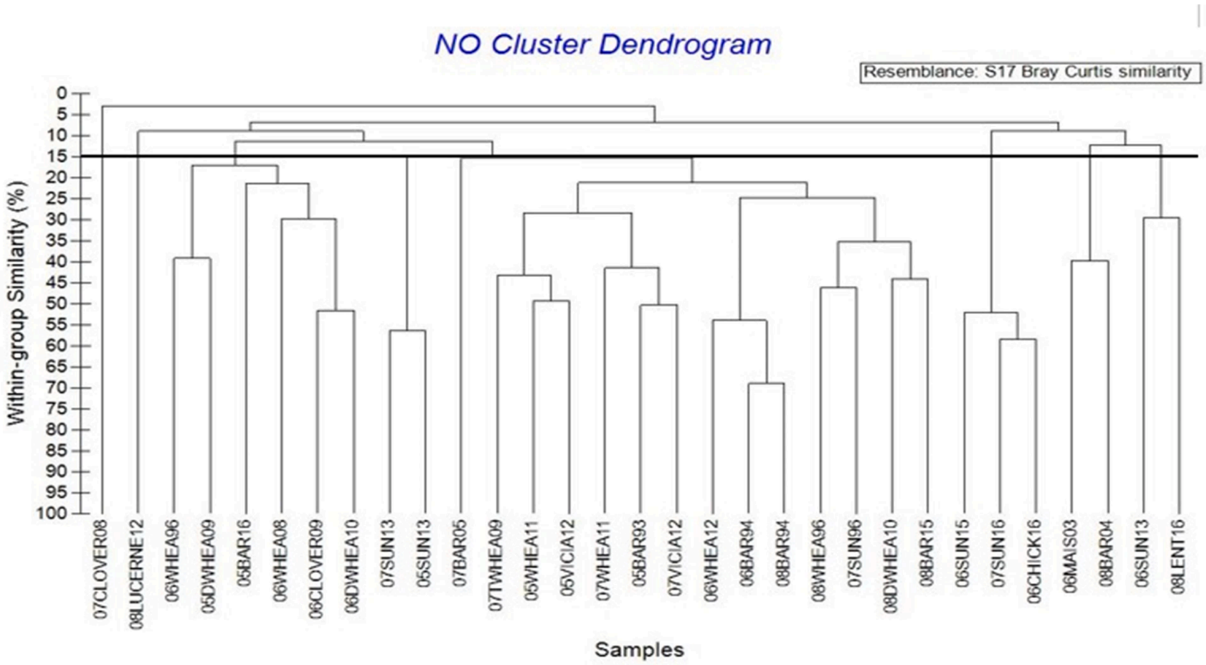

Fig. 3. Cluster dendrogram grouping sample crop-weed sample individuals of the new organic (NO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the species variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. Six groupings and two out-layers were identified at 15 % of within-group similarity.

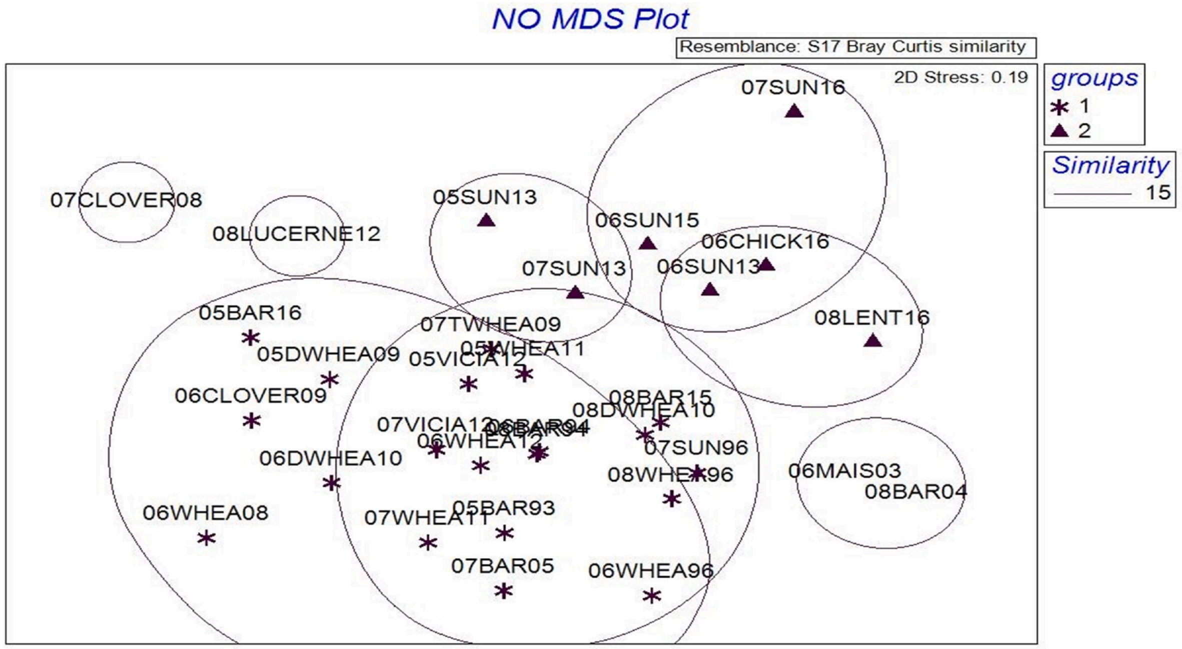

Fig. 4. Superimposition of cluster groupings on the multi-dimensional scaling plot representing crop-weed communities of the new organic (NO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. The stress value of the representation is 0.19. Two major groups were identified at 15 % of within-group similarity, i.e. Group 1 including mainly winter cereals (WC) and legume crops for forage (LF) (labelled with a star, named crop-weed community NO-WC+LF), and Group 2 including row crops (RC) and legume crops for grain (LG) (labelled with a triangle, named crop-weed community NO-RC+LG). Crop-weed communities' composition in terms of species identity and abundance is reported in Table 3.

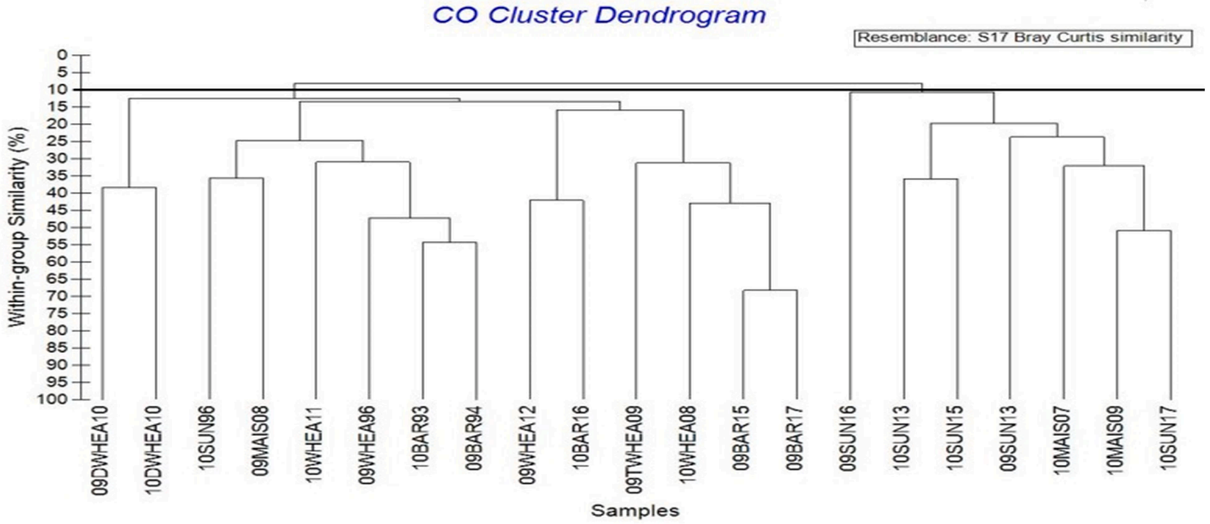

Fig. 5. Cluster dendrogram grouping sample crop-weed sample individuals of the conventional (CO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the species variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. Two groups were identified at 10 % of within-group similarity.

