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An index of ecological value for European arable plant communities

E. Fanfarillo[1] · **A. Kasperski**[2]

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Abstract

The value of arable plant communities from a natural and environmental perspective was recognized only recently. Human-dependent arable plant assemblages are acknowledged to support biodiversity in agroecosystems and to provide numerous ecosystem services. The conservation of such communities relies on low-input, traditional agriculture, which is vanishing worldwide. Both agricultural intensification and land abandonment negatively affected arable plant biodiversity, with a remarkable loss of species and communities of great conservation and ecological interest. In this paper, we introduce a floristic-ecological monitoring tool aiming at the quantification of the ecological value of arable plant communities, named ArEco. Starting from presence-absence community data, the index returns a numerical value derived from species richness and six features of arable vascular plants: life form, Ellenberg nutrient value, alien status, conservation status in Europe, support to pollinator insects, and support to feeding birds. A program for the calculations was written in Java, with a database of about 400 arable plant species. The effectiveness of the tool was tested on 270 arable vegetation plots of different crop types in Italy, a European hotspot of arable plant diversity. The results show that, in the study area, winter arable vegetation has a higher ecological value than summer arable vegetation. In a similar way, extensively managed arable land hosts communities of higher ecological value than those hosted by intensively managed arable land. In view of the present results, ArEco will be a useful tool for monitoring, conservation, and restoration activities of arable plant communities in Europe.

Keywords Agroecosystem · Arable flora · Bioindication · Ecosystem service · Segetal plant · Weed vegetation

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✉ E. Fanfarillo
ema.fanfarillo@gmail.com

[1] Independent Researcher, Alatri, Italy

[2] Department of Biotechnology, Institute of Biological Sciences, University of Zielona Góra, ul. Szafrana 1, Zielona Góra, Poland

Introduction

Arable land is among the main land use types in agricultural landscapes. Tillage practices aiming to create a suitable growing environment for cultivated plants are as old as agriculture itself, since mechanical processing reduces the competition of undesired plants and improves soil physical and chemical features (McKyes 1985). Given its impact on natural landscapes, agriculture is often perceived as a threat to the environment and biodiversity conservation. Nevertheless, centuries of interactions between Man and nature through low-input agriculture shaped characteristic and highly valuable agroecosystems in many areas of the World (Bernués et al. 2014; Altieri et al. 2017). Especially in Europe, agriculture has a long history. Here, the recognition of the environmental, social, and cultural importance of traditional agricultural landscapes led to the development of the concept of High Nature Value farming (HNVf—EEA 2004). Nowadays, the conservation of a high proportion of European biodiversity relies on low-input agroecosystems, which often include Natura 2000 natural and semi-natural habitats (Keenleyside et al. 2014).

Since the beginning of agriculture, the fight against non-crop arable plants was a priority for farmers, because of the competition between such “weeds” and crops. Before the birth of intensive agriculture, arable vegetation was controlled mechanically and through crop rotations (Ferrero et al. 2010). The introduction of chemical control led to a seemingly better and final solution. Nevertheless, resistance phenomena soon appeared and few, very harmful species became widespread and hard to control. This led to the awareness that multiple weed control methods are needed to achieve long-term agricultural sustainability (Shaner 2014).

The worldwide agricultural intensification of the last decades caused the vanishing of low-input agricultural systems. Highly diversified traditional agricultural landscapes hosting mosaics of arable land, woody cultivations, pastures, meadows, and natural vegetation are becoming rarer and rarer (Tscharntke et al. 2005; Loos et al. 2005). They are either being replaced by monocultures, in areas suitable for intensive agriculture, or abandoned and recolonized by natural vegetation, especially in geomorphologically complex areas. The disappearance of low-input practices both due to intensification and land abandonment caused biodiversity loss at all levels of organization (Uchida and Ushimaru 2014; Strohbach et al. 2015).

