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REVIEW ARTICLE

Methods to conduct and analyse weed surveys in arable farming: a review

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Abstract Arable weeds always accompany arable farming; however, species and abundances vary in space and change in time. Surveys assess weeds on a large spatial scale. The regional and national importance, the abundances in which weeds occur, is derived from surveys. Environmental and management background data assist to explain the weed vegetation. Arable weed surveys can have an agronomic, a botanical or an ecological purpose—we approach the agronomic viewpoint. Scientific value results from spatial data about the arable weed vegetation for modelling the dependencies and predicting future changes on a large scale. Researchers, botanists, farmers, advisors, herbicide manufacturers and other industry players engaged in weed control can get rationale spatial impressions of trends in the weed vegetation. This review focuses on methical aspects of weed surveys. Forty-three surveys on farmed fields, mainly but not exclusively undertaken in Europe, done in up to nine crops per survey covering periods of 1 to 67 years and including 59 to 4423 fields were excerpted for suitable methods to conduct and analyse surveys. The methods reflect agronomic and other targets, e.g. from vegetation science. When accessing existing data, the interdependencies of the layout and all targets should be handled with care. When setting up surveys for agronomic purpose, it is worthwhile to include 3 years and apply stratified sampling. We recommend assessing abundances rather than presence only. Weed survey data is most suitable for applying multivariate statistics. We recommend using proven methods, without discouraging to explore others. To collect sound explanatory data demands for robust contacts with land managers. Explanatory variables are important in survey analyses to extract knowledge about the drivers of the weed vegetation. We conclude that extra value can be obtained from existing weed survey data. We propose to setup public–private partnerships as a way to carry on with arable weed surveys.

Keywords Arable weed vegetation · Abundance · Cover · Diversity · Sampling · Multivariate statistics · Europe · Monitoring · Mapping

Content

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Fig. 1 Weed species adapted to oilseed rape (*Anchusa arvensis*)

1 Introduction

Arable land use with mainly annual, occasionally perennial crops is always accompanied by arable weeds—spontaneously emerging plants, mostly annual, some perennial species adapted to arable conditions. While weeds in general are omnipresent under arable use, occurrences and abundances of species differ in space and change in time. Though weeds are indispensable parts of arable systems, farmers take much effort to control them in order to ensure long-term yield quantity and quality, regardless of the type of cropping systems. Weeds are the only spontaneous contribution of arable sites to plant diversity that makes their nature even more double-sided, as they also ensure ecosystem services (Médiène et al. 2011) or are themselves targets of conservation (Meyer et al. 2013).

Surveys or monitoring programmes assess organisms on a large spatial scale—for arable weeds concentrating on arable fields as habitat. The weed vegetation in arable systems of the old world has developed over centuries and thereby supported own and unique multi-species plant communities (Holzner and Immonen 1982). Hence, weed surveys in these arable systems evolved over centuries always delve into a multitude of species, the diversity and the communities they build. This task of arable weed surveys is different from environmental weed surveys as reported by Barnet et al. (2007), which focus single invasive species.

The local, regional and national importance of weed species and the assemblages they perform can be derived from survey data. Processed and aggregated with suitable statistical methods, survey data is helpful to explain why weed species occur and in which assemblages (Fig. 1). Information of weed surveys is valuable for farmers, advisors, herbicide industries and other industries engaged in weed control techniques in order to get reasonable spatial impressions of trends in the current weed vegetation. In research, weed survey data is required for any attempt to model or predict future changes of the arable weed vegetation on a large scale.

Traditionally, arable weed surveys were an action field for vegetation botanists; in Central Europe specifically, the discipline of plant sociology was developed. Extensive collections of relevés from arable land mainly served to systematically describe and examine the vegetation and thus provided the basis for various phytosociological approaches (Braun-Blanquet 1964; Holzner and Immonen 1982; Hüppe and Hofmeister 1990; Glemnitz et al. 2000).

During the last decade, organised large-scale surveys received increasing interest because of their wide scope of application. This includes the integration of weed surveys into national monitoring programmes to assess the overall effect of intensified and/or changed agricultural practice on farmland biodiversity (Lutman et al. 2009; Andreasen et al. 1996; Salonen et al. 2001). Provided that such surveys are repeated or data are collected continuously over a longer period of time, they can be used to quantify changes in species diversity and abundance (Andreasen and Stryhn 2008; Hyvönen et al. 2003; Potts et al. 2010; Lososová et al. 2004). Due to the large areas they cover, they are also suited to reveal regional differences in weed diversity (Šilc et al. 2009; Šilc 2008; Lososová et al. 2004) as well as the related factors determining the occurrence of rare and valuable species (Fried et al. 2010; Hanzlik and Gerowitt 2011).

In general, the role of 'weeds' for production, habitat and conservation strongly depends on which species and how much individuals of them are present. Targets of surveys differ with respect to these general roles, they can be more agronomic, more botanical or more ecological. To detect rare species, other methods than describing the habitat quality ensured by arable weeds are demanded. Connecting weed data with agronomic purposes requires at least that common production conditions are covered by the surveyed sites. The overall purpose also influences how the arable weed vegetation is assessed and described: the presence of species determines the weed diversity, how these occur together is reflected in weed communities, while weed abundances tell about the dimensions in which weeds occur.

In large-scale surveys, the targets have implications for both the setup of the survey and the analyses of the data. Moreover, the available resources are of pronounced impact. Although this is true for almost all practical scientific setups, the large scale of arable surveys together with a short annual time frame for observations is challenging and hence influencing the applied methods.

