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Weed surveys and weed mapping in Europe: State of the art and future tasks

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ABSTRACT

Long-term national European weed surveys, large scale classical phytosociological programs and camera-based documentation systems lead to results which can be documented in form of maps. Comparisons of these visual representations of relative weed positions can be used for the prediction of changing weed spectra and of plant biodiversity changes. Statistical methods connected with mapping software are used for the analysis of environmental factors and of farm managing practices influencing the occurrence of weeds. Maps produced by sensor-driven weed detection devices still differ considerably from maps produced via classical phytosociological approaches. Computer algorithms may allow the precise identification of some weeds in camera images. The present technical solutions are, however, still far from those achieved by experienced botanists. Many weed detection tools based on algorithms are not able to distinguish between closely related weeds yet. A few European countries have a long tradition of surveying weeds in major crops by traditional tools. Various software packages are employed for the analysis, documentation and visualisation of survey results. Large scale comprehensive maps including the infestation of crops over different countries are, however, often biased as not every national research group uses the same methods for the assessment of weed infestation. The ranking of the most common species seems, however, to allow comparable conclusions. The recognition of trends in spectrum changes can only be derived from long term studies as we see it. Our review reflects discussions within the Weed Mapping Working Group of the European Weed Research Society over the last ten years. We try to identify new research trends and to respond accordingly with new research projects. What we see today is a shift from traditional mapping approaches towards the use of digital devices as for example in precision farming projects. Another issue of increasing importance is the mapping of herbicide resistant biotypes.

1. Introduction

Weed scientists observe weed communities often in a different view and with other interests than vegetation scientists or ecologists whose major topic is biodiversity. Weeds have a direct economic impact on agriculture; more know-how on their distribution could contribute to the solution of urgent agricultural problems.

Weed populations are not stable. Several factors have an influence on

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weed flora composition and the level of infestation. Farming practices have changed considerably during the last two centuries and weed populations changed accordingly. Some weeds are typically associated with certain crops as for examples weeds in rice. A number of crops in major agricultural countries have only relatively short histories. Oilseed rape in Canada, soybean in the USA, oilseed rape and maize in many parts of Europe have become large acre crops only within the last century (Kraehmer et al., 2014). Weed management tools have changed also considerably within the last century. The intensive use of herbicides quickly led to the occurrence of herbicide-resistant weeds in several agricultural areas.

The composition of weed communities is not only an issue of farmers. Dominant weeds can also change habitats in a way that biodiversity becomes reduced.

National weed surveys have a long tradition in European countries (Kraehmer and Barberi, 2017). Results from different countries were, however, rarely compared in the past. One form of documentation of surveys is the preparation of maps. Visual representations and the analysis of relative weed positions can be used for all sorts of comparisons, conclusions and predictions.

Weed mapping has become such an important research issue that the European Weed Research Society decided in the year 2009 to establish a Weed Mapping Working Group (http://www.ewrs.org/weed_mapping.asp, accessed on August 1, 2018).

Vegetation scientists, geobotanists and phyto-sociologists have developed numerous graphic depiction tools for the demonstration of distribution ranges of single species or flora. A standard on classical cartographic plant and vegetation documentation was compiled by Pedrotti (2013).

The number of publications reporting on the distribution of European weeds with classical phytosociological tools has decreased considerably within the last decade. One recent review paper summarizing weed survey results based on traditional phytosociological assessments was for example published by Hanzlik and Gerowitt (2016).

A completely different approach for the documentation of weed infestation is the sensor-driven automated weed detection with earthbound or unmanned aerial vehicles (UAVs). It provides completely new tools for the mapping of weeds and especially for precision farming (Ørum et al., 2017; Fernández-Quintanilla et al., 2018). Machine learning has improved the automated identification of weeds within the last ten years considerably (Alexandridis et al., 2017; De Castro et al., 2018). Multispectral cameras and special evaluation tools even make it possible to distinguish between grass weeds and rice (Barrero and Perdomo, 2018) or black-grass in winter wheat (Lambert et al., 2018). One advantage of many automated weed mapping devices is their speed and the relatively short time needed for the assessment of weed infestation within arable fields (Laursen et al., 2017). Unfortunately, the present results are still far from those achieved by experienced botanists. Many weed detection tools based on algorithms are not able to distinguish closely related weed species yet.

The primary objectives for this review paper are the assessment and discussion of

- methods employed in various weed survey projects
- statements on trends in biodiversity and weed composition changes on European arable land
- the correlation of environmental factors and farm management tools with changes in weed spectra and the use of models for the prediction of weed distributions
- tools for the documentation and mapping of herbicide resistant weeds

We will concentrate thereby on weeds in arable crops and on invasive weeds.

2. Methodology and terminology

2.1. Data collection

Data can be collected by ground scouting or by remote sensing. In environmental studies, data are acquired mostly by sampling at defined locations only. Sampling units of different shapes, size and number are used in weed science (Sutherland, 1996 or Brix and Andreasen, 2000). The size of plots depends on the study objectives and it may differ from one type of vegetation to another (Kent, 2012). As a general rule, the plot size should be large enough to represent the vegetation in its close vicinity. For phytosociological studies, Mueller-Dombois and Ellenberg (1974) made general proposals on the optimum size of quadrats for selected vegetation types and for agricultural weed communities. They suggest 25–100 m^2. Based on the concept of minimum sampling area, i.e. the smallest area in which the majority species of a plant community were included, Chauvel et al. (1998) suggested an area of 1000–2000 m^2 for arable weed communities. The shape of the sampling course within a field usually often resembles the form of the letters W or Z. An insufficient number of samples may unfortunately cause interpretation errors (Eckblad, 1991). No general recommendation for the number of replicates exist, but the demand for replications increases with a higher intragroup variance and with the number of explanatory variables. The most common spatial sampling scheme is a simple random sampling approach (Cochran, 1977). A systematic sampling device with plots located for example on a transect or in a grid is also often used, especially in landscape ecology studies (Alignier and Petit, 2012b). Other tools are preferential sampling (Moore et al., 1970), a spatially stratified sampling or a stratified random sampling (Kent, 2012).

2.2. Digital data collection tools (GIS, RS, GPS)

A geographic information system (GIS) is used to store, analyse, manipulate and view geographical data usually related to the Earth surface (Maguire et al., 1991). Remote sensing (RS) of vegetation from aerial and terrestrial vehicles, equipped with different types of cameras (multispectral or hyperspectral), makes use of wavelengths of the electromagnetic spectrum (400–2500 nm) and creates data on weed appearance (Richards and Jia, 2006). Global position system (GPS) provides a global positioning capability concerning a consistent terrestrial reference frame (Bock, 1996). All the above three technologies have been used in regional or in field scale to detect, map, monitor and model distributions of weeds.

2.3. Description of plant abundance indices

Various species abundance parameters may be used in literature. We list and define them here as some terms are used in different ways by different scientific groups.

- Abundance means some quantitative measurement of the presence of a species (Kent, 2012). It can be expressed by several indices such as density, cover, biomass, frequency or mean distances among individuals.
- Cover is expressed as the percentage of ground covered by above ground plant parts (Van Der Maarel and Franklin, 2013). It can be estimated visually, using point or line intercept methods or using image analysis (Ali et al., 2015). Various scales for assessing coverage are still in use. Some examples are the 7-point Braun-Blanquet (1964) scale and modifications thereof (Barkman et al., 1964), the Domin scale (Evans and Dahl, 1955), a five-point quasi-logarithmic cover scale developed by the Uppsala School of Phytosociology or Hult-Sernander scale (Van Der Maarel, 1979), and the Ujvárosi scale (Ujvárosi, 1973) used during National Weed Surveys in Hungary (Novák et al., 2012).