Arable plant species and communities, known as “agrestals” or “segetals”, are characteristic components of agroecosystems (Holzner 1978, 1982). In Europe, arable vegetation evolved under centuries of co-evolution of agriculture and nature, during which it acquired a very characteristic species composition (Oppermann et al. 2012). Arable species like *Agrostemma githago* and *Bromus grossus* evolved within crops themselves and are so specialized to be completely dependent on agriculture, since they do not have a natural habitat. Such species are the so called “anecophytes” or “homeless weeds” (Zohary 1962; Scholz 2007; Koch et al. 2016). Other arable plants (“archaeophytes”) were introduced in Europe during ancient times with crop species and became stable and characteristic components of arable vegetation (e.g., *Centaurea cyanus* and *Lolium temulentum*—Thellung 1911–1912). Following the relatively recent introduction of summer-annual crops, mostly of American origin, other non-native species arrived in the continent and occupied the ecological and phenological niche of summer arable land (“neophytes”: e.g., *Amaranthus retroflexus* and *Datura stramonium* – Brullo and Guarino 2007). More and more attention is being paid to the vanishing of arable plants from European agricultural landscapes, due to the negative ecological implications of such phenomenon. Many taxa strictly dependant on arable land are now threatened and of conservation interest, and became extinct in some areas (Storkey et al. 2012). This is especially true in central and northern Europe, were arable plants become more specialized and consequently more vulnerable (Holzner 1978; Šilc et al. 2014). Segetal plants are widely acknowledged for their contribution to biodiversity in agroecosystems, even supporting insects, birds, and small mammals (Marshall et al. 2003; Storkey 2006; Andreasen and Stryhn 2008; Bretagnolle and Gaba 2015). The ecosystem services they provide are not only beneficial to the environment, but also to crop production by supporting pest enemies and improving soil fertility (Kubota et al. 2015; Storkey and Neve 2018). Biodiversity in general was proven to have positive effects on crop production (Dainese et al. 2019). Diversified segetal communities improve physical and chemical properties of soils, reduce the damage by crop pests, and sustain crop pollinators. Many studies showed no negative effects of arable plants on production, and some recent findings even highlighted that the presence of species-rich arable plant communities mitigates yield losses compared to a species-poor arable vegetation dominated by herbicide-resistant, very competitive species (Blaix et al. 2018; Adeux et al. 2019). For all these reasons, species-rich and well-preserved arable plant communities are indicators of agronomic and environmental sustainability (Storkey and Neve 2018; MacLaren et al. 2020). Biological and ecological synthetic indexes are effective tools for environmental monitoring and are based on the use of living beings as indicators of complex processes. In the last decades, vascular plants were widely used as bioindicators, especially in Europe (Ellenberg 1974; Landolt 1977; Pignatti et al. 2005; Taffetani and Rismondo 2009; Fanfarillo et al. 2017). In the context of agroecosystems, arable plants are considered good indicators of both agronomic management and environmental conditions, as many studies highlighted in the last years (Albrecht 2003; Fried et al. 2008; Hyvonen and Huusela-Veistola 2008; Hawes et al. 2010).

Tools as Shannon and Simpson indexes are among the most popular and frequently used to assess biodiversity in ecological communities. Nevertheless, since relying only on species richness and evenness, these diversity indexes fail to quantify the ecological value of vegetation. This is especially true when they are applied to arable vegetation, which can be considerably diverse even when featured by elements of low conservation and ecological value such as generalist, neophyte, and widely distributed species. Consequently, the importance of taking account of species features in the assessment of the status of plant communities is well remarked (Cretini et al. 2012; Mirazadi et al. 2017). For arable vegetation, Albrecht (2003) suggested to determine the proportion of threatened plants and of plant species that favour useful insects, as well as the number of typical arable weeds based on Hüppe and Hofmeister (1990). The latter can be easily identified by assessing their fidelity to arable habitats through the calculation of fidelity scores, though this requires a sufficient amount of data about surrounding non-arable habitats for comparison (Metcalfe et al. 2019). Recent evidences from Europe showed that specialist and threatened species related to winter arable crops tend to co-occur in the same field or plant community, under a favourable, low-intensity agricultural management. Thus, they are potential indicators of a good conservation status of arable vegetation (Petit and Fried 2012; Fanfarillo et al. 2020a).

In the last years, a lot of emphasis was given to functional diversity, i.e., a measure of the functions of organisms in communities and ecosystems that can be assessed through the related functional traits (Petchey and Gaston 2006). Morpho-functional traits like seed mass, plant height, date of first flowering, and specific leaf area were shown to be useful to group arable species having a similar value for farmland birds and insects, and a similar competitiveness towards the crop (Storkey 2006; Brooks et al. 2012). Nevertheless, the use of functional traits can be challenging, especially regarding data retrieval and quality (Petchey and Gaston 2006).

Past indexes for the monitoring of plant communities were developed taking natural vegetation as a reference for high value. One of the most frequently used is the Floristic Quality Index (FQI—Swink and Wilhelm 1979; Rooney and Rogers 2002; Cretini et al. 2012), which assesses the conditions of vegetation based both on species richness and species features. Other authors proposed indexes to assess vegetation naturalness based on the degree of alteration of plant communities by humans (Ferrari et al. 2008; Taffetani and Rismondo 2009). Machado (2004) developed an index of naturalness for landscapes, according to the levels of anthropic modification of vegetation types.

An index suitable to be applied in man-made contexts, at the ecosystem level, is the Natural Capital Index (ten Brink 2000). It aims at characterizing the state and trends of biodiversity in all types of ecosystems based on a complex set of variables, such as species and habitats quality and quantity. Regarding agricultural ecosystems, the baseline for quality evaluations are traditional agroecosystems.

Given the unsuitability of the already available tools to assess the value of arable vegetation, Fanfarillo et al. (2018) proposed the Arable Land Naturalness Index (ALNI), aiming at the evaluation of the “naturalness” of arable plant communities. This was developed by characterizing arable species according to some “naturalness” proxies, namely species richness, life-form, alien status (and introduction time in case of alien species), and nitrophily. The development of this index was the first attempt to build a tool for the quantification of the value of arable plant communities. Nevertheless, several issues can be raised on its theoretical and methodological soundness, starting from the misleading use of the concept of “naturalness” in artificial habitats. Furthermore, annual species and archaeophytes are considered less valuable than perennial and native ones, respectively, in contrast with the evidence that such taxa are an emblematic and vanishing component of European arable vegetation. Lastly, the ALNI showed a too high dependence on species richness. All these features can result in a biased quantification of the value of arable plant communities.