This review focuses on weed surveys from an agronomic viewpoint. Agronomy is served by relating a range of site conditions and cropping measures to weed diversity and species composition (Andersson and Milberg 1998; Lososová et al. 2004; Fried et al. 2008; Šilc et al. 2009) or by providing valuable knowledge of weed species occurrences and their prospering under different conditions (Frick and Thomas 1992; McCloskey et al. 1996). From an agronomic viewpoint, weed surveys are interesting as they can perform as complement to field experiments. Due to the known spatial variation in the weed vegetation, point estimates from field experiments can lead to inconsistent results due to site effects (Derksen et al. 1993; Milberg et al. 2001). The results of a large number of different sites enable to assess these effects in a more realistic way (Andersson and Milberg 1998; Hallgren et al. 1999; Gunton et al. 2011) and thereby assist in any implementation of the experimental outcome. Such observational or 'on-farm' research proved eligible for the exploration of complex problems like the assessment of farming systems differing in cropping histories, chemical input level and tillage operations with respect to their impact on weed communities (Leeson et al. 1999, 2000).

Arable weed surveys help agronomists to characterise the weed flora typical of specific cropping practices (Leeson et al. 2000; Poggio et al. 2004; Hawes et al. 2010), regions (Kuzniewski 1975; Frick and Thomas 1992; Goerke et al. 2008; Novák et al. 2009) or site conditions (Hallgren 1996; Firbank et al. 1998; Andreasen and Skovgaard 2009). They further serve to detect regional changes in weed species composition and to statistically confirm field observations and expert knowledge on species spreading due to changes in agricultural practice and/or climate (Andreasen and Stryhn 2008; Fried et al. 2009; Lutman et al. 2009). Finally, they can be used to derive predictions for potential weed shifts and expected weed problems (Mehrtens et al. 2005; Firbank et al. 1998; Pinke et al. 2011; Peters et al. 2014).

Regarding the large quantity of information on species responses, species-environment and species-management relations, weed surveys can serve as a tool for the development and improvement of strategies for a sustainable, long-term weed control and the maintenance or even creation of biodiversity in arable land (Derksen 1996). Biodiversity is linked to weed diversity and abundances at different spatial (Firbank et al. 1998; Fried et al. 2008) and temporal scales (Hallgren et al. 1999; Lososová et al. 2004; Májeková et al. 2010).

Sparse and diverse arable weed vegetation can provide a wide range of ecosystem services, including the conservation of soil and water resources and supplying habitats to harmless and beneficial organisms (Médiène et al. 2011). Thus, manipulating weed species composition into a desirable and manageable direction is a basic principle of integrated weed management. For the protection of arable biodiversity and rare plant species, management at various scales appears to be important (Gabriel et al. 2006).

The arable weed vegetation is increasingly regarded and investigated in a landscape context (Petit et al. 2013; Gaba et al. 2010). We here distinguish between 'large-scale' and 'landscape' studies. While the first concentrates exclusively on arable fields, the second takes care of all vegetation elements in a landscape segment, including arable fields. This review is limited to large-scale studies. Obviously, landscape-oriented studies can profit from data of arable weed surveys (Petit et al. 2011).

This review provides an overview about methods used to conduct and analyse weed surveys in an agronomic context. Our goal is to offer ideas and inspiration to weed scientists. We selected surveys and summarise them concerning the general organisation (Section 2: Reviewed surveys—sites, crops and time aspects). Surveying vegetation has a long tradition. Thus, it is not surprising that there are many different methodical approaches. We describe the collection of field data in arable weed surveys (Section 3: Recording field vegetation data). The objective of this article is neither to explain sampling theory nor to give a comprehensive description of sampling methods as done, e.g. by Hayek and Buzas (1997) or Henderson (2003). We briefly discuss pros and cons of sampling techniques and protocols.

Another pronounced aim of this review is to stimulate statistical analyses of survey data which provide aggregated, interpretable results beyond species lists in order to derive more information and support publishing of the results. We therefore describe a variety of mostly multivariate statistical approaches which proved useful for the analysis of large sets of vegetation data in various surveys (see Section 4). This is done elementarily, in order to inspire weed scientists with ideas about analysing weed survey data. Authors more experienced in these techniques provide further help with various books and papers (e.g. Legendre and Legendre 2008; McCune and Grace 2002).

Finally, we summarise some general results of the reviewed surveys (see Section 5). With this section, we attempt to offer examples and applications for surveys and their analyses and thus raise the interest of weed scientists, agronomists and agricultural botanists in these.

2 Reviewed surveys—crops, time, site and field aspects

2.1 Selection of surveys

We searched for large-scale arable weed surveys with a distinct agronomical purpose. This purpose is either directly announced as goal or is indicated by analysing explaining variables from arable farming practice. The term 'large scale' is not scientifically defined; we approximated a minimum of 50 sites and a state- or nation-wide distribution of the sites. We screened scientific sources on large-scale surveys; the majority from Europe, but we did not neglect comparable published approaches in other parts of the world. We filtered for surveys on practically farmed fields and excluded surveys which are based on experimental sites. Moreover, we neglected surveys with an exclusive focus on rare and endangered species. Sequentially repeated surveys with this focus are analysed in a review reporting species losses in time (Richner et al. 2015).