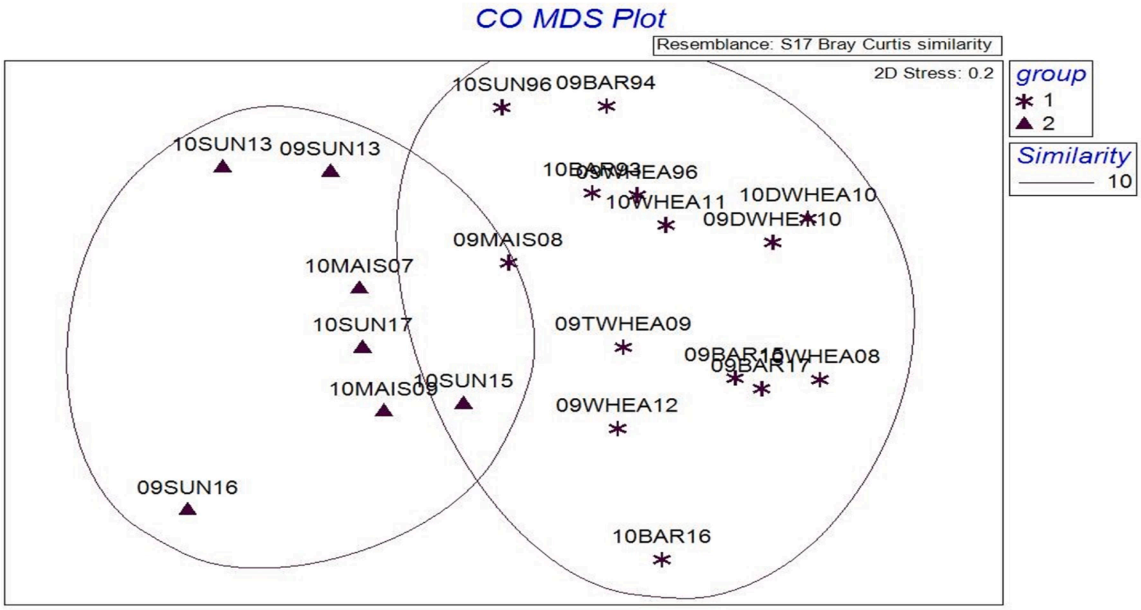

Fig. 6. Superimposition of cluster groupings on the multi-dimensional scaling plot representing crop-weed communities of the conventional (CO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. Results were obtained after standardization by percentage of the variables and calculation of a similarity matrix based on the Bray–Curtis coefficient. Sample labels include information on field, crop and time of observation, respectively. The stress value of the representation is 0.20. Two major groups were identified at 10 % of within-group similarity, i.e. Group 1 including mainly winter cereals (WC) (labelled with a star, named crop-weed community CO-WC), and Group 2 including row crops (RC) (labelled with a triangle, named crop-weed community CO-RC). Crop-weed communities' composition in terms of species identity and abundance is reported in Table 3.

the groupings should be made by superimposing CA groups of farms. OO, NO and CO crop-weed sample individuals were ordered in two major groups at a within-group similarity level of 10 % (OO and CO) and 15 % (NO). In all of the three micro-agroecosystems the two groups represented homogeneous crop categories, i.e. Group 1 (labelled with a star in Figs. 2, 4 and 6), including mainly WCs and LFs, and Group 2 (labelled with a triangle), including mainly RCs and LGs. The only exception to this pattern was due to the absence of legume crops in the CO micro-agroecosystem.

In Figs. 2, 4 and 6 clusters were superimposed on MDS plots. While the level of determination of membership of each sample to one of the two groups was made possible at higher detail thanks to the superimposition of clusters, inter-relations between the samples on a continuous scale were displayed thanks to the MDS configuration on the plot. Clusters are not imposed because the continuum of change remains visible on corresponding MDS plots. Some sample individuals were positioned in the overlapping space between two different groupings when MDS and CA were combined: their attribution to groups was ambiguous. Allocating each sample to a single group (including those in the intersections) was made possible by checking their single membership on the CA dendrogram.

Regarding OO (Fig. 2), exceptionally, 04BAR17 belonged to the RC

Table 3

Results of similarity percentage (SIMPER) analysis for crop weed communities of old organic (OO), new organic (NO) and conventional (CO) macro-groups of crops found at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany. Macro-groups of crops are winter cereals (WC) plus legumes for forage (LF), and raw crops (RC) plus legumes for grain (LG). Macro-group average similarities: OO–WC+LF = 22.2; OO–RC+LG = 16.9; NO–WC+LF = 19.5; NO–RC+LG = 20.4; CO–WC = 19.0; CO–RC = 21.3.

Species	Average abundance (nr.)	Average Similarity (nr.)	Contribution to group similarity (%)	Cumulative contribution (%)
OO–WC+LF (n = 13)				
Fallopia convolvulus (L.) Á.Löve	23.3	7.5	33.7	33.7
Polygonum aviculare L. subsp. *Aviculare*	22.8	5.3	23.9	57.6
Lolium multiflorum Lam.	37.2	2.1	9.5	67.1
Convolvulus arvensis L.	5.8	1.1	4.9	72.0
Anthemis arvensis L.	11.1	1.0	4.6	76.6
Stachys annua L. subsp. *annua*	5.8	0.9	4.1	80.7
Lysimachia arvensis (L.) U.Manns & Anderb.	5.2	0.9	4.0	84.7
Sinapis arvensis L. subsp. *arvensis*	5.1	0.7	3.1	87.9
Trifolium pratense L.	50.0	0.7	3.0	90.9
Kickxia spuria (L.) Dumort.	6.5	0.4	1.9	92.8
Euphorbia helioscopia L. subsp. *helioscopia*	2.5	0.3	1.6	94.3
Papaver rhoeas L. subsp. *rhoeas*	1.0	0.2	1.0	95.3
Lolium perenne L.	2.8	0.2	0.7	96.0
OO–RC+LG (n = 14)				
Setaria italica (L.) P.Beauv. subsp. *viridis* (L.) Thell.	9.1	3.1	18.4	18.4
Sinapis arvensis L. subsp. *arvensis*	3.1	2.2	13.2	31.6
Sorghum halepense (L.) Pers.	3.1	2.0	11.9	43.5
Fallopia convolvulus (L.) Á.Löve	1.5	1.6	9.7	53.2
Convolvulus arvensis L.	1.6	0.9	5.2	58.4
Stachys annua L. subsp. *annua*	0.7	0.8	4.4	62.8
Anthemis arvensis L.	1.6	0.7	4.4	67.2
Helminthotheca echioides (L.) Holub	2.6	0.7	4.1	71.3
Sonchus asper (L.) Hill	1.8	0.7	3.9	75.2
Kickxia spuria (L.) Dumort.	1.1	0.6	3.5	78.7
Lysimachia arvensis (L.) U.Manns & Anderb.	0.8	0.6	3.4	82.1
Cynodon dactylon (L.) Pers.	1.6	0.5	3.1	85.2
Lolium perenne L.	1.2	0.5	2.9	88.0
Chenopodium album L.	1.1	0.4	2.3	90.3
NO–WC+LF (n = 12)				
Fallopia convolvulus (L.) Á.Löve	27.8	5.2	26.8	26.8
Lolium multiflorum Lam.	56.0	3.6	18.6	45.4
Convolvulus arvensis L.	9.1	2.7	14.1	59.4
Polygonum aviculare L. subsp. *aviculare*	15.3	2.6	13.3	72.7
Anthemis arvensis L.	12.5	1.1	5.5	78.2
Sinapis arvensis L. subsp. *arvensis*	3.4	0.8	4.3	82.6
Stachys annua L. subsp. *annua*	6.6	0.8	4.0	86.5
Lolium perenne L.	11.3	0.6	2.8	89.4
Galium aparine L.	3.9	0.3	1.7	91.1
Euphorbia helioscopia L. subsp. *helioscopia*	3.1	0.3	1.6	92.7
Fumaria officinalis L.	1.4	0.3	1.5	94.2
Lysimachia arvensis (L.) U.Manns & Anderb.	2.1	0.2	1.1	95.3
NO–RC+LG (n = 14)				
Setaria italica (L.) P.Beauv. subsp. *viridis* (L.) Thell.	21.6	7.0	34.2	34.2
Sonchus asper (L.) Hill	12.4	3.9	19.2	53.4
Fallopia convolvulus (L.) Á.Löve	1.5	1.3	6.3	59.7
Setaria verticillata (L.) P.Beauv.	9.7	1.2	5.8	65.5
Sinapis arvensis L. subsp. *arvensis*	3.9	1.1	5.4	70.9
Sorghum halepense (L.) Pers.	2.1	1.0	5.0	75.9
Stachys annua (L.) L. subsp. annua	1.8	1.0	4.8	80.7
Euphorbia prostrata Aiton	1.9	0.8	4.0	84.6
Convolvulus arvensis L.	2.1	0.8	3.8	88.4
Chenopodium album L.	1.6	0.7	3.5	92.0
Anthemis arvensis L.	3.8	0.5	2.4	94.3
Kickxia spuria (L.) Dumort.	1.1	0.3	1.7	96.0
Lolium perenne L.	0.8	0.3	1.2	97.2
Cirsium arvense (L.) Scop.	1.1	0.2	0.8	98.0
CO–WC (n = 12)				
Polygonum aviculare L. subsp. *aviculare*	22.2	5.1	26.7	26.7
Fallopia convolvulus (L.) Á.Löve	20.4	4.8	25.2	51.9
Convolvulus arvensis L.	5.0	2.8	14.5	66.5
Lysimachia arvensis (L.) U.Manns & Anderb.	21.9	1.7	8.9	75.3
Galium aparine L.	7.3	1.5	7.7	83.0
Veronica persica Poir.	9.0	0.7	3.7	86.8
Fumaria officinalis L.	2.2	0.7	3.6	90.4
Lolium multiflorum Lam.	4.6	0.5	2.8	93.1
Amaranthus retroflexus L.	9.4	0.3	1.8	95.0
Lolium perenne L.	1.4	0.2	1.1	96.1
Euphorbia helioscopia L. subsp. *helioscopia*	2.2	0.1	0.7	96.8

(*continued on next page*)

Table 3 (*continued*)

Species	Average abundance (nr.)	Average Similarity (nr.)	Contribution to group similarity (%)	Cumulative contribution (%)
Stachys annua L. subsp. *annua*	1.9	0.1	0.5	97.4
CO–RC (n = 12)				
Convolvulus arvensis L.	8.7	7.9	37.3	37.3
Cirsium arvense (L.) Scop.	3.2	4.1	19.4	56.6
Sorghum halepense (L.) Pers.	6.9	2.5	11.8	68.5
Xanthium orientale L.	7.2	1.8	8.6	77.1
Lolium perenne L.	1.7	1.5	7.2	84.3
Xanthium spinosum L.	4.0	0.9	4.2	88.4
Euphorbia prostrata Aiton	0.9	0.5	2.1	90.5
Setaria italica (L.) P.Beauv. subsp. *viridis* (L.) Thell.	1.1	0.3	1.3	91.8
Amaranthus retroflexus L.	0.3	0.2	1.1	92.9
Veronica persica Poir.	1.7	0.2	1.0	93.9
Digitaria sanguinalis (L.) Scop.	0.9	0.2	0.8	94.7
Mentha suaveolens Ehrh.	1.2	0.2	0.7	95.4

Legend: n, average species richness of macro-group categories in the period 2013–2017 for OO, NO and CO micro-agroecosystems.

group, as weed species usually found within RCs were collected in this barley field. 01BAR05 and 01CLOVER08 sample individuals were considered outliers since they resulted as a separate group. In addition, by superimposing clusters at a degree of similarity of 45 % on the MDS plot we isolated groups characterized by LF and LG crop-weed communities that were embedded in larger C and RC groups, respectively.