In this paper, we present a new aggregated index aiming at quantifying the ecological value of European arable plant communities based on their levels of species richness, biological-ecological features of the occurring plant taxa, and the currently known interactions of the latter with birds and insects. This new index represents a substantial evolution and improvement of the previously published ALNI (Fanfarillo et al. 2018), fixing its several theoretical and methodological flaws.

Materials and methods

The ecological value of arable plant communities is here evaluated by quantifying their:

(a) species richness;
(b) degree of preservation as those typical communities related to traditional, low-intensity agricultural practices;
(c) levels of support to birds and insects.

ArEco is calculated for single vegetation plots. The final value results from two evaluation steps. The first one is the evaluation of the ecological value of each occurring plant species, which is attributed a score based on the six biogeographical, biological, and ecological features listed below. The score of each feature (which can be + 1 or − 1) is summed and gives the score of each species, which consequently ranges between − 6 and + 6.

Features of arable plant species as indicators of ecological value

Six features of plant species colonizing arable land were chosen as proxies of ecological value:

1. Life form: Therophytes and bulbous Geophytes (score: +1) are indicators of a higher ecological value. All other perennial species (non-bulbous Geophytes, Hemicryptophytes, Chamaephytes, and Phanerophytes – score: − 1) are indicators of a lower ecological value. The information on life form was retrieved from Pignatti et al. (2017–2019). Annual short-lived species (e.g., *Adonis annua* and *Ranunculus arvensis* in winter arable land; *Digitaria sanguinalis* and *Echinochloa crus-galli* in summer arable land) are a typical component of arable plant communities, as well as many bulbous Geophytes (e.g., *Allium* spp. and *Tulipa sylvestris* in ploughed orchards and vineyards; *Allium nigrum* and *Bunium bulbocastanum* in wheat fields). The intensification of agriculture favours the spread of perennial species (other than bulbous Geophytes) in arable land (e.g., *Cirsium arvense* and *Sylibum marianum*), which are not only noxious to agriculture, but can also form dense stands that threaten the conservation of typical annual and bulbous taxa (MacLaren et al. 2020). Furthermore, perennial species like Hemicryptophytes enter arable land from natural and semi-natural vegetation in the context of abandoned landscapes, indicating the vanishing of agriculture and the start of secondary successions that threaten typical arable plant assemblages (Storkey et al. 2012; Albrecht et al. 2016).
2. Native status: native, archaeophyte, and cryptogenic species (score: + 1) are indicators of a higher ecological value. Neophytes (score: − 1) are indicators of a lower ecological value. This information was retrieved from Galasso et al. (2018) and Bartolucci et al. (2018). Many archaeophytes are typical elements of arable habitats in Europe, with special regards to winter arable land. Species as *Agrostemma githago*, *Centaurea cyanus*, and *Lolium temulentum* have been following cereal crops since the Neolithic and are currently in fast regression due to the disappearance of low-intensity agriculture (Scholz 2007; Storkey et al. 2012). Intensive agricultural practices can promote the spread of neophytes in European arable land, mining the conservation of native and archaeophyte arable species (Lososová et al. 2004; Pinke et al. 2008; Pinke et al. 2009; Pál et al. 2013; Fanfarillo et al. 2019a).
3. Nutrient requirements: species preferring nutrient-poor soils (score: + 1) are indicators of a higher ecological value. Species preferring nutrient-rich soils (score: − 1) are indicators of a lower ecological value. This information was retrieved from Pignatti et al. (2005). Species having an “N” value of 7 or more were considered nutrient-requiring. In the rare case of broad-spectrum species (N = X), the score given by this feature is 0. Intensive agriculture supposes the use of a certain amount of chemical fertilizers. For this reason, intensification-related shifts towards a more nutrient-requiring arable flora were well documented in Europe (Fried et al. 2009; Richner et al. 2015; Fanfarillo et al. 2019a). The most of typical arable species do not thrive well on nutrient-enriched soils, so that fertilizations were detected as one of the main drivers of their regression (Storkey et al. 2010; Isbell et al. 2013; Albrecht et al. 2016).

4. Pollination mode: entomogamous species (score: + 1) are indicators of a higher ecological value. Anemogamous species (score: − 1) are indicators of a lower ecological value. This information was retrieved from Pignatti et al. (2017–2019). Nectariferous arable plants are an important trophic resource for pollinator insects in agricultural landscapes (Marshall et al. 2003; Petit et al. 2011; Bretagnolle and Gaba 2015). This is especially true in those farming systems where wind-pollinated crops, like cereals, prevail. The changes of arable vegetation induced by an intensified agriculture led to a decrease of insect-pollinated arable plants in Europe (Fried et al. 2016; Fanfarillo et al. 2019a).
5. Conservation status in Europe: species considered rare or threatened arable plants on a continental scale are indicators of a higher ecological value (score: + 1). All other species are indicators of a lower ecological value (score: − 1). This information was retrieved from Storkey et al. (2012). The presence of species of conservation interest, such as rare and threatened species, enhances the ecological value of a plant community or of a geographic area, with regards to the conservation of biodiversity and its services (Gaston 1994; Rossi et al. 2008). Besides their conservation value, rare species have a key role in ecosystems due to their support of peculiar functions, and their loss is known to alter ecosystem functioning (Lyons and Schwartz 2001; Mouillot et al. 2013). Specialist and typical arable weeds are good indicators of an ecologically valuable arable habitat thanks to their sensitivity to intensive agriculture (Albrecht 2003; Storkey et al. 2012). Besides, they showed not to be harmful for crops (Twerski et al. 2021).
6. Trophic support to birds: species producing seeds that are food for European farmland birds are indicators of a higher ecological value (score: + 1). All other species are indicators of a lower ecological value (score: − 1). This information was retrieved from Holland et al. (2006), for plant genera. Arable plants are an important trophic resource for farmland birds (Wilson et al. 1999; Marshall et al. 2003; Pinke and Pál 2008). The observed decline of farmland birds in Europe over the last decades was linked to agricultural intensification and the consequent decrease in the availability of arable plants and of their edible seeds (Donald et al. 2006; Butler et al. 2010).