Our aim was to rest the review upon different survey examples in terms of geography and applied methods. In some papers, agronomic purposes are linked with targets of vegetation sciences, pronounced in, e.g. Hidalgo et al. (1990), Sutcliffe and Kay (2000), Lososová et al. (2004, 2006b), Pinke and Pál (2008), Šilc et al. (2008) and Májeková et al. (2010). Those were filtered for interesting applications of different methods in both conducting and analysing weed surveys. We collected 43 surveys, from which setup and results have been published at least once. Table 1 informs about crops, time and space aspects, recording vegetation and explanatory variables and the analysing approach. The same survey data is sometimes used in several papers. While all the papers we found are considered in the text, we tried to limit Table 1 to the underlying surveys.

2.2 Crops surveyed

Surveys under arable conditions can focus one or few crops but can also intend to compare a number of them. The surveys in Table 1 include up to nine crops, the majority concentrates on one to three crops, nine on one and 11 on three crops. Regarding the crops included, cereals are part of most weed surveys (35); however, various other crops are focused, like oilseed rape (22, Fig. 2), maize (19), beets (17), potatoes (12), peas/beans (8), sunflowers (5) or soybeans (3). Gras ley crops were present in eight surveys and 11 took place on the stubble after harvest. The crops included in a survey strongly determine the sampling season. The number of crops is relevant for the appropriate statistical analyses.

The crop actually grown on the sampled field turned out to be the strongest management filter in many studies (Cimalová and Lososová 2009; Fried et al. 2008; Šilc et al. 2008; Pinke et al. 2012; Poggio et al. 2013). Consequently, it may be advantageous to limit sampling to fields of a certain crop whenever the variation of weed vegetation due to factor 'crop' may disguise other effects that are of major interest for the planned investigation. Whenever the weed diversity of a region should be surveyed and thus different crops are included, the analyses should take care of this effect.

2.3 Time scale aspects

We consider two time scale aspects: first the sequential years of surveying and second whether a survey is repeated after a period without information.

The studies summarised in this article rely on a wide range of years which was considered as the survey period. A minimum of 1 and a maximum of 67 years performed as the base for the survey. Four surveys rely on one season only; most frequently, a survey period of 3 years (9) was found. It seems advantageous to conduct a weed survey over at least two, better three seasons in order to take into account seasonal climatic differences which are known to considerably influence the occurrence of some weed species. We recommend this regardless of the numbers of crops involved in the survey.

Although weed surveys are highly valuable when they are repeated after a certain time span, we found only seven examples in our sample where an independently repeated survey was realised (Table 1). In those, the time span between the two surveys ranged from 17 to 47 years (last year to first year). Single surveys which can refer to another survey in the same region usually covered less sequentially surveyed years. Carrying out repeated surveys depends on long-term organised surveying activities and on access to the data of the previous period; this includes weed data but also explaining management variables (see Section 3.5).

2.4 Site or field numbers

While crop and time aspects are internationally equally understood, the term 'site' differs in the inherent aspects included. It can describe just a geographical unit or it can include selected soil, environmental and nutrient variables. In vegetation science, the concept of site conditions determining the vegetation has a long and successful tradition. Clustering and using site conditions to explain plant communities build the base for the concept of Ellenberg indicator values (EIV) (Ellenberg et al. 1992). Hence, 'site' in the sense of vegetation science can represent a comprehensive description. Modern arable management is known to strongly equalise site conditions (Meyer et al. 2013). 'Field' is the spatial unit that is managed in the same way by the same person taking the decisions. Hence, the term describes tenure conditions rather than site conditions. Nevertheless, from an agronomy point of view, a field is mostly handled as a site. Our screening of the 43 surveys did not indicate any rational use of the different possible meanings of