Concerning NO (Fig. 4), eight groups of samples were identified at a degree of similarity of 15 %. Two overlapping groups were composed by WC and LF crop-weed communities and were merged (Group 1). Similarly, three groups were characterized by RC and LG communities and were merged as well (Group 2). Other groups, resembling in total only four sample individuals (i.e. 07CLOVER08, 08LUCERNE12, 06MAIS03 and 08BAR04) were considered as outliers. Regarding CO (Fig. 6), two groups were identified at 10 % of similarity. One is characterized by RC communities, while the other group is mainly featured by WC communities. Overall, we identified throughout all of the three OO, NO and CO micro-agroecosystems two macro-groups of crop-weed communities, i.e. WC+LF and RC+LG, which were later characterized in terms of community composition and contribution of the most representative species to within-group similarity.

3.2. Characterization of the most representative crop-weed communities

In Table 3 the plant species which contribute the most to the within-group similarities of each of the WC + LF and RC + LG macro-groups of crop weed communities are reported for each OO, NO and CO agroecosystem management option.

Results of SIMPER analysis show that in general selected crop weed communities are featured by low levels of within-group similarity, ranging from 16.9 % in the OO RC + LG group to 22.2 % in the OO WC + LF group. Notwithstanding this aspect, which is in line with high levels of biodiversity found in the area, groups of crop weed communities were identified in an unambiguous way and were consolidated by SIMPER results in terms of group composition. Average species richness of crop-weed communities per macro-group category in the period 1993–2017 slightly changed from 13–14 species in OO, to 12–14 species in NO and12 species in CO micro-agroecosystems. If we cut-off from the total number of species those that contribute the least to within group similarity, i.e. those species that cumulatively account for 10 % or less of within group similarity, we found that OO and NO showed higher variety of representative species as compared to CO crop-weed communities both for WC+LF crops (i.e. 9, 9 and 7 species, respectively) and for RC+LG crops (14, 10 and 7 species, respectively).

In all of the groups species that mostly contribute to within-group similarity are those that in the course of 25 years have been stably present. Often, with very few exceptions (e.g. *Trifolium pratense* L. in OO WC + LF group), those species also held higher average abundances and can be considered dominant in corresponding weed communities.

Among those species that mostly contributed (more than 10 %) to within-group similarity *Fallopia convolvulus* L. and *Polygonum aviculare* L. characterized WC + LF communities of both OO, NO and CO micro-agroecosystems (33.7–23.9, 26.8–13.3 and 25.2–26.7 %, respectively). *Convolvulus arvensis* L. characterized WC+LF communities of both NO and CO (14.1 and 14.5 %, respectively) and, to a minor extent, of OO (4.9 %). It seems that competition power of WC+LF crops is high and few species can withstand it. However, if we consider additional representative species (those that cumulatively represent 90 % or more of within-group similarity, excluded the already mentioned dominant species), these systems differ to a broad extent. Four of 6 additional, representative species of OO are equal to those of NO. CO holds only 1 of 4 additional species that is equal to those of OO or NO.

Concerning RC + LG crops, we found even broader difference between organic and conventional crop-weed communities. *Setaria italica* L. *P.Beauv.* subsp. *viridis* L. was found to be the dominant species for OO and NO communities (18.4 and 34.2 %, respectively), followed by *Sinapis arvensis* L. and *Sorghum halepense* L. in OO communities (13.2 and 11.9 %, respectively) and by *Sonchus asper* L. in NO systems (19.2 %). In CO communities *Convolvulus arvensis* L., *Cirsium arvense* L. and *Sorghum halepense* L. resulted to be the most representative species (37.3 %, 19.4 and 11.8 %, respectively). Nine of the 10 most representative species of NO communities are included in the 14 most representative OO species, while this applied to only 3 of the 7 most representative CO species.

Overall, there appears to be a remarkable difference between community composition of organic and conventional WC + LF crops, although potential impact on functional biodiversity by dominant species could be similar. Instead, organic and conventional communities of RC + LG crops seem to be broadly different, which should give rise to corresponding differences in terms of impacts on bio-functionality.

3.3. Results of the FunBies model

FunBies can supply a broad range of results in terms of services produced by a single FT, by a single EF, by aggregated groups of EFs (i.e., provisioning, supporting, regulating and cultural), or of an overall functional biodiversity index. Besides, these results can refer both at the contribution of a single species to functional biodiversity or of an entire plant community. As an example of how FunBies can generate useful outcomes for integrated assessment of functional biodiversity in the following we will present results of the overall functional biodiversity index at cropping system level, of FBI per crop macro-group (WC + LF and RC + LG, respectively) and at species level.

3.3.1. Results of the overall functional biodiversity index at system level

In Fig. 8 FBI results at the level of OO, NO and CO systems are presented, respectively, under two different scenarios: equal weight scenario (WS) and expert based WS. In the equal weight scenario each ES category holds the same weight, i.e. 0.25, while as an alternative experts proposed weights as follows: 0.5 for the provisioning category, 0.2 for the regulating and supporting categories and 0.1 for the cultural category. In this way experts acknowledged the widespread perceptions that weeds are mainly elements of competition against crops and that cultural aspects are secondary.

Results of FBI under the two scenarios did not differ in relative terms. OO showed the best performance (19.32 and −31.03 under the equal and expert-based WSs, respectively) and CO the worst (5.78 and −54.02, respectively), with NO laying in between (13.16 and −35.23, respectively). NO and CO produced 32 % and 70 % less overall ESs than 00 under the equal WS, respectively, and showed a 14 % and 74 % lower FBI under the expert-based WS, respectively. It seems that organic management outperforms conventional for what concerns functional biodiversity and that this difference increases in more mature systems; indeed, OO was converted to organic production 10 years before NO. These differences only slightly modified under different WS.

3.3.2. *Provision of ecosystem services per macro-group of crop-weed communities*

In Figs. 9 and 10 provision of ecosystem services by representative WC + LF and RC + LG crop-weed communities in OO, NO and CO micro-agroecosystem at MOLTE is presented. In this figure we decided to show results by single EFs in order to interpret at a more detailed level the results of the overall functional biodiversity index. EFs considered were erosion regulation, water regulation, pollination, biocontrol, climate regulation and natural hazard regulation (for regulating services), cultural heritage (cultural service), soil formation and nutrient cycling (supporting services) and competitiveness (provisioning service).

Concerning WC + LF, it is evident that OO performed better than NO, which in turn performed better than CO (only WC). This is in line with the results of the overall FBI previously shown. Specifically, the spider diagram shows how OO achieved the highest performance regarding erosion and water regulation, pollination, biological control and cultural heritage.

Unexpectedly, results revert when we consider RC + LG crop category. In this case CO (only RC) performances were higher especially for what concerns climate regulation, supporting services and competitiveness. This can be explained by the large importance that *Convolvulus arvensis* L. holds within the CO RC crop-weed communities (Table 3, 37.3 % of within-group similarity contribution) combined with overall second-best performance of this species in terms of regulating and fifth-best for provisioning dis-service (Fig. 11 and Appendix D, Table D.1, scores of 0.83 and −0.19, respectively).

Concerning the impact of these EFs on the FBI of RC+LG crop-weed communities, it has to be noticed that the beneficial effects of supporting services and climate regulation are partially counterbalanced by the negative impact due to competitiveness.

3.3.3. *Results of the functional biodiversity index at species level*

In Fig. 11 results of the application of FunBies at speciel level are reported, which are specified in Appendix D, Table D.1. Most competitive species resulted to be *Helianthus tuberosus* L., *Helianthus annuus* L. and *Sorghum halepense* L. (provisioning scores equal to −0.35, −0.33 and −0.26, respectively), followed by *Medicago sativa* L. and *Convolvulus arvensis* L. (−0.20 and −0.19, respectively). It has to be noticed that both *H.annuus* L. and *Medicago sativa* L. are ordinary crops used in the rotations and are mainly present as residual individuals of preceding crops. Best performing species for regulating services are *Cirsium arvense* L., *Convolvulus arvensis* L. and *Dactylis glomerata* L. (1.00, 0.83 and 0.44, respectively), for supporting services are *Medicago lupulina* L., *Trifolium pratense* L. and *Veronica persica* Poir. (0.78, 0.76 and 0.70, respectively), for cultural services are *Papaver rhoeas* L., *Equisetum arvensis* L. and *Daucus carota* L. (1.00, 0.62 and 0.40, respectively).