There are several other features or arable plants that are related to their ecological value and could have been taken into account for the calculation of ArEco. These include their contribution in reducing nitrate leaching and soil erosion (Moreau et al. 2020), or functional traits connected to their usefulness for animals (Storkey 2006; Brooks et al. 2012). Nevertheless, one of our aim was to build an index being as simple as possible, in order to maximize its easiness of application. For this reason, we opted for the sole inclusion of simple metrics, widely available or easily collectable in every geographical area.

Calculation of ArEco

From the combination of the six species features described above, 13 possible species types were established (Table 1). Then, each species type was assigned a constant weight based on the sum of features of the species that belong to it.

The ArEco value is calculated by a formula for composite objective function in multicriteria optimization using the weighted sum method with a single set of weights, i.e., with a priori articulation of preferences (Marler and Arora 2010):

Table 1 The 13 established species types, the corresponding attributed weights, and example of species belonging to each type from the Italian flora

No	Reference number of species type	Sum of features	Unnormalized weight	Weight (normalized weight)	Example of species
1	#1	6	6	6/nf ≃ 0.142857142857143	*Centaurea cyanus*
2	#2	5	5	5/nf ≃ 0.119047619047619	*Ranunculus arvensis*
3	#3	4	4	4/nf ≃ 0.095238095238095	*Adonis aestivalis*
4	#4	3	3	3/nf ≃ 0.071428571428571	*Viola arvensis*
5	#5	2	2	2/nf ≃ 0.047619047619048	*Abutilon theophrasti*
6	#6	1	1	1/nf ≃ 0.023809523809524	*Atriplex patula*
7	#7	0	0	0/nf = 0	*Echinochloa crus-galli*
8	#8	− 1	1	1/nf ≃ 0.023809523809524	*Avena fatua*
9	#9	− 2	2	2/nf ≃ 0.047619047619048	*Agrostis stolonifera*
10	#10	− 3	3	3/nf ≃ 0.071428571428571	*Plantago lanceolata*
11	#11	− 4	4	4/nf ≃ 0.095238095238095	*Erigeron canadensis*
12	#12	− 5	5	5/nf ≃ 0.119047619047619	Missing in Italy
13	#13	− 6	6	6/nf ≃ 0.142857142857143	*Paspalum distichum*

nf = 42—normalization factor, established in this way so that the sum of weights of all species types is 1

$$ArEco = \sum_{i=1}^{m} weight(i) \cdot criterion(i)$$

where m = the number of species types (i.e., m = 13); weight(i) = the weight of i′th species type; criterion(i) = signum(sum of features of i′th species type)·(the number of species of i′th species type).

Defined in this way, ArEco is an objective function that quantifies the ecological value of arable plant communities. The weights of species types denote the relative importance of species that belong to the given species type on ArEco. In the weighted sum method, the sum of weights has to be equal to 1 and each weight has to be bigger or equal to zero (Das and Dennis 1997). For this reason, the signum is "part" of the criteria in the presented solution. The signum function returns −1, 0, 1 when the argument (i.e., sum of features of the i′th species type) is respectively: less than zero, equal to zero, greater than zero. The calculations of ArEco were performed using several methods of determining weights of species types. The best solution was chosen based on botanical and ecological expertise, preferring the one for which the final ArEco value optimally reflects the actual features of plant communities. This was achieved using the following formula:

$$\text{weight(i)} = |\text{sum of features of i}'\text{th species type}|/\text{nf} \tag{1}$$

where nf = 42—normalization factor, established in this way so that the sum of species weights is 1, i.e.,

$$\sum_{i=1}^{m} weight(i) = 1$$

All the results presented in this article were obtained using species weights determined according to Formula (1). The weights assigned to each species type are presented in Table 1.

This way of ArEco calculation implies that both the ecological value of the occurring species and species richness play a relevant role in the resulting index value. Increasing ArEco values indicate increasing ecological values of arable plant communities. ArEco is conceived as applicable to vegetation plots, provided that possible differences in plot size do not influence species richness. By means of the application to plots, gradients of ecological value within a given field can be highlighted.

All the calculations presented in this article were carried out using the ArEco program, which was written in Java and can be run on any platform with installed Java Virtual Machine (JVM). The program is available for download at: http://www.uz.zgora.pl/~akaspers/ArEco/ArEco.zip.