- Density is defined as the number of plants per unit area. It is commonly used for the status of endangered or threatened species but is also commonly used for weeds. For example in France, Barralis (1976) proposed a 6-point density scale method inspired by Braun-Blanquet and subsequently used for national weed surveys (Fried et al., 2008).
- Biomass has been used for example as a tool in Finnish weed surveys for years (Salonen et al., 2011). The Finnish approach is based on counting and weighing all weed species from randomly established 0.1 m^2 sample quadrats.
- Frequency expresses the percentage of samples in which a given species has been found.
- According to Thomas (1985) the relative weed abundance is estimated by summing relative frequency, relative uniformity and relative density. More recently, Moeini et al. (2008) proposed an improved version of the Thomas method.

All these parameters provide valuable information. A major issue for the interpretation of weed infestation data is, however, the comparability of results produced with different indices. Maps showing the distribution of the most frequent weeds in arable crops all over Europe would be a major achievement for the prediction of major trends. The existing maps as for example published by Kraehmer (2016) are unfortunately just based on the ranking of species. Mueller-Dombois and Ellenberg (1974) already demonstrate on the other side how some of the above-mentioned indices are linked and how comparability measures could be achieved in classifying vegetation elements. One task for the EWRS Working Group is the preparation of European maps based on the conversion of existing data into comparable values with conversion factors.

2.4. Aspects to be considered before running surveys and before the interpretation of results

Unfortunately, every approach based on quantitative or qualitative tools is prone to errors.

General statements on long-term changes of weed spectra, on factors influencing the weed species composition of arable fields or on regional specificities require a careful analysis of a number of parameters. In this context we have to raise a few questions before and after surveys:

- Are the species assessed distributed randomly in the investigated plots?
- How many samples are sufficient for a reliable interpretation?
- Is the timing of the assessment adequate?
- How many seasons in a row are required for making statements about trends?
- Can the observed changes be connected with weed characteristics and population dynamics at all?
- How can the influence of environmental factors (soil, climate, pests, diseases) be separated from crop management factors?
- How does scale influence the interpretation of data?

Unfortunately, major differences can be observed when different teams assess the same plots. This is especially true for ground cover estimation with low weed densities (Andújar et al., 2010). It appears, however, that the total ranking of weed occurrence based on counting or cover estimation does not differ too much when evaluated by different teams. This is the outcome of a first basic evaluation shown during a workshop of the Working Group in Prague in July 2014. Field evaluations also provided a good validation of the ranking hypothesis in Finnish surveys (Salonen et al., 2011) in which different assessment tools were employed.

2.5. Tools for the analysis of survey data

Several methods can be used for the analysis of data in weed mapping studies. Their selection will depend on the objective of the research project. We mention here just a few tools.

2.5.1. Non-spatial multivariate data analysis

Many complex data sets of surveys can be analysed with multivariate methods. Linear, non-linear and logistic regression, cluster and regression trees analysis (CART), principal component and discriminant analysis have been widely used in relating weed appearance indices with many other factors such as soil, climate and crop management techniques. An extended review of non-spatial statistical issues in weed research is presented by Onofri et al. (2010).

A wide range of software suitable for the analysis of vegetation-related data, for data storage and vegetation analyses is available and is used for the assessment of weed distribution. Some examples are TURBOVEG (input, storage, management and export of data; Hennekens and Schaminée, 2001), JUICE (editing and analyses of phytosociological data; Tichý, 2002), CANOCO (multivariate analyses of ecological data; Ter Braak and Šmilauer, 2002), R (all kinds of statistical and graphics applications; R Core Team, 2019), PC-ORD (multivariate analyses of ecological data (McCune and Mefford, 1999)) and others.

As an example of combining and presenting information from separate weed surveys, two multivariate unimodal methods (Detrended Correspondence Analysis - DCA and Canonical Correspondence Analysis - CCA) were applied to survey data from the Czech Republic and from Finland (Figs. 1 and 2). A comparison of pooled data from 190 spring cereal fields in the Czech Republic (88 fields – 50 conventional, 38 organic) and Finland (102 fields – 52 conventional, 50 organic) was demonstrated.

From indirect multivariate techniques (DCA), we can conclude, which factors are primarily responsible for weed patterns. Environmental (explanatory) variables do not affect the calculation of ordination axes but their relation to species points in the ordination diagram can be interpreted from results. It turned out that the type of farming did not play an important role in the species distribution of the ordination space. Latitude and longitude are more important factors (Fig. 1).

In a direct unimodal CCA (Canonical Correspondence Analysis) we can find out if any of the studied explanatory variables have statistically significant effects on the occurrence of species (Table 1). In both outputs/diagrams the geographical origin of records is demonstrated along the North/East gradient indicating the characteristic weed species for Finland up in the North. DCA methods require more expertise and skills than CCA analyses which in turn is a powerful tool only if the explanatory variables are relevant for the occurrence of recorded weed species.

2.5.2. Distance indices as spatial information tools

Distance based methods incorporate spatial information into the analysis of spatial patterns and require the measurement of coordinates of each plant or each weed survey (Perry, 1995). Spatial analysis by distance indices (SADIE) of weed appearance was used to measure the spatial pattern of *Orobanche crenata* Forsk (Perry and Lopez-Granados, 1999). and also the temporal stability of the same weed in faba bean (Oveisi et al., 2010). It was also employed for the study of weed communities in organic and conventional no-tillage spring wheat systems (Pollnac et al., 2008) and under some other circumstances.

2.5.3. Autocorrelation indices approach

Spatial autocorrelation statistics measure the intensity of the spatial relationship between weed population indices in a neighbourhood defined by a specific distance. The autocorrelation is calculated over the full extent of a study area when global indicators of spatial autocorrelation are used (i.e. Moran's I, Getis-Ord General G) while local indicators (LISA method) are implemented to map local patterns and clusters of spatial arrangement. Autocorrelation indices appear very

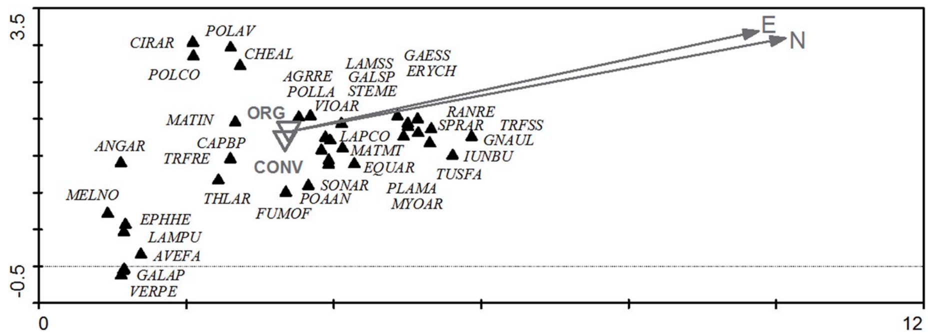

Fig. 1. DCA (Detrended Correspondence Analysis) ordination diagram of the weed survey data from Czech Republic and Finland with passively projected (arrows and open triangles) environmental variables. Minimum species weight to be displayed is 9% (species weight is equal to the sum of abundances of the species taken over all the samples).

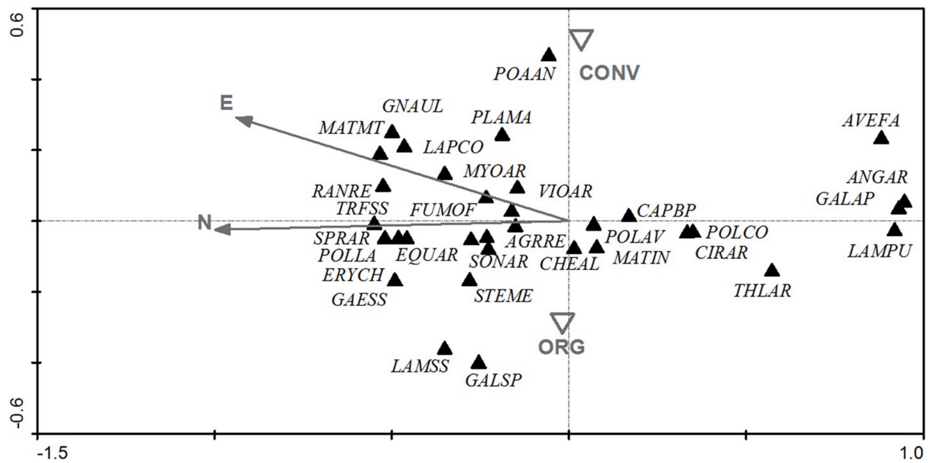

Fig. 2. CCA (Canonical Correspondence Analysis) of the weed survey data from Czech Republic and Finland. Ordination diagram with environmental variables represented by arrows and open triangles. Minimum species weight to be displayed is 9%.