4. Discussion and conclusions

The objectives of the present research were to describe FunBies model, to show how it was validated and to present results of its application for the quantification of ESs delivered by weed communities of organic vs conventional systems. In this section we will discuss validity and validation processes of FunBies single components and results of its application.

4.1. *Valuation of the FunBies crop-weed community component*

To our knowledge no model was developed able to predict the evolution of a vegetation community in cultivated fields under the disturbance imposed by different management techniques on site scale. It is common for agronomists to model the impact of weeds on a given crop but not vice versa. This aspect must not be underestimated if we want to model the contribution of weed communities to ESs produced in agroecosystems. Ecologists seem to be one step forward in this direction: You et al. (2015) carried out a review of ecological models of riparian vegetation under disturbances. Outcomes of the review are particularly important as riparian vegetation communities hold similarities with vegetation communities in cultivated fields, i.e. crop-weed communities, in terms of the quantity and, to a given extent, quality of anthropogenic and climate disturbances they suffer. They identify three types of models commonly used in the study of vegetation communities: statistics-based, empirics-based and analytics-based.

The crop-weed community component in FunBies is indeed designed as an empirical model. A general empirical model is based on field data, experiments, natural rules of the environment, and vegetation attributes such as biomass, density or richness of species, whereas the features of the experimental method are reasonable assumption and accurate control on setting sample plots, controlling the experimental progress, and explaining the result or phenomena (You et al., 2015).

The FunBies crop-weed component was built based on a 25-year-old including records on biomass, density and richness of species collected within organic and conventional fields of the Montepaldi long term experiment. They cover 97.6 % and 70.4 % of crop categories and crop species, respectively, as indicated by the last Italian census of agriculture for Tuscany inland hill arable land (Istituto Nazionale di Statistica (ISTAT), 2010). Crop-weed community samples were collected in the same experimental site (i.e., MOLTE) to allow for comparison between alternative cropping systems under the same soil conditions. Rotations slightly changed concerning crop species during 25 years due to climate change (sunflower replaced maize) and market reasons (LG partially replaced LF), which resulted in a broad range of crops sampled under different climatic conditions.

Besides, the empirical model was refined using MVA statistics. Such a wealth of observations was ordinated according to similarity among communities of crop categories and corresponding virtual, representative weed communities for both organic and conventional rotations typical of Tuscany inland hill arable land were modeled considering average species richness and species mostly contributing to within-group similarity.

4.2. *Valuation of the FunBies conceptual model: a trait-based approach*

Zakharova et al. (2019) reviewed two decades of trait-based modeling in ecology. They state that trait-based models often require less parameterization effort than species-based models, facilitate scaling-up, and produce more generalizable results that can be projected to other systems, which is a highly appreciable feature in applied ecology studies. Furthermore, trait-based modeling reinforces simplification, which is at the core of all modeling. They see potential for the reinforcement of trait-based modeling approaches in areas such as the assessment of ecosystem services, biodiversity studies and, especially, the prediction of community and ecosystem responses under climate and

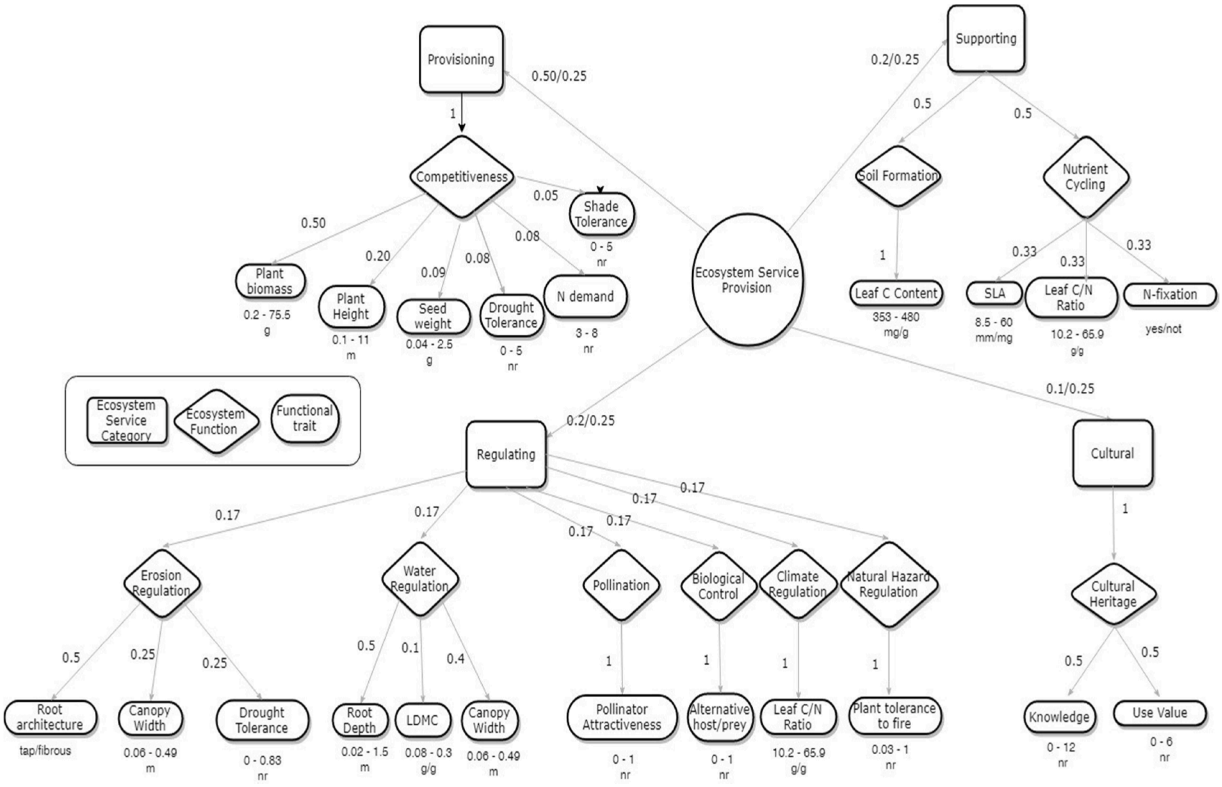

Fig. 7. . FunBies model structure. FunBies was applied to each species of the most characterizing weeds of organic and conventional micro-agroecosystems at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany. For each ecosystem service (ES) category (rectangles), corresponding ES category alternative weights (i.e., numbers along the arrows between the ES provision circle and rectangles), ecosystem functions (EFs, diamonds), EF weights (numbers between rectangles and diamonds), functional traits (FTs, ellipses), FT Weights (numbers between diamonds and ellipses), and FT score ranges (numbers below ellipses with corresponding measure units) are reported. Legend: SLA, specific leaf area; LDMC, leaf dry matter content.

land-use changes.

However, even the most recent studies dealing with trait-based models of ecosystem services developed for the agricultural sector focus only on grassland management in semi-natural habitats (Lochon et al., 2018; Schirpke et al., 2017), with none considering arable cropping systems. Furthermore, they privilege the depth of the modeling approach used to assess land-use option performances at the expense of the wideness of ESs considered (“only” five, i.e. forage production and quality, soil fertility, water quality and carbon storage).

FunBies conceptual model consider all of the MA ES categories and 10 different EFs that cover all EFs of De Groot’s classification (De Groot et al., 2002) among those ascribable to weed communities in agroecosystems, i.e. climate regulation, disturbance prevention, water regulation, soil retention, soil formation, nutrient regulation, pollination, biological control, competition towards production functions of food, raw materials, genetic, medicinal or ornamental resources, cultural and historic information. Besides, FTs considered for aggregated assessment of functional biodiversity in FunBies relate to the whole set of plant organs including leaves but also stem and roots, which is in line with the plant economics spectrum approach to ecosystem service provision (Reich, 2014).

4.3. Validation of the FunBies linear additive multi-criteria model

All elements of the above reported aggregation scheme, including the standardization procedures, the three weighting systems and the FT ranges were assessed using a face validity test carried out by an independent panel of experts (Tables 1 and 2). Testing for face validity was chosen as the validation procedure as it is the most appropriate approach when no real-system data are available (Qureshi et al., 1999).

Aggregation in FunBies of FT indicators is based on a LAM model. In general, as reported from Dodgson et al. (2009) “Models of this type have a well-established record of providing robust and effective support to decision makers working on a range of problems and in various circumstances”. However, this flexibility is subject to the condition that the assessment criteria (represented by FT indicators in the present scheme) are mutually preference independent. Mutual independence of preferences is obtained by imposing to indicators FT ranges so that preference of any given criterion is unaffected by preference on the others (Dodgson et al., 2009). In this way we achieved a conceptually and theoretically robust structure of the FunBies FT indicator aggregation scheme (Fig. 7).

One potential limitation of the applied validation procedure concerns the choice to select only academic experts, which opens to risks connected with the underrepresentation of the agro-food system actors/stakeholders. At present we gave priority to the need to validate FunBies from a sound scientific standpoint. As it was conceived, FunBies fits requirements for practical real-world applications; however, for such applications FunBies weighting systems should be reviewed by a broader panel of experts including agro-food system actors/stakeholders, especially for what concerns weights attributed to ES categories, which can highly affect final results in terms of FBI and hold a more subjective component.