Table 1 Overview on 43 arable weed surveys

Country	Fields (net)	Sampling period	Sampling area per field/method	Season	Species data	Species traits	Herbicide	Crops	Dependent variable(s)	Environment	Site	Management	Statistics — Univariate	Statistics — Multivariate	Reference
Western Balkan Peninsula	2426	1939–2006	2–1000 m² square	summer ×	Abundance (Braun-Blanquet)			Cereals, Stubble, Maize, Oilseed, Beets, Potatoes, Grass leys, other ×	Mean EIV, species cover % (square-rooted)	Altitude, phytogeographic region	Season, year	Crop ("cereals" vs. "root crops")	GLM (net effects of continus v.), ANOVA (net effect of categorial v.), regression analysis, Whittaker's measure of β-diversity	DCA with post-hoc correlation of variables, pDCA (interpretable patterns beyond expl. v.), (p)CCA (gross / net effects, variation partitioning)	Silc et al. (2009)
Slovenia	482	1937–2004	NA	spring ×	Abundance (Braun-Blanquet)			Cereals, Maize, Beets, Potatoes ×	Species frequencies	Altitude	Season, year, mean EIV	Crop ("percentage of cereals" vs. "percentage of root crops")	Fidelity (phi (φ) coefficient)	Hierarchical clustering (Euclidean distance, Ward's method for linkage, TWINSPAN), PCA of clusters (with post-hoc correlation of EIV)	Silc et al. (2008)
Slovenia		1937–2004	NA	autumn ×	Abundance (Braun-Blanquet)			Cereals, Maize, Beets, Potatoes ×	Species cover % (sq.-rooted), species richness (residuals)	Altitude, phytogeographic region, climatic district, temperature, precipitation	Year	Crop ("cereals" vs. "root crops")	GLM (net effects of expl. v. on species richness), β-diversity (Sørensen dissimilarity)	DCA with post-hoc correlation of variables, (p)CCA (gross / net effects)	Silc (2008)
Great Britain	668	1971–1973	2 × 2 km (tetrad, Ordnance Survey National Grid lines)		p/a (rare spp.), abundance classes (3) (frequent spp.)		yes ×	Cereals, Stubble, Maize, Oilseed, Beets, Potatoes, Peas beans ×	Species frequencies				Species frequency		Chancellor (1977)
Great Britain	>700	1987–1988	2 × 2 km (tetrad)		p/a		yes ×	Cereals, Stubble, Maize, Oilseed, Beets, Potatoes, Peas beans ×	Species frequencies, p/a of species		Soil type		Spatial smoothing of distribution data, probability of species occurrence on soil groups, logistic regression		Firbank et al. (1998)
Central southern England	1021	1981–1982	Whole field	spring ×	Abundance classes (6 for grasses, 5 for dicot. weeds)		yes ×	Cereals ×	Species frequencies, (mean) score of abundance			Crop height, headland management	Descriptive statistics (ranking, distribution of frequencies and abundance scores)		Chancellor and Froud-Williams (1984)
Central southern England	156	1962–1964	10 – 50 m² square	×	Domin cover-abundance		yes ×	Cereals, Beets ×	Presence / absence, total species				Comparison of species frequency in both surveys (Wilcoxon's test), linear relationship between total number of species and rare species per site		Sutcliffe and Kay (2000)
	100	1997	5 × 10 m² square, whole field	×	Domin cover-abundance in quadrats, p/a for rest of field		yes, no ×	Cereals, Maize, Beets, Peas beans ×	species number, number of rare species						
Southern England	106 × 36	1970–2005	5 × 2 –10 m² squares	×	Abundance classes (6)	biol. (2)	yes ×	Cereals ×	Abundance, species number (total)		Year	Herbicide efficacy, farm management (3 rotation types)	GAM, GLM, ANOVA, relative change of % occurrence (ratio GAMfit2005 / GAMfit1970, t-test for significance ≠ 1)		Potts et al. (2010)
Scotland, Great Britain	112	2007	21 quadrats of 0.5 m² (3 transects with 7 sample points, each 10m apart)	×	Density (plants/ m²), 1.5l mixed soil to depth of 15 cm		yes, no ×	Cereals ×	Species densities (emerged/ seedbank), species composition p/a (emerged / seedbank)		Field size, margin width, soil properties (13)	Farm type, herbicide active ingredients, fertilisation (2), grass / winter crops in rotation, relative yield, management intensity indicator (PC1 scores)	Species diversity (S,H,E) at 3 spatial scales, species-accumulation curves, generalised linear regression (yield:weed density), generalised ANOVA (yield:farm types)	PCA (factors), Canonical Variates Analysis (CVA, species data).	Hawes et al. (2010)
Southern and central Finland	252	1982–1984	4 to 5 × 0.25 m²	×	Density (plants / m²), biomass (dry weight)		yes ×	Cereals ×	Species density, species dry weight (both log transformed)	Temperature, rainfall	Soil texture, soil moisture, soil pH	Crop cover, crop yield, rotation type, frequency of herbicide use	Descriptive statistics (frequencies of weed infestation classes, proportion of spp. of total weed density / biomass)	CA, (p)CCA (covariables: geographical regions), RDA – all for biomass AND density data	Salonen (1993)
Southern and central Finland	690	1997–1999	10 × 0.1 m² squares	×	Density (plants/ m²), biomass (dry weight), p/a in 1 m² around counting frame,		yes ×	Cereals ×	Species p/a, species number, total and spp. density / dry weight	Geographic region		Farm type (organic vs. conventional sprayed / unsprayed)	Hill's evenness index, rarefaction (expected species number of regions and farm types), descriptive statistics	Hierarchical clustering (Jaccard's similarity, average-linkage)	Salonen et al. (2001)
Southern Sweden	2700	1970–1990	2 × 0.25 m² squares	×	p/a, biomass (fresh weight)	biol. (life cycle)	yes ×	Cereals, Oilseed, Beets ×	Species p/a, species fresh weight		Soil texture, soil organic matter (SOM)	Crop	Frequency, contingency table analysis (two-way classification, chi²-test) for species occurrence on different soils	PCA, contingency table analysis	Hallgren (1996)
Southern Sweden	2672	1972–1992	2 × 0.25 m² squares	×	p/a, biomass (fresh weight)	biol. (life cycle)	yes ×	Cereals, Oilseed, Beets ×	Total fresh weight (square root transformed)	Temperature, rainfall, geographical region	soil type	Crop type (4)	Coefficient of variation (CV) (biomass),	PCCA (biomass data of spring- and autumn-sown crops separately), variation partitioning	Hallgren et al. (1999)

Table 1 (continued)