The program database is separated from the program and has been organized as an XML database (Zicari et al. 2003). Information about species types and their weights is stored in XML files, in order to ensure high flexibility and universality of the program (available for download at: http://www.uz.zgora.pl/~akaspers/ArEco/species.xml and http://www.uz.zgora.pl/~akaspers/ArEco/weights.xml). If needed, species types and their weights are modifiable according to the geographic area (e.g., if the native status changes) and an unlimited number of new species can be added. At present, the program database includes about 400 typified European arable taxa. The use of data from the real world allowed including accidental species from habitats different from arable land, which often occur in arable vegetation. Thus, we considered as "arable" any taxon that was observed in arable land.

Besides manual calculation, the ArEco program allows the automatic import of presence/absence data from TURBOVEG.csv export files (Hennekens and Schaminée 2001), through a connector program downloadable at http://www.uz.zgora.pl/~akaspers/ArEco/ArEco.zip. The connector program outputs a file that can be then directly processed in the ArEco program.

Species nomenclature follows Bartolucci et al. (2018) for native species and Galasso et al. (2018) for alien species.

Though ArEco is conceived as applicable to vegetation plots, data at different scales (e.g., the flora of a field or of a geographic area) are suitable as well to be assessed.

ArEco validation by application to real data

To test its effectiveness, ArEco was applied to 270 vegetation plots located all across Italy. Part of the plots (145) were original samples, whereas the rest were retrieved from phytosociological literature (Baldoni 1995; Baldoni et al. 2001; Brullo et al. 2001; Fanelli 2002; Fanfarillo et al. 2019b). The unpublished data are available in GBIF in the form of species occurrences (Fanfarillo et al. 2020b). The main crop types of the country are represented: winter-annual crops, summer-annual crops, perennial dry crops, perennial irrigated crops, and orchards. The size of all the original plots was 16 m^2, as suggested for the sampling of European plant communities (Chytrý and Otýpková 2003). The plots from literature had a mean size of about 30 m^2, ranging from 4 m^2 to 50 m^2. Since ArEco can be highly influenced by species richness and phytosociological sampling is known to give biased estimations of species richness (Chytrý 2001), these plots were selected from a bigger pool after checking that no relationships between plot size and species richness were present, through a Pearson's test.

The plots are located all across Italy, in very different environmental and agricultural contexts. The elevation range of the plots is between the sea level and 1100 m a.s.l. The phytoclimate goes from Temperate to Mediterranean, with mean annual temperature ranging between 10 and 19 °C and mean annual precipitation ranging between 500 mm and 2000 mm (Pesaresi et al. 2017). Lithology is much diversified too, including several sedimentary and volcanic types with different chemical reactions, which produce as different soil types (Costantini et al. 2013). The agricultural contexts broadly represent the variability of those present in Italy. They span from areas of highly intensive agriculture of the Po plain to traditional low-input agricultural areas of central and southern Apennines, across many intermediate shades of agricultural intensity and management.

Results

As expected, ArEco resulted to be significantly positively correlated with the species richness of the vegetation plot (Pearson's test: cor = 0.68, $p < 0.001$—Fig. 1). It was instead negatively correlated with the plot size (Pearson's test: cor = − 0.38, $p < 0.001$), despite the fact that the latter did not influence species richness in our database (Person's test, species richness *vs* plot size: cor = − 0.08, p = 0.2).

The application of ArEco to the vegetation plots in our database resulted in a very high variability in ecological value of the studied arable plant communities (Online Resource 1). The highest values resulted for the arable vegetation of winter annual crops, basically winter cereals such as *Avena sativa*, *Hordeum vulgare*, and *Triticum* spp., but also winter-annual legumes like *Vicia* spp. and mixed cereal-legume fodder crops. Such plots had also the highest variability of ArEco values. The lowest values came out for arable plant communities of irrigated woody crops (Fig. 2).

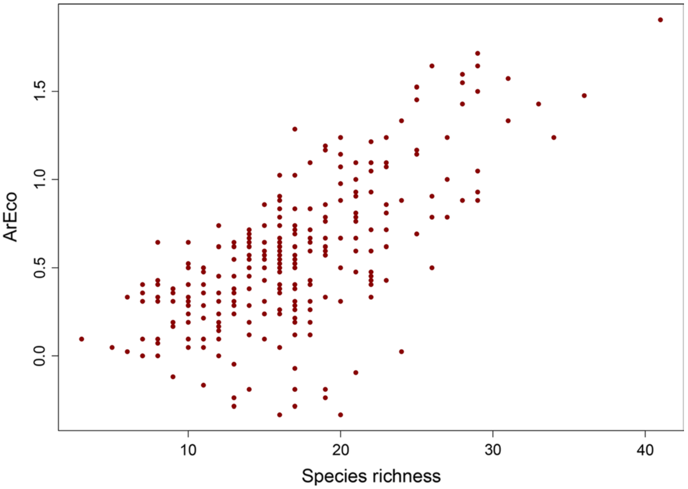

Fig. 1 Scatter plot of ArEco values against species richness (Pearson's test: cor = 0.68, $p < 0.01$)