4.4. Example of application: organic vs conventional

FunBies was applied to compare organic vs. conventional management options and supplied outcomes at different levels including the overall FBI calculated at cropping system level (OO, NO and CO, Fig. 8), FBI calculated at crop category level (WC + LF and RC + LG, Figs. 9 and 10, respectively) and FBI calculated at species level (Appendix D, Table D.1).

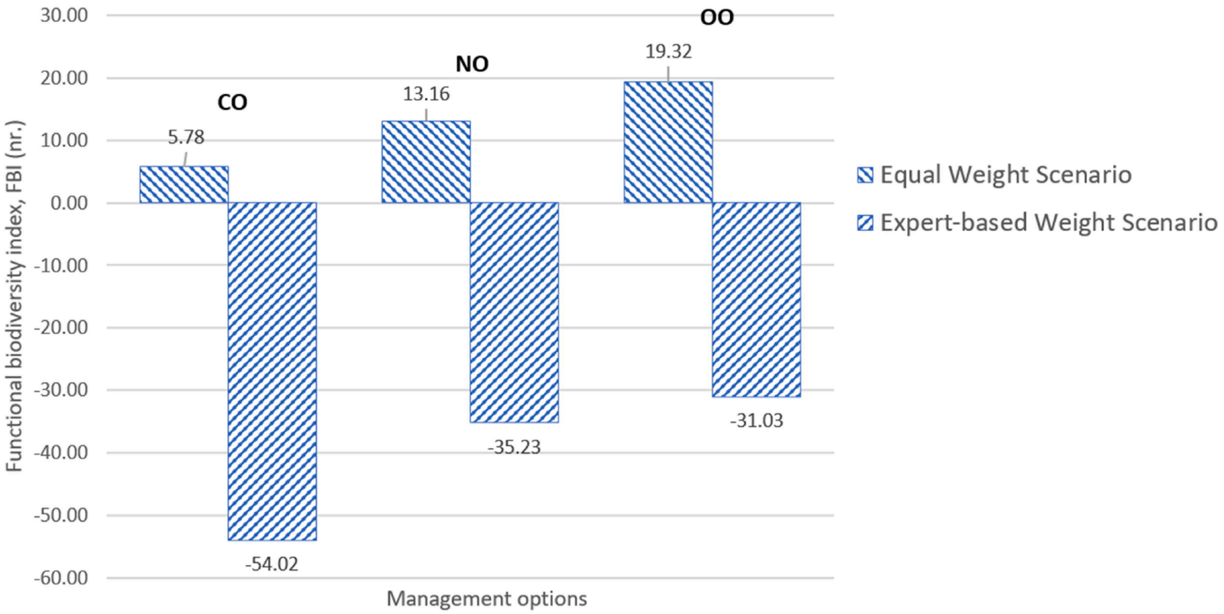

Fig. 8. Results of functional biodiversity index of representative crop-weed communities of the old organic (OO), new organic (NO) and conventional (CO) management options at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. ES provision is expressed in terms of yearly averages of the functional biodiversity index (FBI) and was calculated under two scenarios: equal weight scenario and expert-based weight scenario. Experts proposed weights as follows: 0.5 for the provisioning category, 0.2 for the regulating and supporting categories and 0.1 for the cultural category.

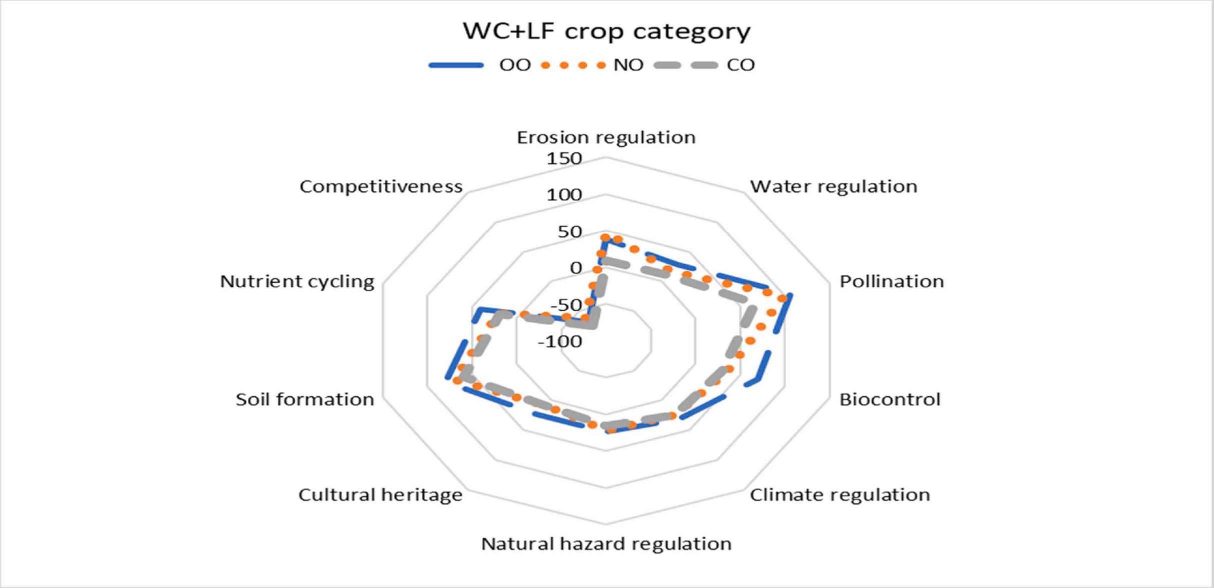

Fig. 9. Provision of ecosystem services by representative crop-weed communities of winter crops plus legume crops for forage (WC+LF) category groups in the old organic (OO), new organic (NO) and conventional (CO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. In FunBies we consider that regulating services are supplied by a number of ecosystem functions including erosion regulation, water regulation, pollination, biocontrol, climate regulation and natural hazard regulation; cultural services are supplied by cultural heritage; supporting services are supplied by soil formation and nutrient cycling; competitiveness represents the ability of weeds to generate a negative impact on provisioning services.

Results at cropping system level clearly indicated that organic systems have the potential to supply considerably higher ESs than conventional systems, where chemical-synthetic herbicides and fertilizers were applied (Appendix A, Table A.1). Demand of ecosystem services is increasing worldwide as well as knowledge of which agroecosystem management option can best host EFs providing them. FunBies was developed to answer this demand of knowledge and, at least for the present application, seem to be able to do it. Even more interestingly, FunBies could capture the dynamics of ES provision in time. Indeed, looking at the overall FBI outcomes in Fig. 8, it is clear that there is a steady increase of ES provision starting from time of conversion from conventional to organic management. It seems that the ES provision increases together with the evolution of the phytocoenosis. This particular aspect is confirmed at the level of WC + LF crops (Fig. 9), even accompanied by a considerable diversification of ESs, especially towards regulating and supporting services. Acquiring knowledge on these aspects is of vital importance in view of improved understanding of the complex dynamics underlying ecosystem service provision, which

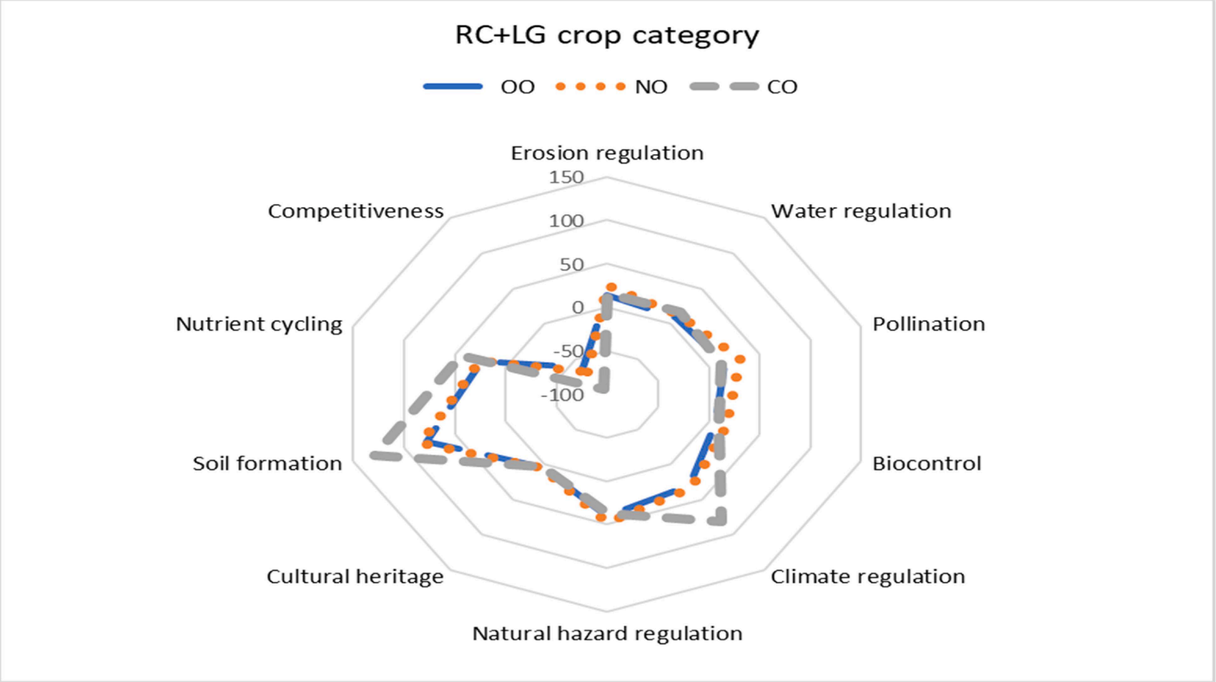

Fig. 10. Provision of ecosystem services by representative crop-weed communities of row crops + legume crops for grain (RC+LG) category groups in the old organic (OO), new organic (NO) and conventional (CO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. In FunBies we consider that regulating services are supplied by a number of ecosystem functions including erosion regulation, water regulation, pollination, biocontrol, climate regulation and natural hazard regulation; cultural services are supplied by cultural heritage; supporting services are supplied by soil formation and nutrient cycling; competitiveness represents the ability of weeds to generate a negative impact on provisioning services.