Table 1
Factors contributing to variability in a CCA analysis.

Environmental variable	Covariable	Sum of all canonical eigenvalues[b]	F-ratio[c]	P-value[d]	%
All	-	0.633	4.663	0.001	7.0
N, E[a]	Type of farming	0.552	6.093	0.001	6.1
Type of farming	N, E	0.081	1.786	0.387	n. s.

[a] N, E – latitude, longitude.
[b] Sum of all eigenvalues (total inertia = 9.054); % – percentage of explained variance.
[c] F-ratio for the test of significance of all (first) canonical axes.
[d] P-value – corresponding probability value obtained using the Monte Carlo permutation test (999 permutations).

often in weed mapping studies (e.g. Kalivas et al., 2010, 2012; Alignier et al., 2012a, b). It should be considered as a prerequisite when non-geostatistical interpolation methods are used to reveal the existence of spatial dependence in weed appearance.

2.5.4. Spatio-temporal interpolation

Interpolation is the procedure of predicting the value of attributes at unsampled sites from measurements made at point locations within the same area or region. The most common interpolation methods are the Inverse Distance Weighting (IDW) and the Kriging which is based on the theory of geostatistics (Isaaks and Srivastava, 1989). Both methods predict a value at an unsampled site by using weights to adjust measured values at nearby sites. Kriging weights are based on the theoretical variogram model which relates the variance of a variable to the spatial location of the sampling sites. Interpolation methods in predictive weed mapping have been widely used (e.g. Heisel et al., 1996, 1999; Jurado-Exposito et al., 2009; Kalivas et al., 2010, 2012).

2.5.5. Methods used for precision farming objectives

The methodology employed is based on digital data from sensors and on weed identification software which allows the recording of key weeds on farmers' fields (e.g., Gutjahr and Gerhards, 2010; Keller et al., 2014a, 2014b; Streibig et al., 2014). Based on the spatial variance in a weed population the process tries to aggregate the population distribution and thus potentially contributes to pesticide savings in precision agriculture applications.

2.6. Graphical interpretation of results

2.6.1. Two-dimensional maps

Maps are an effective tool for the presentation of survey results. Cartography as described for example by Longley et al. (2011) provides different tools for the creation of thematic maps. The most common maps adopted in weed science are:

- Choropleth maps; they use colour, shading, or symbols to convey one or more statistical variables in non-overlapping areas.
- Grid maps divide territories systematically (Pedrotti, 2013), an example is shown in Fig. 3.

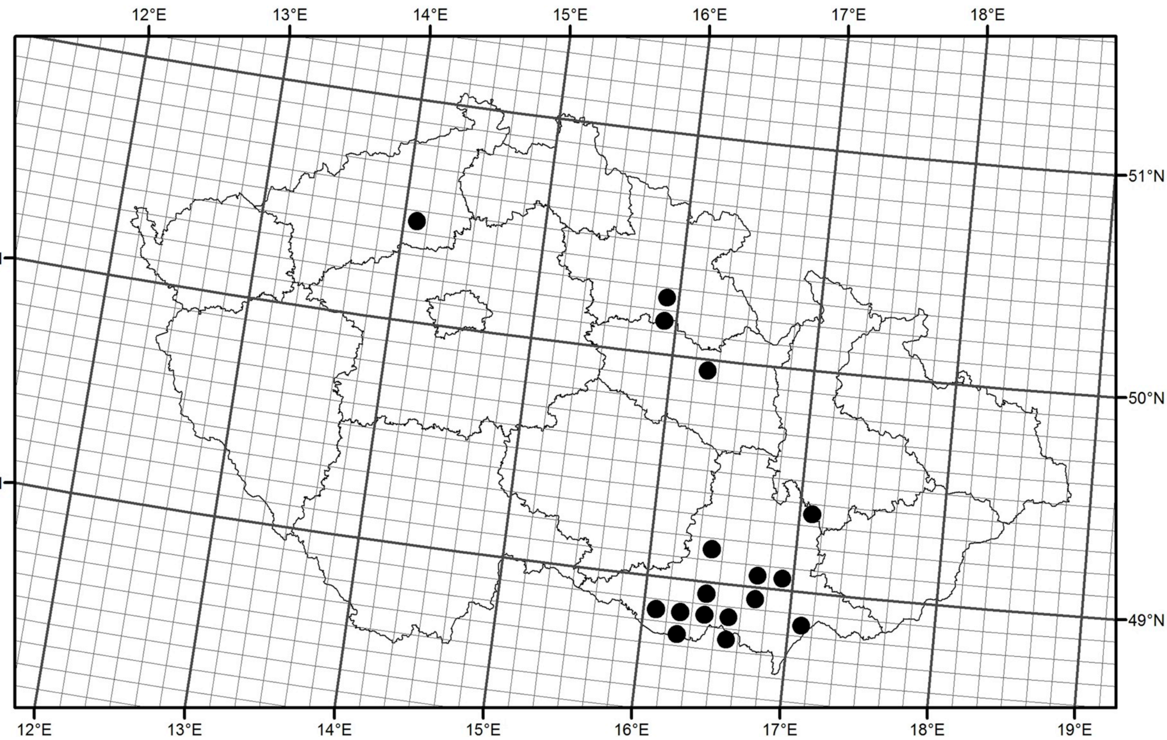

Fig. 3. Grid map showing the distribution of *Amaranthus powellii* in the Czech Republic (cells of 10 min of longitude and 6 min of latitude); based on research between 2007 and 2008.

- Binary maps or indicator maps; these are maps with areas divided into two classes.
- Dot distribution maps; each dot represents the recording of a plant.
- Chart maps; column or other type charts represent a set of attributes for each area unit (Fig. 4)
- Range maps or sometimes distribution maps; defined by a polygon or group of polygons delimiting an area of species or another attribute distribution.
- Contour maps, also isoline or isopleth maps; the maps consist of isolines, i.e. lines connecting points with equal values of displayed variables (Fig. 5).