Country	Fields (net)	Sampling years	Sampling area per field / method	Season	Species data	Species traits	Herbicide	Crops	Dependent variable(s)	Environment	Site	Management	Univariate	Multivariate	Reference
France	694	2002–2004	2×2000 m² squares	Spring	Density classes (6) (Barralis 1976)		yes	Cereals, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Soybeans, Sunflower	Species densities	Temperature, rainfall, longitude, latitude, altitude, landscape type	Field topography, soil texture, soil pH	Crop, preceding crop, sowing date, tillage system, tillage depth	ANOVA (α-diversity), patterns of β-diversity	CCA, pCCA (gross / net effect of variables, complete data vs. nested subsets of samples)	Fried et al. (2008)
France	59 / 212	1973–1976, 2002–2006	2000 m² (40 × 50 m)	Spring	Density classes (6) (Barralis 1976)	biol. (10), EIV (5), others (2)		Cereals, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Soybeans, Sunflower, Other	Frequency of species traits, species / traits matrix	Temperature, rainfall, evapotranspiration, altitude	Soil texture, soil pH	Crop, preceding crop, sowing date, tillage system, tillage depth	Spearman's rank correlation test	Reciprocal scaling (RS), CCA, Outlying Mean Index analysis (OMI), InOVal, Species mean socio-ecological distances (Sophy)	Fried et al. (2010)
													Fisher's Exact Tests (trait attributes: increasing vs. decreasing spp. / between functional groups), changing status (mean frequency rank), one-way Anova (MCA axes scores), mean dissimilarity coefficient (functional groups / changing statuses), test for covariation with family / genus	Multiple Correspondence Analysis (MCA), Hierarchical clustering (Euclidian distances from MCA, Ward linkage algorithm), K-means clustering	Fried et al. (2009)
Central Southern Spain	201	1983–1984	5000 m² (each field twice)	Summer, Spring	Abundance classes (5), overall infestation index (scale 1–5)	biol. (Raunkiaer life forms)	yes, no	Cereals, Maize, Beets, Peas/beans, Sunflower, Other	Corrected species frequency, infestation index			Crop	Descriptive (maximum infestation index, mean infestation index, proportion of spp. life forms in each crop)	Hierarchical clustering (χ^2 distance, unweighted centroid clustering)	Hidalgo et al. (1990)
Central Southern Spain	231	1982–1984	2000 m² (each field twice)	Summer, Spring	Abundance classes (5)		yes, no	Cereals, Maize, Beets, Peas/beans, Sunflower, Other	Abundance index		Soil pH, soil texture, carbonate content, slope	Crop, irrigation (3)		Two way indicator species analysis (TWINSPAN)	Saavedra et al. (1990)
Denmark	491	2001–2004	20 × circles of 0.1m² (Raunkiaer 1934)	Spring	p/a (circles)		no	Cereals, Oilseed rape, Beets, Potatoes, Peas/beans, Other	Frequency classes (7)		Soil properties (7)		Beta-binomial regression analysis	Hierarchical clustering (Euclidean distance, complete linkage algorithm), CCA	Andreasen and Skovgaard (2009)
Denmark	213, 240	1987–1989, 2001–2004	10 × circles of 0.1m² (Raunkiaer 1934)	Spring	p/a (circles)		no	Cereals, Oilseed rape, Beets, Peas/beans, Other	Frequency classes (10)			Crop	Beta-binomial distribution, likelihood ratio (LR) test		Andreasen and Stryhn (2008)
Denmark	316	1987–1989	10× circles of 0.1m² (Raunkiaer 1934)	Spring	p/a (circles)		no	Cereals, Oilseed rape, Beets, Peas/beans	Frequency classes (10)		Year, soil properties (7)	Crop	Linear logistic regression analysis (backward selection, over-dispersion parameter)		Andreasen et al. (1991)
Denmark	139, 213	1967–1970, 1987–1989	10× circles of 0.1m² (Raunkiaer 1934)	Spring	p/a (circles)		no	Cereals, Oilseed rape, Beets, Peas/beans, Other	Frequency classes (10)			Crop	Linear logistic regression analysis (over-dispersion parameter)		Andreasen et al. (1996)
Czech Republic; Slovakia	2653	1954–2003	8 – 100 m² square	Summer	Abundance (Braun-Blanquet)			Cereals, Stubble, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Other	Cover % (square-rooted)	Altitude		Crop ("cereals" vs. "root crops")	Regression analyses, analysis of β-diversity (Sørensen dissimilarity)	DCA with post-hoc correlation of variables, pCCA (gross / net effect of variables), Hierarchical clustering (chord distance, beta-flexible clustering method)	Lososová et al. (2004)
Czech Republic	698	1955–2000	100 m² square	Summer	Abundance (Braun-Blanquet)			Cereals, Stubble, Maize, Oilseed rape, Beets, Potatoes, Peas/beans	Cover % (square-rooted)	Altitude, altitudinal floristic region	Season, year, soil type	Crop, crop height, crop cover	Species fidelity		Lososová et al. (2006a)
									Cover % (arcsin transformed)			Crop ("cereals" vs. "root crops")	General linear model (backward selection, net effects of variables)	Hierarchical clustering (chord distance, beta-flexible clustering method)	Pyšek et al. (2005)
Czech Republic	2033	1954–2004	12–100 m² square	Summer	p/a, frequency	biol. (8), EIV (6), distribution, phylogeny		Cereals, Stubble, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Other	Species traits	Altitudinal region		Crop ("cereals" vs. "root crops")	Regression tree analysis (species attributes / species abundance), multiple regressions (PCoA species scores / species regional abundance, for phylogeny)	Principal coordinates analysis (PCoA, phylogeny)	Lososová et al. (2008)
Czech Republic	2715	1954–2003	100 m² square	Summer	Abundance (Braun-Blanquet)	biol. (10), phylogeny (BiolFlor)		Cereals, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Other	Cover % (square-rooted)		Year, season	Habitat (arable field: cereals vs. root crops, settlement: village vs. town)	Regression analyses (logistic, linear least-square, multiple: species traits / pCCA, 1st axis species scores AND / OR cMDS species scores)	DCA with post-hoc correlation of variables, pCCA (net effect of habitat), classical Multidimensional Scaling (cMDS, effect of phylogeny)	Lososová et al. (2006b)
Moravia (Czech Republic)	174	2001–2003	20 m² square	Summer, Spring	Abundance (Braun-Blanquet)	biol. (immigration status)		Cereals, Maize, Other	Cover % (square-rooted)	Altitude, temperature	Soil type (FAO), soil pH, season	Crop ("cereals" vs. "root crops")		DCA with post-hoc correlation of variables and Ellenberg indicator values, (p)CCA (gross / net effects)	Cimalová and Lososová (2009)
Moravia (Czech Republic)	434	1997–2004	20 m² square	Summer, Spring	Abundance (Braun-Blanquet)			Cereals, Maize, Beets, Potatoes, Other	Cover % (square-rooted)	Altitude, temperature, precipitation	Month of sampling	Crop ("cereals" vs. "root crops")	One-way ANOVA, GLM (partial effects), correlation	DCA with post-hoc correlation of variables, CCA (gross effect of each variable)	Lososová and Cimalová (2009)
Eastern Slovakia	347 / 120	1949–1955, 2002–2006	100 m² square	Summer	Abundance (Braun-Blanquet, Westhoff & van der Maarel, 1978)	biol. (4), phylo-sociol. units		Cereals, Stubble, Maize, Oilseed rape, Beets, Potatoes, Peas/beans, Other	Species composition, frequency	Mean EIV, diversity (H)			Diagnostic species analysis (frequency and fidelity (ϕ>0.24)), correlation analyses, one-way ANOVA and Tukey post-hoc test for multiple comparisons	DCA post-hoc correlation of variables, hierarchical clustering (β-flexible clustering algorithm), Sørensen similarity coefficient	Májeková et al. (2010)