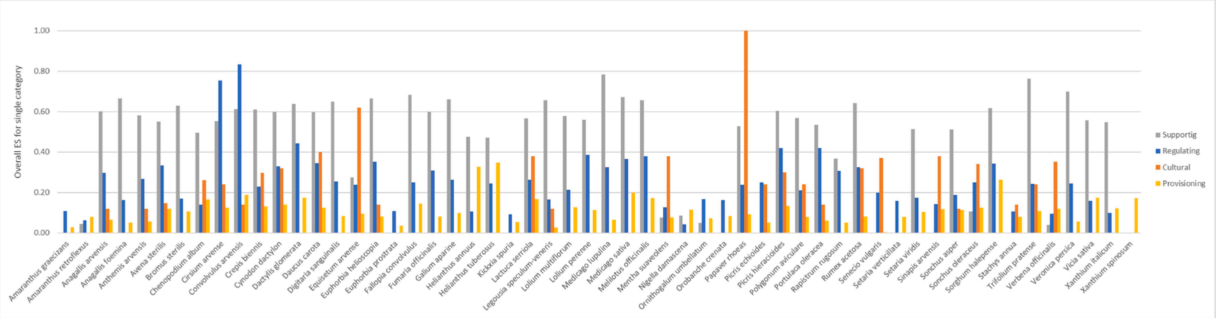

Fig. 11. Supporting, regulating, cultural and provisioning services supplied by each single species collected in the old organic, new organic and conventional micro-agroecosystems at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 1993–2017. The species scores of the ecosystem service categories range between 0 and 1 and represent the contribution to functional biodiversity of either a single individual or of a single unit of dry matter weight. Category scores result from sequential, linear additive aggregation of standardized scores of functional trait indicators. The more abundant is a species in a field, in a hectare or in whatever reference area, the more it can contribute to ecosystem services and overall functional biodiversity. Provisioning (dis)service due to competitiveness is reported in absolute terms; indeed, species values hold negative impacts on functional biodiversity. .

involve multiple trophic levels including e.g. insects responsible for pollination and biocontrol or micro-organisms responsible for nutrient cycling and nutrient formation. As stated by Lavorel et al. (2009) trait linkages within and across trophic levels can also guide ecological engineering through the choice of plant trait assemblages that promote the recovery of a multi-trophic community most likely to provide the desired ecosystem services. FunBies has the potential to help in such an intervention as single plant species fitness to hold trophic relations geared to the above-mentioned ESs can be easily verified by withdrawing relevant information on ESs at species level (Fig. 11 and Appendix C, Table C.10).

Agroecosystems dynamics are overwhelmingly complex and, indeed, results of ESs for RC + LG crops are reverted as compared to WC + LG (Figs. 10 and 9, respectively), with the only exception of pollination. Higher CO performances in terms of nutrient cycling, soil formation and climate regulation are partially counterbalanced by the competitiveness negative impact. All of these services are related to carbon and nutrient cycling processes, which are primarily driven by traits of the most abundant (dominant) species according to “the biomass ratio hypothesis” by Grime (1998). In CO RC crop category the dominant species is *Convolvulus arvensis* L. (Table 3), i.e. one of the best performing species for the above-mentioned ESs. In this context and for the relevant ESs, FunBies seems to be in line with Grime’s hypothesis.

However, what FunBies is not able to do is to assess niche complementarity that might result by non-overlapping trait distributions for some of the other EFs. In OO and NO RC+LG weed communities species evenness is considerably higher as resulted from MVA statistics (Table 3, 14 and 10 species cover 90 % of contribution of within-group similarity in OO and NO RC + LG, respectively, versus only 7 in CO RC) and this could have a positive effect in terms of such functional complementarity.

Table A.1
Ordinary weeding, fertilization and tillage operations at the MoLTE experiment. Legume crops were used only in the organic micro-agroecosystems.

Crop type	Winter cereals (WC)			Row crops (RC)			Legumes for grain (LG) Legumes for forage (LF)	
Crop management option	OO	NO	CO	OO	NO	CO	OO	NO
Primary tillage[a]	Plowing/chisel plowing	Plowing/chisel plowing	Plowing/chisel plowing	Plowing/chisel plowing	Plowing/chisel plowing	Plowing/chisel plowing	Plowing/ chisel plowing	Plowing/ chisel plowing
Pre-sowing fertilization[a]	Green manure/ organic fertilizer	Green manure/ organic fertilizer	Diammonium phosphate	Green manure/ organic fertilizer	Green manure/ organic fertilizer	-	-	-
First fertilizationa[a]	-	-	Ammonium nitrate	-	-	20.10.10	-	-
Second fertilization[a]	-	-	Urea	-	-	Urea	-	-
Chemical weeding[a]	-	-	Axial (a.i. pinoxaden 10.6 % and cloquintocetmexyl 2.55 %) Axial Pronto (a.i. pinoxaden 6.4 % and cloquintocetmexyl 1.55 %) + Logran (a.i. triasulfuron 20 %)	-	-	GOAL (a.i. oxyfluorfen)	-	-
Mechanical weeding[a]	Weed harrowing	Weed harrowing	Weed harrowing	Weed hoeing	Weed hoeing	Weed hoeing	-	-

[a] During the 25-years of MoLTE experiment, ordinary agronomic operations could change due to year-specific production and climatic condition.

Table A.2
Time schedule for species sampling.

Month	Crops	Semi-natural habitats[1]
April (before first cutting)	*Medicago sativa* L. *Trifolium squarrosum* L. *Trifolium pratense* L. *Trifolium alexandrinum* L.	First check
April-May	*Triticum durum* L. *Triticum aestivum* L. *Hordeum vulgare* L.	
May-June	*Zea mays* L. *Helianthus annuus* L. *Vicia faba minor* L. *Vicia lens* L. *Cicer arietinum* L.	Second check

[1] Verges, ditch edges, areas around hedges and trees, permanent pastures, long duration leys after first cutting, set-aside.

Table B.1
Ecosystem function, functional traits, disservice and corresponding descriptions of the MA provisioning category.

Ecosystem function	Functional trait	Disservice	Description
Production of biomass	Dry matter biomass	Competitiveness with the main crop	A larger weed biomass results in higher competitiveness with the main crop
	Canopy height		The higher the weed height, the lighter weeds capture (and less the main crop)
	Shading tolerance		A higher shading tolerance means more tolerance towards the shading crop and hence more competitiveness
	Nitrogen requirement		Higher N required means higher competitiveness especially in N-poor conditions
	Drought tolerance		Higher drought tolerance means higher competitiveness especially in dry conditions
	Seed weight		Competitive effect is associated with initial plant size (seed weight and rate of emergence)

E.g., Woodcock et al. (2019) published a meta-analysis revealing how management practices increasing not just pollinator abundance, but also functional divergence, could benefit oilseed rape agriculture, and this could be also applied to functional divergence of those plants that host pollinators and therefore indirectly increase the pollination service.

Another feature that is not supported by FunBies, which could cause underestimation of OO and NO ESs is that intra-specific variability is not considered. All individuals of a species are considered equal in terms of the level of ESs they supply, regardless if they grew in an organic or a conventional field, while it is reasonable to think that use of herbicides could depress relevant EFs.

In the present exercise FunBies was applied at cropping system level to compare organic and conventional agriculture; however, it could be easily adopted for alternative phytocoenosis databases, including those of farm semi-natural habitats and ecological infrastructures. FunBies empirical database offered a wealth of data on floristic richness under a 25-year long time-span featured by changing climatic conditions and a vast range of crops. Although pedo-climatic conditions of MoLTE can be considered to a given extent as representative of Tuscany inland hill arable land, the extent to which this assumption applies is questionable.

Table B.2
Ecosystem functions, functional traits, services and corresponding descriptions of the MA regulating category.