2.7. Country surveys in Europe and changes of weed communities over years

Weed surveys in arable fields provide information on the

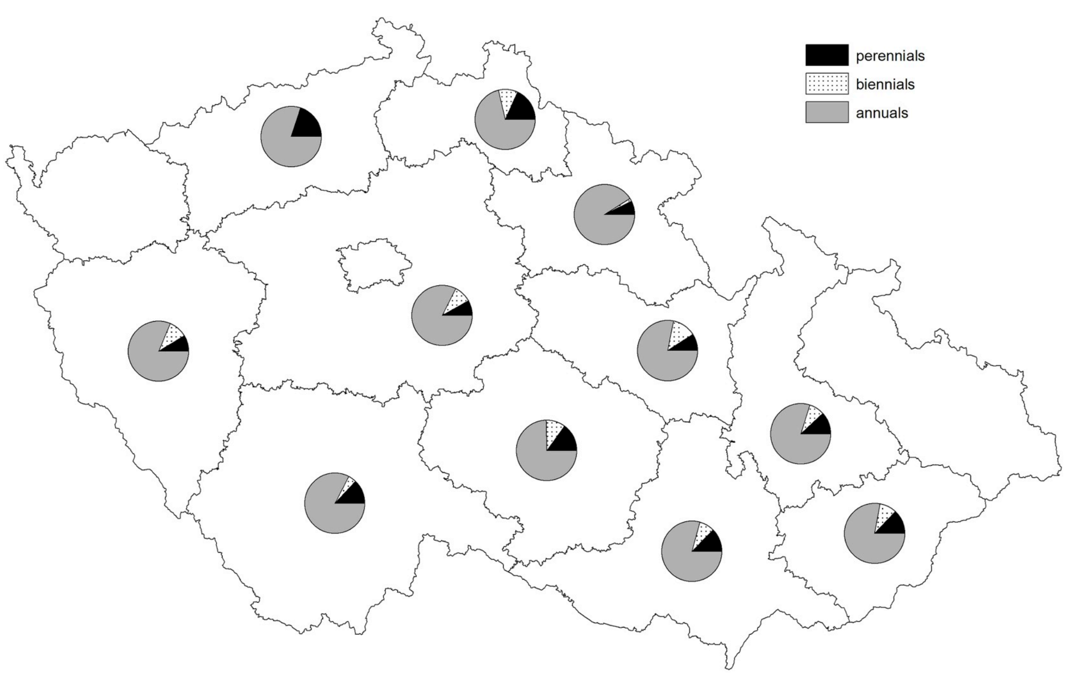

Fig. 4. Pie chart map displaying share of species based on their perennating character (annuals, biennials, perennials) in conventional farming in the Czech Republic between 2007 and 2008. Regions with no pie were not surveyed.

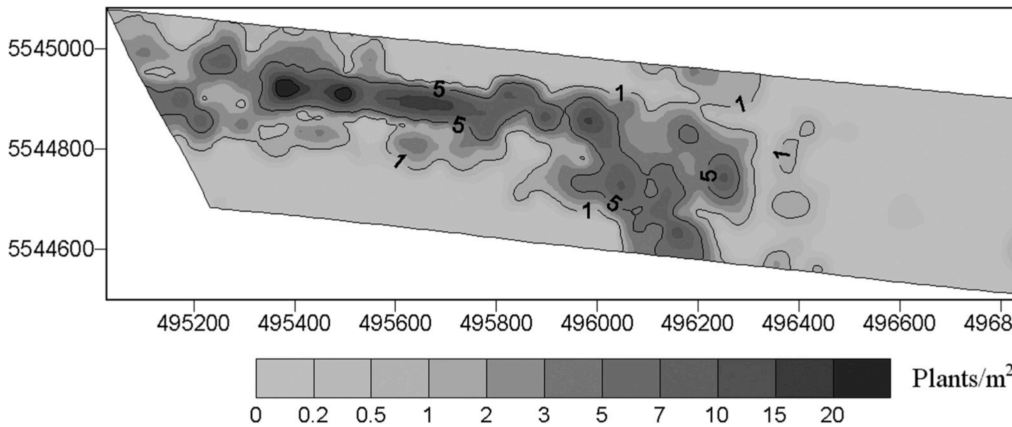

Fig. 5. Filled contour map of *Galium aparine* distribution in a trial field according to Hamouz et al. (2004).

composition of the weed flora both in terms of frequency of occurrence and abundance in general.

Both Denmark and Finland have succeeded in carrying out repeated surveys of weed floras on arable land. In Denmark, surveys date back 100 years (Haas and Streibig, 1982) and in Finland 50 years (Mukula et al., 1969), respectively. The most recent data are from the first decade of the 21st century (Andreasen and Stryhn, 2008; Salonen et al., 2011, Andreasen et al., 2018). Although hundreds of weed species have been recorded across these countries, only a fraction of species is of economic importance for crop production. A change of weed ranks over decades is quite apparent (Tables 2–4). This change obviously correlates with agricultural practices (Andreasen and Streibig, 2011; Salonen et al., 2013). A shift from summer to winter annual crops has taken place in Denmark favouring species such as *Apera spica-venti* (L.) P. Beauv., *Tripleurospermum inodorum* (L.) Sch. Bip. and *Veronica* spp. In Finland, spring cereals still dominate the cropping of arable land and species like *Chenopodium album* L., *Galeopsis* L. spp., *Stellaria media* (L.) Vill. and *Viola arvensis* Murray have been important broad-leaved weeds over decades (Table 2). *Elytrigia repens* (L.) Gould syn *Elymus repens* (L.) Gould and *A. spica-venti* are the most troublesome grass weeds in Nordic countries while *Poa annua* L. is the most common one in Denmark, but *E. repens* the most common grass weed in Finland.

In Hungary, the fifth national weed survey was carried out in 2007–2008 following the principles of the first survey in 1947–1953 (Novák et al., 2012). The methods of Balázs-Ujvárosi were applied in all the five national weed surveys. They took place at the same locations from the second national weed survey onwards following the principles set by Miklós Ujvárosi. The results of the fifth survey are depicted in detailed maps reflecting intensities of weed infestation by the intensity of colours. In addition to changes in agricultural practices, changes in the ownership of farms and arable land have influenced the occurrence of weeds over decades (Tables 5 and 6). Currently, *T. inodorum, Ambrosia artemisiifolia* L., *A. spica-venti*, *Cirsium arvense* (L.) Scop and *Galium*

Table 2
Changes in the ranks of weed species over the decades based on their frequency of occurrence in spring cereal fields in Finland (according to Salonen et al., 2011 and literature referred to in this paper).

Weed species	1962–1964	1982–1984	1997–1999	2007–2009
Viola arvensis	5	3	1	1
Stellaria media	4	4	2	2
Galeopsis spp.	1	2	4	3
Galium spurium	36	13	9	4
Lapsana communis	13	7	6	5
Fallopia convolvulus	12	5	8	6
Chenopodium album	2	1	5	7
Elytrigia repens	15	10	3	8
Fumaria officinalis	21	12	10	9
Polygonum aviculare	20	8	7	10
Myosotis arvensis	11	9	11	11
Lamium spp.	45	17	15	12
Tripleurospermum inodorum	14	15	14	13
Taraxacum officinale	26	[a]	22	14
Sonchus arvensis	25	16	16	15

[a] not observed.

Table 3
Ranking of weed species in Danish winter wheat fields based on surveys done in 1967–70, 1987–89 and 2001–04, respectively (from Andreasen et al., 1996; Andreasen and Stryhn, 2008).

Weed species	1967–70	1987–89	2001–04
Poa annua	3	2	1
Viola arvensis	2	3	2
Stellaria media	1	1	3
Capsella bursa-pastoris	17	11	4
Veronica arvensis	20	7	5
Myosotis arvensis	4	4	6
Tripleurospermun inodorum	5	8	7
Fallopia convolvulus	9	5	8
Apera spica-venti	[a]	14	9
Polygonum aviculare	7	9	10
Chenopodium album	19	15	11
Veronica persica	10	6	12
Galium aparine	10	16	13
Lapsana communis	26	26	14
Matricaria discoidea	22	12	15

[a] Not observed.

Table 4
Ranking of weed species in Danish spring barley fields based on surveys done in 1967–70, 1987–89 and 2001–04, respectively (from Andreasen et al., 1996; Andreasen and Stryhn, 2008).

Weed species	1967–70	1987–89	2001–04
Viola arvensis	7	5	1
Poa annua	6	2	2
Stellaria media	1	1	3
Fallopia convolvulus	5	4	4
Capsella bursa-pastoris	15	11	5
Chenopodium album	3	3	6
Polygonum aviculare	4	7	7
Veronica persica	9	9	8
Triplerospermun inodorum	16	14	9
Myosotis arvensis	20	6	10
Persicaria maculosa	11	8	11
Veronica arvensis	18	12	12
Lamium hybridum	39	15	13
Elytrigia repens	13	17	14
Persicaria lapathifolia	39	10	15

Table 5
Changes in the ranks of weed species over the decades based on their dominance in winter cereal fields in Hungary (Novák et al., 2012).