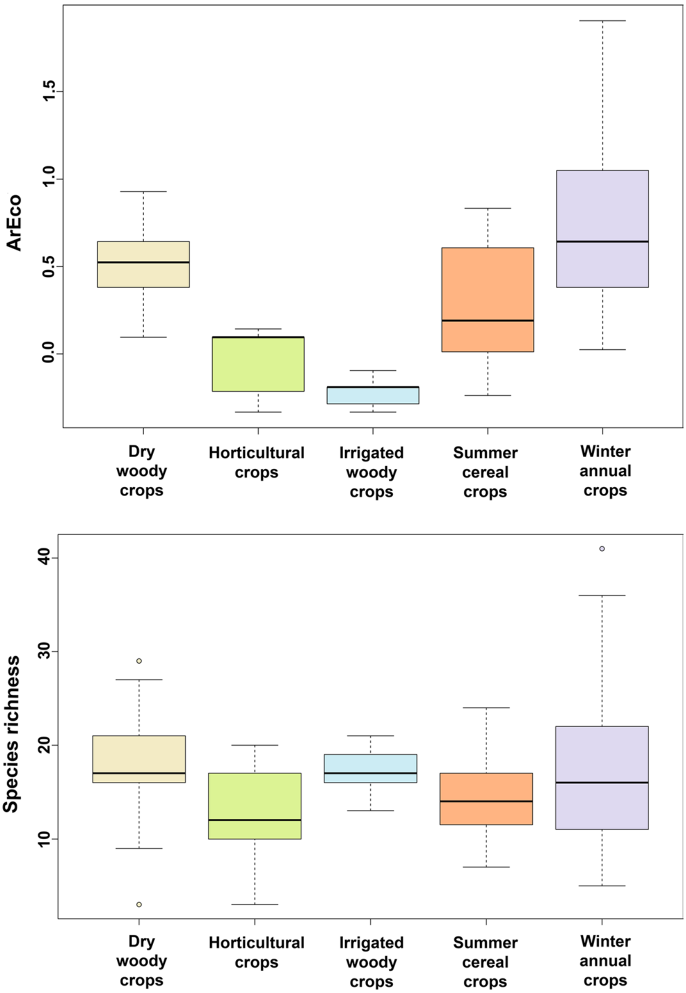

Fig. 2 Boxplots for ArEco values and species richness of arable vegetation according to main crop types

Figure 2 shows the boxplots for ArEco values and species richness of the studied arable vegetation plots according to the five main crop types.

Figure 3 shows a comparison of ArEco values for the arable communities of 20 intensively managed winter annual crops, 20 extensively managed winter annual crops, and 6 extensively managed winter annual crops located in contexts of vanishing agriculture.

Examples of arable plant communities and their ecological value

Table 2 shows detailed examples of arable plant communities that are representative of the five crop types.

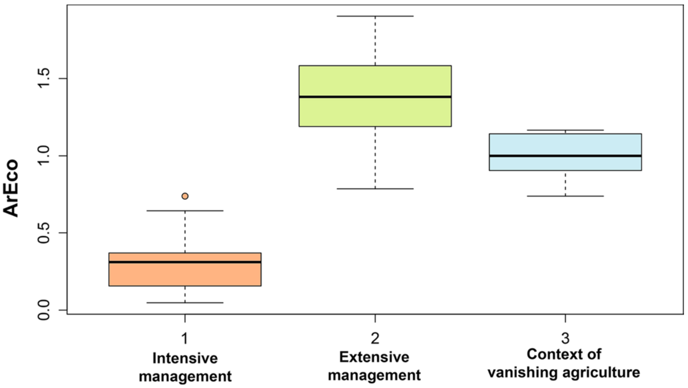

Fig. 3 Boxplots for ArEco values of vegetation plots from 20 intensively managed winter annual crops, 20 extensively managed winter annual crops, and 6 extensively managed winter annual crops located in contexts of vanishing agriculture, taken from the analyzed dataset

Discussion

Comparison between ArEco and ALNI

One of the main reasons for developing a new index through this work was the recognition that the previously published Arable Land Naturalness Index (ALNI—Fanfarillo et al. 2018), though useful in synthetizing some features of arable vegetation related to sustainability, has some flaws and gaps that weaken its usefulness (e.g., high correlation with species richness, overestimation of the value of perennial species, and underestimation of the value of archaeophytes). For several reasons, the new index is considerably better in the ecological evaluation of arable vegetation.

The concept of "naturalness" itself can be misleading when discussed in the context of arable fields, even if intended in a relative way like in the ALNI. Indeed, these habitats are non-natural by definition, being a product of human activities. The concept of "ecological value" is much more used in natural sciences (e.g., Bryan et al. 2010; Seitz et al. 2014; Arsénio et al. 2020) and it seems more appropriate to quantify the importance of arable vegetation for the sustainability of agroecosystems (Marshall et al. 2003; Storkey and Neve 2018; Smith et al. 2020).

Another theoretical weakness of ALNI, related to its relying on the concept of "naturalness", is that it considers perennial species more valuable than annual species, though typical perennial noxious weeds (e.g., *Cirsium arvense*) are given a lower value than perennial species from semi-natural habitats (e.g., *Bromopsis erecta*). Impoverished and banalized communities of intensive agricultural areas are known to be richer in perennial species that replace annual taxa, mining the conservation of rare arable plants (Salonen et al. 2013; Fanfarillo et al. 2020c). Furthermore, an increase of perennial species from semi-natural habitats is a consequence of land abandonment, which causes the quick disappearance of typical annual arable plant communities (Albrecht et al. 2016). The occurrence of such species in arable land should thus not be considered a positive sign in the perspective of evaluating the conservation and ecological value of arable vegetation, since linked to its vanishing.