Ecosystem function	Functional trait	Service	Description
Erosion regulation	Root architecture (tap/fibrous)	Prevention of damage from erosion	Fibrous roots have a better impact in soil erosion control
	Crown (canopy) width		A wider canopy may cover a larger portion of soil while preventing soil erosion due to intensive rain
	Drought tolerance		A plant which tolerates drought periods will be able to protect soil from erosion even in summer (when more intensive meteorological phenomenon occurs)
Water regulation	Root depth	Drainage, filtering and storage of water	Deeper roots perform better in maintaining a good soil structure and hence allowing water retention
	Crown (canopy) width		Plant canopy decreases the kinetic energy of drops that cause erosion
	Leaf dry matter content		LDMC is the parameter that better predict organic matter decomposition
Pollination	Müller class X Flowering Phenology Richness X Flowering type	Pollination of wild plant species and crops	Role of pollinators in movement of floral gametes, weighted by the flowering period of each species and the type of flower (Eg. composite flowers are made up of inflorescences and each of them may provide pollen)
Biological control	Hosting pests	Control of pests and diseases	Plants more likely visited by pests likely support also natural enemies/predators
Climate regulation	Leaf C/N ratio	Carbon sequestration	It indicates the capability of organic matter to decompose (CO2 fixed into the soil) instead of emitting CO2 into the atmosphere)
Natural hazard regulation	Plant tolerance to fire	Role of forests in dampening extreme events	Plants might reduce fire damages with their structural characteristics

Table B.3
Ecosystem functions, functional traits, services and corresponding descriptions of the MA supporting category.

Ecosystem function	Functional trait	Service	Description
Nutrient cycling	Nitrogen fixation	Nitrogen fixation into the soil	Leguminous species provide nitrogen to the system
	Leaf C/N ratio	Nitrification conditions	A good soil structure quality can lead to nitrification conditions and therefore favor nitrate formation
Soil formation	Leaf carbon content per leaf dry mass	Carbon supply from leaf decomposition	Carbon can be supplied to the soil from leaf decomposition
	Specific leaf area	Organic matter supply	It determines the rate and speed of organic matter decomposition

Table B.4
Ecosystem functions, functional traits, services and corresponding descriptions of the MA cultural category.

Ecosystem function	Functional trait	Service	Description
Local memory of the use	Use reported in local literature	Preserve traditional knowledge	The citation of the use of a species in local literature is considered an indicator of the locals' memory
Cultural heritage	Presence of a species in local literature	Sense of place and identity	The citation of a species in local literature is considered an indicator of the traditional heritage value

For instance, FunBies was not calibrated and tested in ordinary farms, where management conditions in terms of timing of operations, care and control and expert knowledge available can differ from those of an experimental context. As for all models, the extent to which FunBies can be considered applicable depends on the specific aim and the scope of the application, which could result in limitations in the use of this model. Indeed, FunBies calibration and testing in ordinary farms is a further step of the present research process.

4.5. Concluding remarks

FunBies was validated and tested and showed strong potential to assess ES performance of weed communities at production system, crop and species levels and at different levels of aggregation. Its validity is confined to Tuscany inland hill arable land, which is the reference area of MOLTE experimental fields, rotation and crops, where we expect to find very similar crop-weed communities. The extent to which these expectations are acceptable depends on the specific aim of the proposed application and further testing and calibrations in ordinary farms. Provided that region-specific testing and calibration were performed, FunBies (more specifically its conceptual and aggregation components) hold the potential to be applied in several agroecological contexts, paving the way to a new, critical, and scientific way to evaluate weed ecosystem services.

The FunBies application showed in the present article give hints on how this tool could be used under a number of different contexts. Among them we see two of major importance: (i) design of biodiversity components within agro-ecosystems to optimize ES provision, and (ii) justification and sizing of organic and more in general agri-environmental payments of rural development plants. Concerning this last point, the way in which FunBies is formulated would facilitate integration with any kind of integrated ecological-economic farming systems model and matching of ES provision figures with figures retrieved from ecological models on e.g. potential risk of pesticide use, nitrogen leaching and soil erosion.

CRediT authorship contribution statement

Gaio Cesare Pacini: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Data curation. **Piero Bruschi:** Investigation, Supervision. **Lorenzo Ferretti:** Investigation. **Margherita Santoni:** Investigation, Writing – review & editing, Visualization. **Francesco Serafini:** Writing – review & editing, Visualization. **Tommaso Gaifami:** Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Data curation.

Table C.1
Müller classes with relative characteristics and the corresponding typical pollinators which differ in length of proboscis and corresponding scores.

Müller class[1]	Characteristic[1]	Typical pollinators[1]	Score[2]
A	flowers with open nectar	beetles, flies, syrphids, wasps, medium tongued bees	1.0
AB	flowers with partly hidden nectar	syrphids, bees	0.9
B	flowers with totally hidden nectar	bees, bumblebees, wasps, bombylides, syrphids	0.7
B`	flower associations with totally hidden nectar	bees, bumble bees, wasps, bombylides, syrphids	0.7
H	hymenoptere flowers	hymenoptere	0.5
Hb	bee flowers	bees	0.6
Hh	bumble bee flowers	bumble bees	0.4
Hw	wasp flowers	wasps	0.1
Hi	ichneumonide flowers	ichneumonidae	0.1
F	butterfly flowers	butterflies, long tongued bees, syrphids	0.3
Ft	butterfly flowers	butterflies	0.1
Fn	moth flowers	moths	0.05
D	fly flowers	flies	0.1
De	nasty flowers	muscidae	0.1
Dke	trap flowers	very small dipteres	0.05
Dkl	clamp trap flowers	flies, bees	0.05
Dt	deceptive flowers	flies	0.1
Ds	syrphid flowers	syrphids	0.2
Kl	small insect flowers	small ichneumonide, flies, beetles	0.3
Po	pollen flowers	short tongued bees, syrphids, flies, beetles	0.3
W	wind flowers	-	0.0
Wb	wind flowers occassionally visited by insect	short tongued bees, syrphids, flies, beetles	0.3
Hy	water flowers: pollination on or under water	-	0.0
ABDe	transition type flowers with partly hidden nectar - nasty flowers	flies, beetles	0.9
AD	transition type flowers with open nectar - fly flowers	flies	0.1
ADe	transition type flowers with open nectar - nasty flowers	flies, beetles	0.9
B`F	transition type flower associations with totally hidden nectar - butterfly flowers	bumble bees, lepidoptera	0.3
BD	transition type flowers with totally hidden nectar - fly flowers	flies	0.1
BF	transition type flowers with totally hidden nectar - butterfly flowers	bees, flies	0.6
BH	transition type flowers with totally hidden nectar - bee flowers	hymenopteres	0.5
BHb	transition type flowers with totally hidden nectar - bee flowers in a narrow sense	bees, tongue < 7 mm	0.4
BHh	transition type flowers with totally hidden nectar - bumble bee flowers	bees, tongue > 7 mm	0.6
BHw	transition type flowers with totally hidden nectar - wasp flowers	wasps	0.1
DsB	transition type syrphid flowers - flowers with totally hidden nectar	syrphids	0.2
FD	transition type butterfly flowers - fly flowers	lepidoptera, flies	0.2
FHb	transition type butterfly flowers - bee flowers in a narrow sense	lepidoptera, bees	0.4
FHh	transition type butterfly flowers - bumble bee flowers	lepidoptera, bumble bees	0.3
FnH	transition type moth flowers - bee flowers	moths, hymenoptera	0.1
HF	transition type bee flowers - butterfly flowers	bees, lepidoptera	0.4
HFt	transition type bee flowers - butterfly flowers	bees, butterflies	0.4
HhDs	transition type bumble bee flowers - syrphid flowers	bumblebees, syrphids	0.3
HhF	transition type bumble bee flowers - butterfly flowers	bumblebees, lepidoptera	0.2
HhFn	transition type bumble bee flowers - moth flowers	bumblebees, moths	0.2
HhFt	transition type bumble bee flowers - butterfly flowers	bumblebees, butterfflies	0.2
PoA	transition type pollen flowers - flowers with open nectar	beetles, flies, syrphids, wasps, medium tounged bees	0.8
PoAB	transition type pollen flowers - flowers with partly hidden nectar	beetles, flies, syrphids, wasps, medium tounged bees	0.8
PoDe	transition type pollen flowers - nasty flowers	short tongued bees, syrphids, muscids, beetles	0.3
PoWb	transition type pollen flowers - wind blossoms occassionally visited by insect	short tounged bees, syrphids, muscids, beetles	0.3

[1] Durka et al., 2002.
[2] Expert-based.

Table D.1
Ecosystem service (ES) provision by ES category and functional biodiversity index, FBI, for each of the species collected in the old organic (OO), new organic (NO) and conventional (CO) micro-agroecosystem at Montepaldi long term experiment, San Casciano Val-di Pesa, Florence, Tuscany, in the period 19932017. FBI is calculated with equal ES category weights.