Weed species	1947–53	1969–71	1987–88	1996–97	2007–08
Tripleurospermum inodorum	44	15	1	1	1
Ambrosia artemisiifolia	20	9	4	4	2
Apera spica-venti	37	22	6	7	3
Cirsium arvense	2	3	10	2	4
Galium aparine	103	29	3	3	5
Convolvulus arvensis	1	2	2	6	6
Consolida regalis	9	13	22	14	7
Papaver rhoeas	12	8	7	8	8
Elytrigia repens	22	12	18	13	9
Fallopia convolvulus	7	1	11	10	10
Stellaria media	63	16	9	11	11
Chenopodium album	10	5	5	5	12
Viola arvensis	40	18	15	22	13
Capsella bursa-pastoris	56	42	14	19	14
Polygonum aviculare	4	10	29	17	15

Table 6
Changes in the ranks of weed species over the decades based on their dominance in maize fields in Hungary (late summer results) (Novák et al., 2012).

Weed species	1947–53	1969–71	1987–88	1996–97	2007–08
Ambrosia artemisiifolia	18	6	4	1	1
Echinochloa crus -galli	7	1	1	2	2
Chenopodium album	3	4	3	4	3
Setaria pumila	5	2	6	12	4
Amaranthus retroflexus	13	5	2	3	5
Cirsium arvense	2	7	10	8	6
Datura stramonium	107	38	12	5	7
Panicum miliaceum	119	121	15	10	8
Amaranthus powellii	62	10	7	7	9
Convolvulus arvensis	1	3	5	6	10
Sorghum halepense		55	11	9	11
Persicaria lapathifolia	20	15	8	13	12
Elytrigia repens	32	17	18	14	13
Hibiscus trionum	16	8	9	15	14
Abutilon theophrasti		285	40	16	15

aparine L. are the most critical weeds in winter wheat. The three most important weeds in maize are *Echinochloa crus-galli* (L.) P. Beauv., *A. artemisiifolia* and *C. album*. A rapid expansion of several annual grass weeds such as *Setaria pumila* (Poir.) Schult., *Setaria viridis* (L.) P. Beauv., *Panicum miliaceum* L. and *Digitaria sanguinalis* (L.) Scop. was observed in maize. Besides *A. artemisiifolia*, the results of the surveys confirmed the rapid spread of some other invasive alien weed species: *Abutilon theophrasti* Medik., *Asclepias syriaca* L. and newly *Cyperus esculentus* L. var. *leptostachyus* Boeck. in Hungary. A high increase of perennial weeds was recorded in surveys conducted in Greek cotton during two different sampling periods (1995–1997 and 2007–2009) in 118 cotton fields in Central Greece (Economou et al., 2005, 2010). During the first survey (1995–97), 15 weed species were recorded belonging to 11 botanical families while in the second survey (2007–09) 17 weed species were recorded belonging to 9 botanical families. In general, the rank of the main weeds, estimated by their frequency and density, varied widely within the two surveyed periods. Particularly, the most important weeds during the first sampling period in diminished rank were *Solanum nigrum* L., *Chrozophora tinctoria* (L.) A. Juss., *Convolvulus arvensis* L., *Cyperus rotundus* L., *Xanthium strumarium* L. and *Cynodon dactylon* (L.) Pers. whereas, in the second sampling period the order of species according to rank was: *C. rotundus*, *C. arvensis*, *C. dactylon*, *S. nigrum* and *Portulaca oleracea* L. *C. rotundus* populations increased remarkably between the two periods while the number of annual weeds declined.

Changed agricultural practices associated with a new land ownership structure have been primary factors influencing the composition of weed floras in Latvia (Vanaga, 2011). Survey results have been available since 1947. *V. arvensis* has been a dominant species over the decades. *T. inodorum* and *S. media* have become more frequent later.

A comprehensive weed survey in Germany describes the composition of weed floras in oilseed rape, *Brassica napus* L. (Goerke et al., 2008; Hanzlik and Gerowitt, 2012). Data were collected in 2005–2007 from 1364 winter oilseed rape fields in 12 federal states. Regional differences in weed densities were recorded for example for *Capsella bursa-pastoris* (L.) Medik, *C. album*, *G. aparine*, *Lamium* sp., *Matricaria* sp., *S. media* and *V. arvensis*. Both, non-inversion tillage and early sowing enhanced the species richness but did not affect the level of weed infestation.

Likewise, regional and repeated investigations on the long-term changes (1968–2005) in weed floras were carried out on the Sussex Downs in England (Potts et al., 2010). The abundance of 214 weed species was observed. Over years, 16 weed species had been lost and 15 gained to the area. Perennial dicotyledons showed an increasing trend due to the loss of traditional leys. The New Atlas of the British Irish Flora, edited by Preston et al. (2002) provides maps with species distributions as a result of multi-year surveys.

Results from long-term surveys in France were published in a number of papers (e.g., Fried et al., 2008, 2012). The comparison of weed frequencies between 1973 and 2006 revealed for example that in winter wheat 19 species decreased in frequency, four did not show significant frequency differences and 16 increased in frequency. *G. aparine*, *V. arvensis* and *P. annua* for instance belonged to those species which increased in frequency (Table 7). INRA (Institut National De La Recherche Agronomique) used to provide the direct access to online weed maps for several European countries in the past. This service is now indirectly available via http://www2.dijon.inra.fr/hyppa/hyppa-f/noms_sc.htm#S.

Weeds in winter cereal fields were studied in north-western Spain in the mid-2000s with a reference dating back to 1976 (Cirujeda, 2011). *Papaver rhoeas* L., *Lolium rigidum* Gaudin, *Avena sterilis* L. and *C. arvensis* were the main species out of the 175 species recorded. A striking increase of grass weeds, a substantial decrease in the number of weed species found per field and a lower frequency of many weed species were the main trends.

2.8. Factors influencing weed species composition

Weed species composition on arable land is influenced by several management and environmental factors, and there have been numerous studies which tried to assess and rank the influences of such factors. Hüppe and Hofmeister (1990) primarily classify the weed vegetation of

Table 7
Changes in the ranks of weed species over the decades based on frequency ranks in winter wheat of France (Fried et al., 2012).

Weed species	1973–76	2003–06
Galium aparine	8	1
Veronica hederifolia	2	2
Stellaria media	3	3
Viola arvensis	11	4
Senecio vulgaris	>32	5
Alopecurus myosuroides	1	6
Veronica persica	5	7
Poa annua	13	8
Tripleurospermun inodorum	6	9
Papaver rhoeas	4	10
Lolium spp.	15	11
Polygonum aviculare	7	12
Sinapis arvensis	14	13
Fumaria officinalis	17	14
Capsella bursa-pastoris	21	15

arable fields on the basis of soil acidity. Altitude and related climatic factors are the most important variables according to Lososová et al. (2004), while Šilc et al. (2009) found that a phytogeographical region is a major factor determining the composition of arable weed species. On the other side, recent European studies suggest that human management factors are more important than environmental ones with crop type, crop cover, preceding crop, fertilizers and herbicides being the main determinants of weed vegetation (Andreasen and Skovgaard, 2009; Cimalová and Lososová, 2009; Fried et al., 2008; Hanzlik and Gerowitt, 2011; Pinke et al., 2011, 2014). Growing conditions in the headland often differ from the rest of the field due to compact soil caused by heavy traffic and plant invasions from field margins. This means that the site context can also influence the weed species composition (Pinke et al., 2012). Several studies showed that many weed species are usually restricted to the outermost few metres of the fields resulting in substantial weed diversity in the field edges (Wilson and Aebischer, 1995; Fried et al., 2009a). The effect of surrounding landscape can also influence the weed communities of arable fields. Many studies demonstrated that at local scale weed diversity within cultivated fields was higher at local scale when the surrounding landscape was more heterogeneous (Gaba et al., 2010; Guerrero et al., 2010; José-María et al., 2011). Complex landscapes generally offer more diverse non-crop habitats likely to shelter rare weed species (Roschewitz et al., 2005; Gabriel et al., 2005; Fried et al., 2008).