Table 2 Examples of arable plant communities colonizing the five main crop types

Crop	Plot ID	Species richness	Plot size	ArEco	Floristic composition
Triticum turgidum subsp. *durum*	93	18	16 m^2	0.71	*Ammi majus, Avena sterilis, Cerastium glomeratum, Kickxia spuria, Lysimachia arvensis, Papaver apulum, P. rhoeas, Poa annua, P. sylvicola, Polygonum aviculare* agg.*, Ranunculus parviflorus, Rumex obtusifolius, Trifolium campestre, T. nigrescens, Urtica urens, Veronica persica, Vicia sativa* agg.*, Viola arvensis*
Vitis vinifera	22	16	40 m^2	0.52	*Alopecurus myosuroides*, *Calendula arvensis*, *Capsella bursa-pastoris*, *Convolvulus arvensis*, *Diplotaxis erucoides*, *Euphorbia helioscopia*, *Geranium rotundifolium*, *Lamium amplexicaule*, *L. purpureum*, *Malva sylvestris*, *Muscari comosum*, *Ornithogalum divergens*, *P. rhoeas*, *Stellaria media*, *Veronica hederifolia*, *V. persica*
Cucurbita pepo, *Phaseolus vulgaris*	121	10	50 m^2	0.09	*Agrostis stolonifera, Chenopodium album, C. vulvaria, Convolvulus arvensis, Digitaria sanguinalis, Echinochloa colona, Ornithopus compressus, Persicaria lapathifolia, Raphanus raphanistrum, Setaria pumila*
Zea mays	85	12	40 m^2	0.19	*Amaranthus retroflexus, C. album, Convolvulus arvensis, D. sanguinalis, Echinochloa crus-galli, Equisetum arvense, Fallopia convolvulus, Heliotropium europaeum, Helminthotheca echioides, Persicaria maculosa, P. aviculare, Setaria italica*
Citrus bergamon	76	19	50 m^2	– 0.19	*Amaranthus hybridus*, *A. retroflexus*, *C. vulvaria*, *Cyperus esculentus*, *C. rotundus*, *Datura stramonium*, *D. sanguinalis*, *E. crus-galli*, *Galinsoga quadriradiata*, *H. europaeum*, *Parietaria judaica*, *Portulaca oleracea*, *S. pumila*, *S. verticillata*, *Solanum nigrum*, *Sonchus asper*, *S. oleraceus*, *Sorghum halepense*, *Urtica membranacea*

Cultivated species, plot ID in our dataset, species richness, plot size, ArEco value, and full species composition are reported. Plant genera are punctuated after their first mention

Similarly, in the calculation of ALNI, archaeophytes are considered as of lower value, as they are alien, though among alien species they are given a higher score than neophytes. This is misleading, since many archaeophytes (and anecophytes) are among the most threatened arable plants in Europe (Storkey et al. 2012).

The negative relationship between ArEco values and plot size is indirectly due to the fact that, in our database, the lowest values resulted for plots from literature with relatively big sizes. The highlighted dependence of ArEco on species richness was quite high, but restrained if compared to that highlighted by ALNI (0.68 *vs* 0.95). This result indicates that the features of arable plants, determining the ecological value of plant communities, have a much higher importance in the definition of ArEco. This is partially due to the fact that ALNI does not take into account the importance of plant species for pollinators and birds. Furthermore, contrarily to ALNI, ArEco was built to emphasize the "bad" features of arable plants (i.e., if they are neophyte, wind-pollinated, nutrient-requiring) by attributing them a negative value. With the introduction of negative weights, we avoided the possibility of giving a high value to vegetation types with a high species-richness but with a poor ecological value in terms of species composition. In the past, such biased estimations were highlighted through the use of the Floristic Quality Index on wetland vegetation, where sites with a high number of low value species got a higher score than sites less species-rich, but with many valuable species (Taft et al. 1997; Miller and Wardrop 2006; Cretini et al. 2012).

Through its application to real data, ArEco proved to be effective in synthetizing in one numerical value the ecological value of arable plant communities.

Comparison with other approaches

Former approaches rather focused on single species and their grouping into categories, than on the evaluation of the whole arable community. Instead, our index allows to obtain a single output synthetizing the ecological value of the whole plant community. The different metrics used to characterize arable plants, and then vegetation, in our approach are of much easier collection with respect to some functional traits used in the past, and can be rapidly adjusted if needed.

In past works, functional grouping was the main approach that was used to characterize arable plants in relation to their ecological value. From this perspective, Storkey (2006) defined seven functional groups of arable plants based on flowering time, life form, maximum height, seed size, and timing of germination, and provided a method to assign species to one of these groups. Species belonging to the same group were then shown to have similar functions with regards to their support to birds and invertebrates. Later, Brooks et al. (2012) highlighted how such functional groups of arable plants have stable trophic links with functional groups of beetles in Great Britain. These evidences allow the detection of different ecological values for arable plants, according to their pertaining group.