Table 1 (continued)

Country	Fields (net)	Sampling years	Sampling area per field / method	Season	Species data	Species traits	Herbicide	Crops	Dependent variable(s)	Environment	Explanatory variables: Site	Explanatory variables: Management	Statistics: Univariate	Statistics: Multivariate	Reference
Bulgaria	244	2004–2006	Whole field (mean 61 ha)	NA	Cover % (visual scoring / density)		No	Cereals, Stubble, Maize, Sunflower, Other	Frequency, mean density						Milanova et al. (2007)
Central eastern Poland	1450	1967–2006	NA	NA	Abundance (Braun-Blanquet)		Yes	Cereals, Maize, Beets, Potatoes	Coverage coefficient (D, constancy t1 / constancy t2)		Soil type				Kapeluzny and Haliniarz (2007)
Hungary	3780	2007–2008	16 m² square	Autumn, Summer	Dominance (cover %)		Yes	Cereals, Maize	Species cover %, total cover %				Descriptive (dominance ranking of species, comparisons with 4 previous surveys with same locations and method)		Novák et al. (2009)
Hungary	243	2009	4 × 50 m² squares (1 field edge, 3 field centre)	Autumn	Cover (%)		Yes	Cereals, Maize, Sunflower, Other	Species cover (%), Hellinger transformed	Altitude, temperature, rainfall	Soil properties (10 variables), field size, plot location, neighbouring habitat	Sowing season, crop type, preceding crop, fertilization		RDA / pRDA (gross and net effects of 24 sign. expl. variables, variation partitioning, 10 species with greatest fit to each variable group)	Pinke et al. (2012)
Hungary	102	2010	4 × 50 m² squares (1 field edge, 3 field centre)	Autumn	Cover (%)		Yes	Cereals	Species number, species cover (%) Hellinger transformed	Altitude, temperature, rainfall	Soil properties (16 variables), field size, plot location, neighbouring habitat	Sowing season, preceding crop, herbicides (11, g ai / ha), mechanical weed control, manure, fertilization, crop cover, crop row spacing	Paired Wilcoxon rank sum test (species richness of field cores vs. Edges)	RDA / pRDA (gross and net effects of 15 sign. expl. variables (minimal adequate model), variation partitioning, 10 species with highest response to most important management factors)	Pinke et al. (2011)
Western Hungary	1698	1995–2005	50 m² (stripe, square)	Autumn, Summer	Abundance (Braun-Blanquet)	biol. (3), threat	Yes	Cereals, Maize	Frequency, mean EIV		Soil texture, soil pH		Diagnostic species analysis (fidelity φsp ≥ 11), G-test for mean comparisons (proportions of life forms)	Hierarchical clustering (based on frequencies, similarity ratio, Ward's algorithm), Principal Coordinates Analysis (PCoA)	Pinke and Pál (2008)
Western Hungary	184	1995–2005	50 m² (stripe, square)	Autumn, Summer	Cover %	biol. (2)	Yes	Cereals, Maize	Species cover (%), Hellinger transformed	Altitude, temperature, rainfall	Soil pH, soil texture	Crop (aspect)		(partial) RDA (gross / net effects), Variation inflation factors (VIF)	Pinke et al. (2010)
Germany	2602	2000–2004	10 × 0.1 m² squares	Autumn	Density (plants / m²)		Yes	Maize	Frequency (%), density (plants / m²)		Soil texture	Maize in crop rotation (%)	Descriptive (frequency of species in soil classes and classes of different maize cropping intensity)		Mehrtens et al. (2005)
Germany	752	2005–2007	10 × 0.1 m² squares	Autumn	Density (plants / m²)		Yes	Oilseed	Frequency (%), density (plants / m²)	Altitude, longitude, latitude, temperature, rainfall	Soil texture, soil pH, soil quality index, field size, distance field edge, year and date of survey (covariables)	Preceding crop, crop rotation (4), duration of oilseed rape cropping, tillage system, sowing date, crop variety, crop density, fertilization	Indicator species analysis (ISA)	CCA, pCCA (gross / net effect of variables, complete data vs. subsets of common / frequent / rare spp.), non-hierarchical clustering (partitioning around medoids (PAM), expl. variables)	Hanzlik and Gerowitt 2011