2.9. Biodiversity changes in arable fields

Weed communities are in constant flux and changes in agricultural practice have and will continue to modify weed floras (Froud-Williams, 1988; Cousens and Mortimer, 1995). Farming practices have become increasingly intensive (from the post-war period to nowadays) leading to a reduction in diversity at the field scale, as well as at the landscape scale (Roschewitz et al., 2005). The diversity of species within an ecosystem has intrigued scientists for a long time. Diversity is defined by the number of species in an ecosystem and their proportional abundance (Magurran, 1988; Walker, 1989). Weed species are, however, distributed unevenly and, consequently, diversity is not expected to be homogenous within a field. Also, Podani (2006) pointed out that diversity indices do not reflect structural aspects of communities, because the structures of communities are scale related. The intensification of agricultural practices (increased input per unit of land) often leads to weed communities with a low degree of weed biodiversity (José-Maria et al., 2010). Several arable plant species have become endangered in Europe and elsewhere for many reasons (Meyer et al., 2013; Nowak et al., 2014; Richner et al., 2015; Storkey et al., 2012.). According to Kolářová et al. (2013), some of the endangered species (e.g., *Centaurea cyanus* L. and *Adonis aestivalis* L.) are, however, reappearing again due to changes in ownership relations and associated changes in land management in the nineties of the last century.

The influence of herbicides on weed community structure and diversity is also an issue of major concern. The intensive use of herbicides continues and weed density and species numbers have declined in Canada (Leeson et al., 2005). It is, however, evident that despite continuous applications of efficient herbicides, the populations of a large number of species still poses problems to farmers who are forced to apply different kinds of weed control measures. While there is a tendency for most species to decrease in frequency of occurrence, some show local increases and few species, notably some winter annual species (e.g., *Veronica arvensis* L. and *V. arvensis* Murray), grass weeds (*Poa annua* L., *A. spica venti*) and nitrophilous species (*C. bursa-pastoris, Cirsium arvense* (L.) Scop, *G. aparine* L., *T. inodorum*) have been favoured (Andreasen and Stryhn, 2012).

2.10. Invasive weeds

Invasive weeds are plants that are introduced accidently or deliberately into a natural environment where they are not normally found, with serious negative consequences for their new environment. This definition is derived from that of the European Commission for invasive alien species (https://ec.europa.eu/environment/nature/invasivealien/index_en.htm). Surveying and mapping of invasive weeds is the objective of several European and global organisations. A few examples are DAISIE (Delivering Alien Invasive Species Inventories for Europe), IUCN (International Union for Conservation of Nature) and NOBANIS (North European and Baltic Network on Invasive Alien Species). CABI (formerly Commonwealth Agricultural Bureaux International) provides an Invasive Species Compendium on the internet (http://www.cabi.org/isc) with a large number of data and metadata. Invasive species are dynamically changing their range of occurrence. Repeated mapping can help to concentrate on preventive and direct management actions to specific areas and to quantify the speed of the species spread within a country. Invasive weeds are often mapped within individual countries by chance. This is also true for the description of the detailed distribution in smaller regions (Osca, 2013). The first detailed map of invasive and potentially invasive arable weeds in the Czech Republic was published in 1973 (Hejný et al., 1973). This compilation does not only contain quadrat maps, but also a detailed description of all known locations of their occurrence. Data obtained during the following years were summarised in a publication by Jehlík (1998). For Central Europe, maps were recently published for example with the analysis of selected invasive Asteraceae weed species (Follak et al., 2013) and *Abutilon theophrasti* Medik. (Follak et al., 2014). Based on these publications, regions with a higher risk of future invasions can be identified. If the present distribution of invasive species is well mapped, data can be used not only for the prediction of their future spread but also for modelling the impact of environmental factors such as climate changes on their distribution (Quin et al., 2014).

2.11. Mapping of herbicide resistant weeds

Herbicides are the most extensively used weed control measure, accounting for up to 50% of the global plant protection market (Massa et al., 2013). The high adaptability of weeds together with an over-reliance on herbicides, in particular those with a specific metabolic target, has resulted in the selection of herbicide-resistant weed populations at a large scale. Monitoring and early detection are critical steps in managing the invasion of herbicide resistant (HR) weeds. In this context, the availability of frequently updated maps (Mascanzoni et al., 2018) provides valuable information for a proper resistance mitigation management of farmers, advisors, national and local decision makers as well as the agrochemical industry.

In-field surveys have been used to detect the presence of HR weeds at various geographical scales ranging from a single field (Preston and Powles, 2002), or the fields surrounding a single HR seed source (Falk et al., 2005) up to country level (Panozzo et al., 2013, 2015a, b). Structured random or partially random surveys are generally used in relatively small (Menchari et al., 2006) and/or relatively large but homogeneous areas (not common in Europe, most used in the USA or Australia, see for example Owen et al., 2014). Surveys based on reported herbicide failures (also called complaint monitoring) are common and the aim is only to confirm the presence of resistance in sampled fields. Though important to detect new herbicide resistant cases, this approach does not allow the estimation of the frequency of resistant (R) individuals at field level nor the real distribution of resistance in a given area.

Resistance maps have been developed at different scales. The only maps at a global and continental scale are available on the website of the International Survey of Herbicide Resistant Weeds. These maps are based on reported numbers of resistant biotypes per country or State or according to the herbicide site of action (SoA, Heap, 2014). The project is funded by the Global Herbicide Resistance Action Committee (HRAC) and CropLife International and the main aim is to maintain scientific accuracy in the reporting of HR weeds globally. Inputs and updates depend on researchers or users. They are checked by the director. Before a new resistant biotype is listed on the website, it must fulfil several criteria (Heap, 2005). The outputs are maps of "unique cases" (i.e. unique species per SoA considering also the resistance mechanism).

Examples of medium and small-scale mapping in Europe are sporadic in the literature. They deal with limited areas or only with specific weed species at a given time. Most maps are not regularly updated and made publicly available. Massa et al. (2013) recently developed a geo-referenced database (Weedscout 2.0) in which the distribution of herbicide-resistant populations of *A. spica-venti* is mapped at a European level. The survey is based on farmers' complaints and includes data from Germany, Poland and the Czech Republic. Resistance was tested in a greenhouse through whole-plant experiments that included several herbicides with different SoA (ALS-, ACCase- and PSII- inhibitors). Samples are divided into two categories, resistant (R) and not resistant (not-R), and these two categories were used to label data from different samples.

Another approach, based on the identification of the seven mutations within the gene encoding the plastidic ACCase (acetyl-CoA carboxylase) was presented by Menchari et al. (2006) and Chauvel et al. (2006). They studied herbicide resistant *A. myosuroides* populations in France. Two surveys were carried out either by complaint monitoring or by random at a national and regional level, respectively. Maps of the geographical distribution of the seven point-mutations across France were produced. Instead, Bayer Crop Science collected more than 2500 weed populations from fields in France, Germany and Great Britain, where herbicide performance was lower than expected and reported the geographical distribution of resistance to ACCase inhibitors indicating the predominant resistance mechanisms (target-site and not-target-site based) (Ruiz-Santaella and laber, 2011).

A recent example of mapping tools is iMAR (interactive MApping of Resistance), an innovative web-based application for mapping herbicide resistance at a national scale in Italy (Panozzo et al., 2013, 2015 a and b). The aim of the database, containing more than 2000 resistance cases and the linked web application, is not to determine the spatial frequency of HR biotypes but to identify the areas affected. It does not provide quantitative but only qualitative information. iMAR is entirely based on open-source software tools and is freely accessible on the website of the Italian herbicide resistance working group (Gire, 2014), where an English version is also available. Fig. 6 shows a characteristic map for the distribution of resistant *Echinochloa* species in Italy. This interactive mapping system allows an automatic and easy updating of the maps whenever new cases are added to the database. National and regional decision makers are frequently using the maps generated by iMAR to make informed decisions on agro-environmental measures and integrated weed management regulations.