In terms of ecological value related to biodiversity conservation, species dependent on arable habitats are much more valuable than others. A useful approach to distinguish strictly arable species from transient species entering the field from surrounding habitats is the one adopted by Metcalfe et al. (2019), i.e., the use of fidelity scores. A limitation of such method is that it requires the collection of information on species growing in the surroundings of the field, which implies additional efforts. Based as well on field observations and the following calculation of several indexes, Fried et al. (2010) classified the arable flora of France into generalist and specialist species. From this perspective, our approach allows to easily distinguish between typical arable plants and accidental species mainly based on life form, by grouping annual and bulbous geophytes against the rest of perennials. The addition of nutrient requirements and conservation status in Europe further circumscribes the pool of typical European arable plants.

Patterns of ecological value of arable plant communities across crop types and agricultural contexts

The analysis revealed that arable plant communities developing in different crop types have different levels of ecological value. The arable vegetation of winter annual crops was the most valuable one. Plant communities developing between fall and early summer were in general more valuable than those developing between summer and early autumn. This was expected, given the features of winter-annual arable vegetation in Italy and Europe: high proportion of native or archaeophyte species, mostly annual, and with low nutrient requirements (Lososová et al. 2004; Šilc et al. 2009; Fanfarillo et al. 2020d). Our results are consistent with these findings. Furthermore, winter arable plant communities can be considerably species-rich in Italy, as shown by our data and highlighted before (Fanfarillo et al. 2020c). Our results also showed that winter arable vegetation was more valuable in terms of support to pollinators and hosted more species that are rare or threatened. On the contrary, summer arable communities showed the highest proportion of species providing resources for farmland birds, probably due to a high occurrence of Poaceae, one the most important plant families from this perspective (Holland et al. 2006). Despite this, the ecological value of summer arable vegetation was the lowest, due to the high representation of neophytes, nutrient-requiring, and wind-pollinated species.

A high variability in ecological value was observed as well within arable plant communities of the same crop type, and especially of winter annual crops. This is clearly due to the different management intensity of arable fields, and it is particularly evident for winter arable crops thanks to the higher number of plots. Communities of fields located in intensive agricultural areas of the Po Plain showed the lowest ArEco values, whereas those developing in traditional fodder crops of the southern Apennines showed the highest values of the entire dataset. In the mountain belt of central Apennines, arable plant communities showed intermediate ArEco values despite the traditional agricultural context. This was explained by the ingression of perennial species from the surrounding natural vegetation, due to the isolation of the fields and to the extremely low intensity of management in those areas, indicating the vanishing of agriculture and the consequent risk of disappearance of arable vegetation (Storkey et al. 2012; Albrecht et al. 2016; Metcalfe et al. 2019).

Though ArEco was validated only on a set of Italian data, the principles it is built upon make it applicable to the whole of Europe. On the contrary, the index will need some adjustments to be used in other areas, for instance where the European concept of archaeophyte and neophyte cannot be applied. Even within Europe, species features and types could need to be redefined according to local situations. It is the case, for instance, of the need to change the alien status of species that are native or anciently introduced in southern Europe and recently moved northwards (Follak and Essl 2013; Follak et al. 2017). Another limit to the use of the index can be missing information about species features in some geographic areas across Europe, a gap that will be hopefully filled in the future.

Conclusions

Arable land is being more and more acknowledged in Europe for its value as a unique habitat. Plant species and communities that are adapted to soil tillage acquired a great value for scientists since changes in agriculture began to threaten them. In this work, we built a new floristic-ecological index (ArEco) that uses biological, chorological, and ecological features of segetal plants, besides floristic richness, as indicators of the ecological value of arable habitats.

The validation of the index, achieved by its application to 270 vegetation plots from different kinds of arable fields in Italy, confirmed its effectiveness in estimating the ecological value of arable vegetation. This new tool allowed for the synthesis of the several pieces of information on arable plants that we considered relevant to characterize arable vegetation from the perspective of ecological value. Compared to the previously developed ALNI, it proved to be much less influenced by species richness and able to distinguish the low ecological value of some communities that, though biodiverse, are featured by species of low value for agroecosystems such as neophyte, wind-pollinated, or nitrophilous ones. The index also highlighted the lower value of arable vegetation in contexts of vanishing agriculture, where the ecological succession threatens the conservation of segetal biodiversity and of its functions.

The future application of ArEco to larger datasets from wider territories, to different types of arable land, and to data collected at different times could be a useful way to monitor the status of this habitat in Europe, in the perspective of planning conservation measures.

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Author contributions E.F. collected the unpublished and published data, selected species features, built the species features database, took care of all the botanical and ecological aspects of the work, and wrote the manuscript. A.K. defined species weights and the index, wrote the ArEco program, took care of all the mathematical aspects of the work, contributed to the writing of the manuscript, and critically revised the manuscript. Both the authors conceived the work.

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Availability of data and material The unpublished data used in this work are available in the form of species occurrences at https://www.gbif.org/dataset/d1f724bf-8d68-49c8-a87f-5c9e7a7b9deb.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

Consent to participate This research did not involve human subjects.

Consent to publish All the data used in this research are of property of the authors or available in the scientific publications that were cited in the article.

Ethical approval All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2000. Informed consent was obtained from all patients for being included in the study.”

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