Germany	2764	2000–2009	10 × 0.1 m² squares	Autumn	Density (plants / m²)		Yes	Maize	Frequency (%), density (plants / m², Hellinger transformed	Longitude, latitude, temperature, rainfall	Sand content, soil productivity, humus content	Maize in crop rotation (%), maize cropping within last two years, oilseed rape in rotation (%), tillage system, crop density, slurry appl.		PCA, RDA, Variation Partitioning (gross / net effect of single variables and variable groups)	De Mol et al. (2015)
Eastern Ethiopia	240	1998	4 to 6 × 4 m² (inverted W pattern (THOMAS, 1985))	Summer	Cover (%)	biol. (life cycle)	Yes	Cereals, Maize, Peas/beans, Other	Cover (%)	Region, altitude, annual rainfall	Soil texture, topography, cover % of Parthenium hysterophorus, date of survey (covariable)	Month of planting, number of ploughings, fertilisation, number of weedings, crop	Frequency (%), field uniformity (%)	DCA, pCCA	Tamado and Milberg (2000)
Eastern China	1550	1987–1992, 1994–1996	10 adjacent fields = 1 sampling site	Spring	Dominance (visual scoring / density-cover relative to crop height, 7 classes)			Oilseed	Overall weed infestation index (OWII, Qiang & Li, 1990, cited in Qiang (2005))		Soil type, soil pH	Soil submersion period, cropping system, crop, preceding crop, following crop	Dominant species analysis (mean OWII comparison between classified groups, Duncan's new multiple range test)	PCA (dominance values), CCA	Qiang (2005)
Saskatchewan, Canada	4423	1976–1979	20 × 0.25 m² ("W", locations 20 paces apart)	Spring	Density (plants / m²)		Yes	Cereals, Oilseed, Peas/beans	p/a (sample point, field), species and total density				Frequency (classes), field uniformity, relative abundance		Thomas (1985)
Saskatchewan and Manitoba, Canada	3108	1976–1981	20 × 0.25 m² ("W", locations 20 paces apart)	Spring	Density (plants / m²)		Yes	Cereals, Maize, Oilseed	Species density (log transformed)	Geographic region	Topography, soil texture, field area	Crop, preceding crop, sowing date & technique, tillage, herbicide regime (3), fertilization (3), fallow		DCCA, pCCA (covariables; geographic zone / soil zone)	Dale et al. (1992)
Ontario, Canada	593	1988–1989	20 × 0.25 m² ("W", squares 20 paces apart)	Spring	Density (plants / m²)	biol. (monocots / dicots)	Yes	Cereals, Maize, Oilseed, Soybeans	p/a (sample point, field), species and total density			tillage system	Frequency (classes), field uniformity, relative abundance		Frick and Thomas (1992)
Rolling Pampas, Argentina	84	2003–2005	3 × 100 m² (fencerow, field edge, field centre)	Summer	Species richness	biol. (life-form), natives vs. exotics	Yes	Cereals, Soybeans, Sunflower, Other	Species number (α / β / γ diversity)		Field position, type of surrounding landscape	Crop type	Frequency (classes), field uniformity, relative abundance, scatterplot, frequency versus mean occurrence field density	Additive partitioning of diversity, linear mixed effect models	Poggio et al. (2013)

Surveys are grouped by country; 35 surves were done in Europe and eight outside Europe

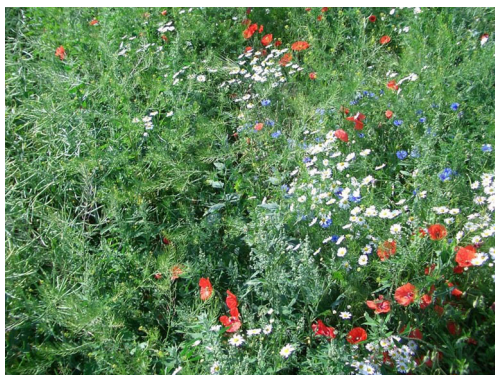biol. biological traits, p/a presence/absence of species, EIV Ellenberg indicator value, NA no information given

Fig. 2 Diverse weed infestation in a winter oilseed rape field

'site' and 'field'—it appears that it is rather used more or less synonymously. Hence, we handled this in the same way, although we cannot definitely exclude that more than one sampling site is located in one field. The latter may become even more relevant in those parts of Europe where socialistic collectivization after World War II has extremely increased field sizes (Baessler and Klotz 2006). Nevertheless, we use the term 'field' to describe the 'macro-sites' in the surveys, while the 'micro-sites' are subsumed under sampling units in fields in the following Section 3.4.