3. Discussion

When creating maps, we visualise numeric results in the form of a graphic representation. The documentation of weed surveys in the form of maps usually triggers questions, especially when recognizing characteristic visual patterns. We ask ourselves immediately if local climatic and soil conditions or if regional cropping traditions have led to characteristic weed distribution patterns. Systematic mapping often creates

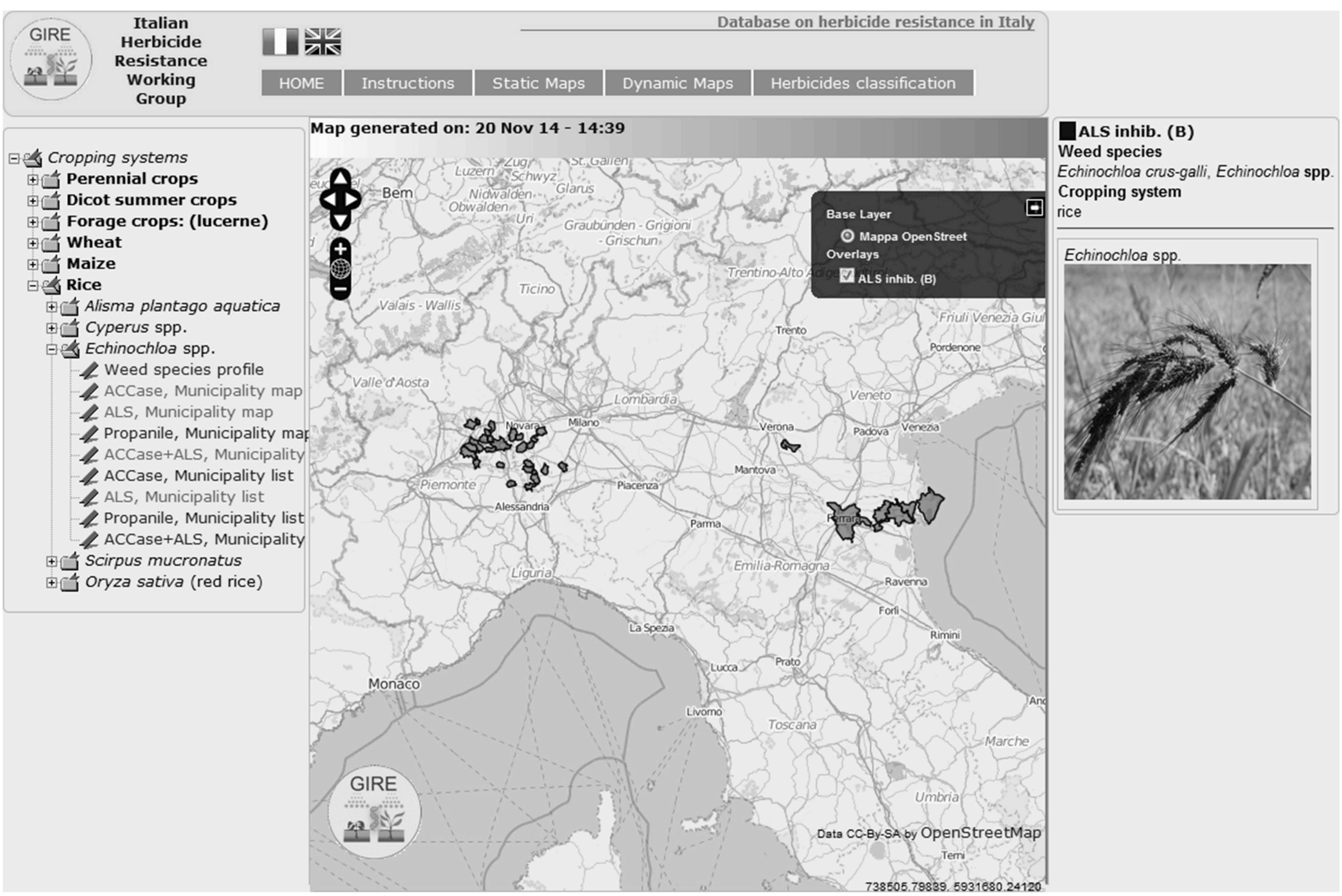

Fig. 6. Example of a resistance map of the iMAR "static" system: cases of Echinochloa spp. resistant to ALS inhibitors in paddy rice. On the left the tree menu for choosing features. The description of the map based on the selection is visualized on the right. Municipalities where at least one case of resistance has been reported are highlighted by the system.

evidence for broad research questions in different disciplines (Randall and James, 2012). We must be aware of the fact, however, that many maps are the result of extrapolations. Maps that encompass large areas show average weed infestations or generalisations and do not reproduce different details as they exist in reality. Fig. 7 for example shows volunteer cereals (primarily barley, *Hordeum vulgare* L., and wheat, *Triticum aestivum* L.) and *Elytrigia repens* (L.) Gould as the most common weeds in oilseed rape in Europe. This map does, however, not provide information on local infestation levels.

Scale, in general, plays a significant role when mapping weeds. Scientists are often tempted to use a few findings for the generalisation of statements on weed distributions over large areas. A general aspect which may end up in entirely different results is the assessment timing. Some colleagues assess their plots before harvest. At this time, usually not many weeds are left in conventionally cropped fields often because herbicides are efficient control tools and do not leave many individuals after application. On the other hand, weeds may disappear during the season due to other management tools or natural reasons such as drought, diseases or pests. This means that one assessment only at the end of the season does not reflect the actual biodiversity scenario nor does it allow conclusions on factors influencing the biodiversity scenario. An alternative is to perform at least two weed surveys, one at the beginning of the growing season (before post-emergence herbicide sprays) and a second at the end of the season (after all weeding operations) making an analysis of changes in weed densities possible throughout the cropping season (Fried et al., 2015). Weeds are usually controlled chemically or mechanically in farmer fields without untreated strips or untreated plots as in experimental fields. Untreated plots show us the original infestation of a field and allow us conclusions about the actual effect of weed management measures. This is not possible with just one pre-harvest assessment in farmer fields.

Methods employed in weed surveys differ from country to country (Table 8).