Species	Provisioning	Regulating	Supporting	Cultural	FBI
Amaranthus graecizans L.	-0.03	0.11	0.00	0.00	0.02
Amaranthus retroflexus L.	-0.08	0.06	0.05	0.00	0.01
Lysimachia arvensis (L.) U. Manns & Anderb.	-0.06	0.30	0.60	0.12	0.24
Lysimachia foemina (Mill.) U.Manns & Anderb.	-0.05	0.16	0.66	0.00	0.19
Anthemis arvensis L.	-0.06	0.27	0.58	0.12	0.23
Avena sterilis L.	-0.12	0.33	0.55	0.15	0.23
Bromus sterilis L.	-0.11	0.17	0.63	0.00	0.17
Chenopodium album L.	-0.17	0.14	0.50	0.26	0.18
Cirsium arvense (L.) Scop.	-0.12	0.75	0.55	0.24	0.35
Convolvulus arvensis L.	-0.19	0.83	0.61	0.14	0.35
Crepis biennis L.	-0.13	0.23	0.61	0.30	0.25
Cynodon dactylon (L.) Pers.	-0.14	0.33	0.60	0.32	0.28
Dactylis glomerata L.	-0.18	0.44	0.64	0.00	0.23
Daucus carota L.	-0.12	0.34	0.60	0.40	0.30
Digitaria sanguinalis (L.) Scop.	-0.08	0.25	0.65	0.00	0.21
Equisetum arvense L.	-0.09	0.24	0.27	0.62	0.26
Euphorbia helioscopia L. subsp. *Helioscopia*	-0.08	0.35	0.67	0.14	0.27
Euphorbia prostrata Aiton	-0.04	0.11	0.00	0.00	0.02
Fallopia convolvulus (L.) Á.Löve	-0.14	0.25	0.68	0.00	0.20
Fumaria officinalis L.	-0.08	0.31	0.60	0.00	0.21
Galium aparine L.	-0.10	0.26	0.66	0.00	0.21
Helianthus annuus L. subsp. *Annuus*	-0.33	0.11	0.48	0.00	0.06
Helianthus tuberosus L.	-0.35	0.25	0.47	0.00	0.09
Kickxia spuria (L.) Dumort.	-0.05	0.09	0.00	0.00	0.01
Lactuca sativa L. subsp. *serriola* (L.) Galasso, Banfi, Bartolucci & Ardenghi	-0.17	0.26	0.56	0.38	0.26
Legousia speculum-veneris (L.) Chaix subsp. *speculum-veneris*	-0.03	0.16	0.66	0.12	0.23
Lolium multiflorum Lam.	-0.13	0.21	0.58	0.00	0.17
Lolium perenne L.	-0.11	0.39	0.56	0.00	0.21
Medicago lupulina L.	-0.07	0.32	0.78	0.00	0.26
Medicago sativa L.	-0.20	0.37	0.67	0.00	0.21
Trigonella officinalis (L.) Coulot & Rabaute	-0.17	0.38	0.66	0.00	0.22
Mentha suaveolens Ehrh.	-0.08	0.13	0.08	0.38	0.13
Nigella damascena L.	-0.12	0.04	0.09	0.00	0.00
Ornithogalum umbellatum L.	-0.07	0.17	0.05	0.00	0.04
Orobanche crenata Forssk.	-0.08	0.16	0.00	0.00	0.02
Papaver rhoeas L. subsp. *rhoeas*	-0.09	0.24	0.53	1.00	0.42
Helminthotheca echioides (L.) Holub	-0.05	0.25	0.00	0.24	0.11
Picris hieracioides L.	-0.13	0.42	0.60	0.30	0.30
Polygonum aviculare L. subsp. *Aviculare*	-0.08	0.21	0.57	0.24	0.24
Portulaca oleracea L.	-0.06	0.42	0.53	0.14	0.26
Rapistrum rugosum (L.) All.	-0.05	0.31	0.37	0.00	0.16
Rumex acetosa L. subsp. *acetosa*	-0.08	0.33	0.64	0.32	0.30
Senecio vulgaris L.	-0.00	0.20	0.00	0.37	0.14
Setar *Setaria verticillata* (L.) P.Beauv.	-0.08	0.16	0.00	0.00	0.02
Setaria italica (L.) P.Beauv. subsp. *viridis* (L.) Thell.	-0.10	0.17	0.51	0.00	0.15
Sinapis arvensis L. subsp. *arvensis*	-0.12	0.14	0.00	0.38	0.10
Sonchus asper (L.) Hill	-0.11	0.19	0.51	0.12	0.18
Sonchus oleraceus L.	-0.12	0.25	0.11	0.34	0.14
Sorghum halepense (L.) Pers.	-0.26	0.34	0.62	0.00	0.17
Stachys annua L. subsp. *annua*	-0.08	0.11	0.00	0.14	0.04
Trifolium pratense L.	-0.11	0.24	0.76	0.24	0.28
Verbena officinalis L.	-0.12	0.09	0.04	0.35	0.09
Veronica persica Poir.	-0.06	0.24	0.70	0.00	0.22
Vicia sativa L.	-0.17	0.16	0.56	0.00	0.14
Xanthium orientale L.	-0.12	0.10	0.55	0.00	0.13
Xanthium spinosum L.	-0.17	0.00	0.00	0.00	-0.04

Legend: FBI, functional biodiversity index.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Appendix A

Table A.1, Table A.2

Appendix B

Table B.1, Table B.2, Table B.3, Table B.4

Ecosystem functions (EFs), functional traits, (dis)services and corresponding descriptions included in the FunBies model, reported for each of the Millennium Ecosystem Assessment (MA) EF categories.

Appendix C

Table C.1

Appendix D

Table D.1, Table D.2

Example of calculation procedure for functional biodiversity index at single species level.

The objective of the present section is to supply an example of the calculation procedure of the functional biodiversity index, FBI, of a given species of the FunBies database. Such calculation procedure is equal for the whole set of species of the FunBies database.

Calculation procedure is based on a simplified version of Equation (3) in the manuscript text, where the species summation component was deleted. The modified equation is reported below.

$$FBI_{sp} = \sum_{ES=1}^{4} w_{ES} * \left[\sum_{EF=1}^{x} w_{EF} * \left(\sum_{FT=1}^{n} w_{FT} * A_{Sp} * S_{FT} \right) \right]$$

Where W_{ES} is the weight attributed to each of the four ecosystem service categories, W_{EF} is the weight attributed to each ecosystem function, W_{FT} is the weight attributed to each functional trait, A_{Sp} is the abundance of a species either in terms of number of individuals (nr/m^2) or of dry matter weight (g/m^2), S_{FT} is the FT score per each species unit expressed either in terms of number of individuals or grams.

If we suppose ASp = 1, by sequentially aggregating FT scores at the levels of EFs and ES categories we obtain a functional biodiversity index (FBI) at species level that ranges between 0 and 1. It has to be noticed that this specific FBI represents the contribution that each species single unit can supply to functional biodiversity. Of course, the more abundant is a species in a field, in a hectare or in whatever reference area, the more it can contribute to overall functional biodiversity.

Table D.2

Functional trait contributions to ecosystem functions (EFs), ecosystem services (ESs) and functional biodiversity index at specie level (FBIsp) calculated for *Cirsium arvense* L. Scop. For attribution of functional trait (FT) contribution to EFs) reference is made to Fig. 7. For the purpose of the example $A_{sp} = 1$.

Functional traits per ES category	S_{FT}	A_{Sp}	w_{FT}	Trait contributions to EFs $w_{FT} * A_{Sp} * S_{FT}$	w_{EF}	Trait/EF contributions to ES categories $w_{FT} * A_{Sp} * S_{FT} * w_{EF}$	w_{ES}	Trait/ES contributions to FBI$_{sp}$ $w_{FT} * A_{Sp} * S_{FT} * w_{EF} * w_{ES}$
Provisioning								
Plant biomass	-0.01	1	0.50	-0.01	1.00	-0.01	0.25	0.00
Plant height generative	-0.34	1	0.20	-0.07	1.00	-0.07	0.25	-0.02
Seed weight	-0.15	1	0.09	-0.01	1.00	-0.01	0.25	0.00
Drought tolerance	0.00	1	0.08	0.00	1.00	0.00	0.25	0.00
Nitrogen demand	-0.40	1	0.08	-0.03	1.00	-0.03	0.25	-0.01
Shade tolerance	-0.05	1	0.05	0.00	1.00	0.00	0.25	0.00
Overall Provisioning disservice						-0.12		-0.03
Regulating								
Root architecture	1.00	1	0.50	0.50	0.17	0.09	0.25	0.02
Canopy width	0.39	1	0.25	0.10	0.17	0.02	0.25	0.00
Drought tolerance	0.00	1	0.25	0.00	0.17	0.00	0.25	0.00
Root depth	1.00	1	0.50	0.50	0.17	0.09	0.25	0.02
Leaf dry matter content	0.60	1	0.10	0.06	0.17	0.01	0.25	0.00
Canopy width	0.39	1	0.40	0.16	0.17	0.03	0.25	0.01
Pollinator attractiveness	0.55	1	1.00	0.55	0.17	0.09	0.25	0.02
Alternative host/prey	1.00	1	1.00	1.00	0.17	0.17	0.25	0.04
Leaf C/N ratio	0.57	1	1.00	0.57	0.17	0.10	0.25	0.02
Plant tolerance to fire	1.00	1	1.00	1.00	0.17	0.17	0.25	0.04
Overall Regulating ES provision						0.75		0.19
Supporting								
Leaf carbon content	0.82	1	1.00	0.82	0.50	0.41	0.25	0.10
Specific leaf area	0.29	1	0.33	0.10	0.50	0.05	0.25	0.01

(continued on next page)

Table D.2 (*continued*)

Functional traits per ES category	S_{FT}	A_{Sp}	w_{FT}	Trait contributions to EFs $w_{FT} * A_{Sp} * S_{FT}$	w_{EF}	Trait/EF contributions to ES categories $w_{FT} * A_{Sp} * S_{FT} * w_{EF}$	w_{ES}	Trait/ES contributions to FBI_{sp} $w_{FT} * A_{Sp} * S_{FT} * w_{EF} * w_{ES}$
Leaf C/N ratio	0.57	1	0.33	0.19	0.50	0.09	0.25	0.02
N-fixation	0.00	1	0.33	0.00	0.50	0.00	0.25	0.00
Overall Supporting ES provision						0.55		0.14
Cultural	0.24	1	1.00	0.24	1.00	0.24	0.25	0.06
Overall Cultural ES provision						0.24		
FBI at species level								0.36

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