The results presented in Tables 2–6 show that weed spectra change

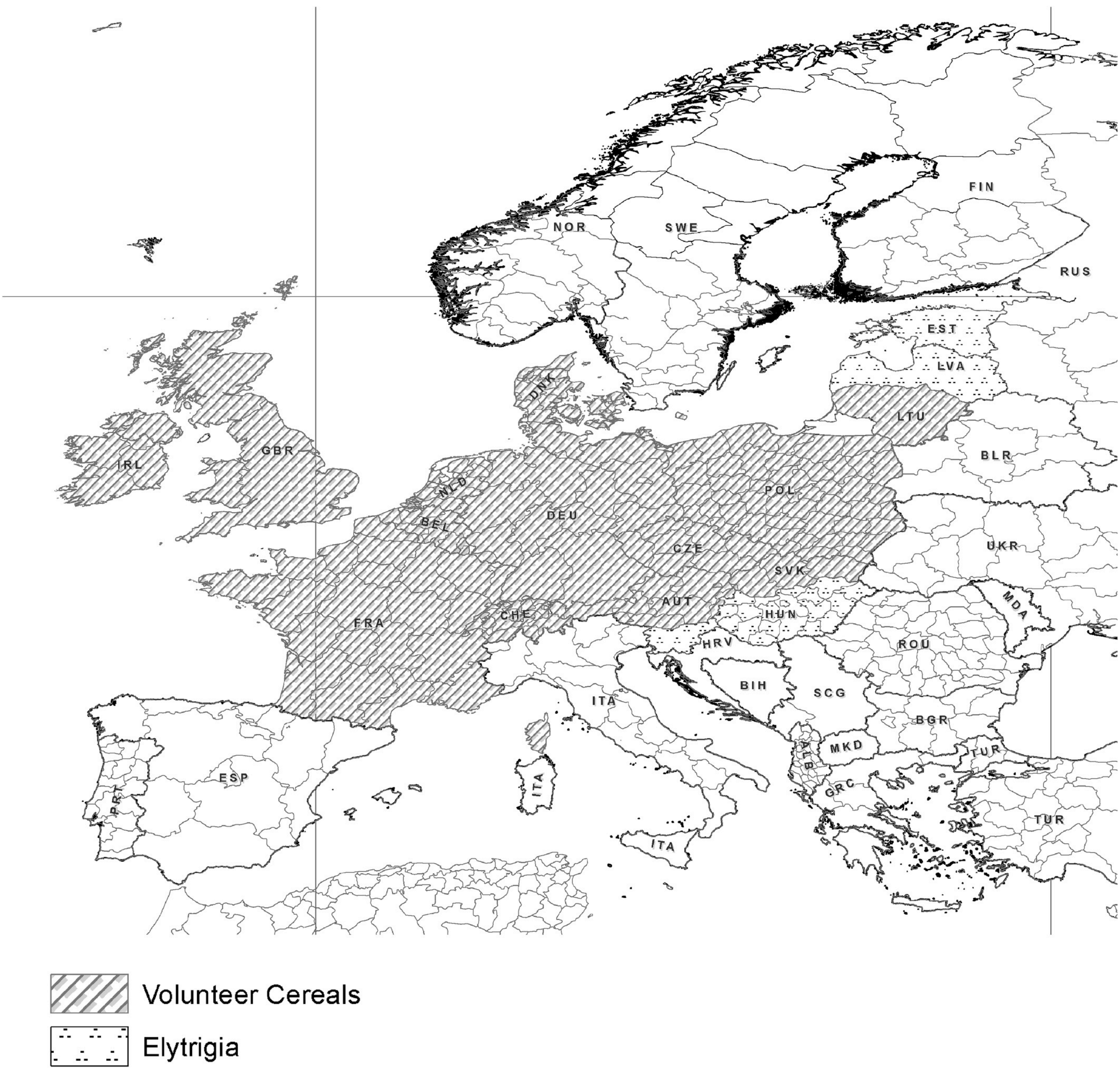

Fig. 7. Distribution of the most common grass weeds of oilseed rape in Europe.

Table 8
Comparison of methods employed in field surveys of different countries.

Country	Methods/Parameters	Documents	Span of surveys	Crops	Comparability
CZ	Braun-Blanquet cover-abundance scale, Domin scale	Tables, Maps, Ordination diagrams, WeedMap[a]	1955–2015 (parallel data collection of independent research teams)	Major crops	Ranks of dominance
DK	Raunkiær analysis; presence/absence of species in 10–20 circles of 0.1 m^2)	Tables	1911–1915, 1945, 1960–1970, 1987–1989 and 2001–2004	Major crops	Changes of frequencies
FI	Frequency (within each region)	Tables, WeedMap[a]	1962–64 1982–84 1997–99 2007–09	Spring cereals	Ranks of dominance
	Density (within each field)	Tables, WeedMap[a] (modified as cover)	1962–64 1982–84 1997–99 2007–09	Spring cereals	Ranks of dominance
	Biomass (within each field)	Tables	1962–64 1982–84 1997–99 2007–09	Spring cereals	Ranks of dominance
FR	Density on 2000m^2 plots	Tables	1973–1976 2002–2010	Major annual crops	Ranks based on frequency of occurrence
HU	Ujvárosi scale	Choropleth maps	1947–2015	Major crops	Ranks of dominance
LV	Occurrence of species recorded as prevalence percentage	Tables	1947	Winter cereals	Ranks of dominance
	Plant densities (plants/m^2)	Tables	1972–1979	major crops	Density changes
	Occurrence species recorded as frequency percentage	Tables	1980–1982, 1994–1999, 1999–2002; 2013–2015	major crops	Changes of frequencies

[a] www.weedmap.eu.

continuously over time. Only long-term surveys allow, however, conclusions on clear trends such as the Danish, Finnish, French and the Hungarian surveys demonstrate. Some trends such as increases of *V. arvensis*, *P. annua* (Denmark, France), *G. aparine* (France, Hungary) or C. *bursa-pastoris* (all 3 countries) to a lesser degree, are very consistent across winter cereals of different countries. Such changes in frequency of common weeds may reveal similar changes in agricultural practices taking place at large-scale. A comparison based on specific taxa is however strongly limited by the differences in the regional pool of species. It is evident that some weed species grow preferably in northern European countries such as *Poa annua, Viola arvensis* or *Stellaria media* whereas others prefer the warm climates of the Mediterranean area such as *Cynodon dactylon* or *Xanthium* species. One way to detect trends at a European scale would be to use weed traits and to gather species in plant functional response groups (Fried et al., 2009b). In this case, even if species differ between countries, similar trends would be expected for species belonging to the same functional group and the detection of the underlying agronomic causes would become easier. Some weed spectra depend on cropping regimes. Weed spectra of winter crops differ from those in spring crops. Biodiversity is therefore strongly related to cropping systems as described by different authors (e.g., Robinson and Sutherland, 2002; Storkey et al., 2012; Fried et al., 2012). Modern agriculture seems to favour nitrophilous species in principle (Fried et al., 2009a).

Automated weed detection by sensors and computer algorithms has achieved a high technological level. Unfortunately, most of these systems take pictures from above the canopy and often miss essential information. Growth stages of weeds are often hard to determine for example. Plant shape changes during development which results in an enormous effort to teach the systems. The resolution of pictures is often not good enough to detect tiny characteristics such as hairs, ligule shape and size needed by a botanist to distinguish species. Also, weeds growing below the crop canopy or below taller weeds lead us to the conclusion that this technology will not provide the same information classical phytosociological tools guarantee. We may, however, use this technology for other purposes than those in plant community research. Large-scale information on dominating weeds or special weeds may be gained faster and easier. Automated devices also produce data which can be used for targeted weed control in precision agriculture.

4. Conclusions

Highly advanced software allows the documentation of spatial weed patterns in the form of maps. A large number of options enable us today to depict and to document spatial and temporal weed distribution in different forms. Statistical analysis tools linked to spatial information can provide insight on weed composition influencing parameters such as soil type, climate and weed management. The synoptic demonstration of weed survey results from different countries is an ideal tool to demonstrate distribution gradients of weeds within Europe. Spreading of weed resistance can also be monitored with weed mapping tools as shown for example by Italian mapping approaches. An open issue is the comparability of data produced with different methods. So far, frequency ranking provides the only tool to show similarities or differences in trends.

The above-mentioned points led to the following mid and long-term objectives and planned activities of the EWRS Weed Mapping Working Group:

- Specifically designed field trials at different sites in Europe with different evaluation methods for a comparability evaluation
- Analysis of existing European data sets on weed spectra in selected crops and correlation of results with weed management tools
- Improvement of existing maps for the most frequent weeds as displayed on the EWRS Weed Mapping Working Group website (http://www.ewrs.org/weedmapping/) and in the Atlas of Weed Mapping (Kraehmer, 2016)
- Standardisation and expansion of weed resistance maps as published for example by Mascanzoni et al., (2018).
- Comparison of existing survey results with data predicted by species distribution and habitat suitability models
- Development of European maps for rare weeds
- Demonstration of weed mapping working tools in summer schools for students

The coordination of common efforts on these activities should yield more coherent and comparable information on weed distribution in Europe which, in turn, will favour the implementation of integrated weed management approaches.

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