As mentioned above, the term 'large scale' has not been defined for weed surveys in the literature yet. The general attempt is to cover the entire weed vegetation instead of focusing on single problematic species and usually include at least several hundred arable fields across a landscape or a nation. Surveys in Table 1 included a minimum of 59 sites and a maximum of 4423. Fifteen surveys rely on up to 250 fields and 15 on more than 1000 fields.

2.5 Distribution of sampled fields

A wide variety of fields ensures that cause–effect relationships can be checked for generality (Andersson and Milberg 1998). How this multitude of sites shall be optimally distributed over the study region is an item of discussion. Alternatives to haphazard sampling (often called 'random' though not following a randomisation scheme) are systematic or regular sampling with fields spaced at regular intervals (grid design) (Chancellor 1977; Firbank et al. 1998) or subjective sampling with fields chosen to fit specific criteria, e.g. to 'represent the diversity of cultural practices and environmental conditions present' (Fried et al. 2008) or fit desired farming systems (Leeson et al. 1999). While caution is recommended when subjectively sampled data are used to make objective statements regarding the study area as a whole, systematic sampling of fields was found to yield data that are comparable to those of random sampling for large data sets and even more precise when sampling is done along (environmental) gradients (Hayek and Buzas 1997). Surveying large areas with

usually limited resources in time and labour generally calls for organising the sampling. As many other aspects, sampling is shaped by the general goal of the survey. Stratification of sampling fields in the context of weed surveys means to define homogenous subunits (e.g. geographical or administrative regions, crops or tillage systems) within the entirety of locations and to adjust the sampling intensity within these units to reflect their proportion or importance across the whole surveyed area. Deliberate stratification allows the calculation of overall estimates that are highly representative for the whole survey area even if important factors (e.g. the frequency of a sampled crop within different regions) vary substantially (Hayek and Buzas 1997; McCune and Grace 2002). It can also be applied to avoid regional oversampling when working with stored vegetation data from various sources (Lososová et al. 2004; Šilc et al. 2009).

2.6 Conclusions

It is not at all surprising that the large-scale surveys differed in their general layout concerning crops, time, site and field aspects; despite that they are done on commonly farmed fields and have an agronomic purpose in general, additional targets of the surveys differed. Additional targets often rooted in vegetation science and focused on deriving phytosociological units for arable weeds. With respect to additional targets of weed surveys, we do not recommend the optimal size and period for surveys on arable weeds. For agronomical purpose, it is worthwhile to include at least 3 years and apply a stratified sampling. Though it is feasible to conduct surveys in all arable crops, strong interdependencies between the chosen crop, the number of crops included and sampling the fields need to be carefully considered when setting up a survey. When existing survey data is accessed, the interdependencies of all the specific targets and the layout should always be handled with care.

3 Recording vegetation and explanatory data

In this section, we describe and discuss methodical items of the observation itself that are known to have a considerable impact on the quality and comparability of the collected weed vegetation data and therefore should be considered carefully before conducting a weed survey. These include the sampling season, inclusion or exclusion of herbicide treatment, the numbers of subsamples per site, the choice of a measure of species abundance, the size and design/placement of the sample area and, last but not least, a careful selection of relevant site and management parameters to be measured or collected from interviews. The latter are required as additional explanatory variables in several statistical approaches.

3.1 Sampling season

Weed surveys are mainly undertaken either in autumn, spring or summer (Table 1). Repetition in two or more seasons within a cropping year is not very common. Substantial differences due to different phenological stages of the weed vegetation during the growing season are bound to appear when the survey includes spring and autumn sown crops (Hallgren et al. 1999). Regarding the sampling season, it was found that even within the same crop more variation of the weed vegetation was explained by the season aspect (spring vs. summer) than by any other management or environmental parameter (Pinke et al. 2010). For this reason, the sampling date (described, e.g. as 'month of sampling', 'Julian Day' or by 'growing degree days') ought to be considered when analysing weed vegetation samples from different seasons (Lososová and Cimalová 2009). The time of sampling usually is settled according to the chosen survey conditions. These could be, e.g. maximum ground cover of the crop, completion of all management measures (Leeson et al. 2000; Poggio et al. 2004) or maximum homogeneity of field conditions during flowering (Fig. 3) and seeding of the crop (Thomas 1985; Qiang 2005).

3.2 Herbicide application

An issue strongly determining the time of sampling is the decision whether to sample with or without herbicide treatment in the current crop. In the 43 surveys in Table 1, samples were taken in plots without herbicides in 15, with herbicides in ten cases. Seven surveys had both, samples taken in plots with and without herbicides, while 11 surveys did not report about herbicide use or other direct weed control. Sampling before herbicide treatment records the potential weed vegetation. This is useful to analyse site and management effects other than herbicides. Herbicide effects in the current crop are known to superimpose all other influences (Andreasen et al. 1991; Mehrtens et al. 2005). However, when sampling is done before spraying, a large proportion of the weeds are usually in very early growth stages. Thus, a reliable distinction of species within the same genus may be impossible. This is a clear disadvantage of early sampling weed data. How severe this disadvantage is strongly depends on the goal of the survey. If the goal is to get an overview of common species or genus, this is acceptable, but if a more precise picture of the plant diversity is wanted, accurate identification on species level is indispensable (Fig. 4). To abandon herbicides during the whole cropping period is particularly required if the potential weed vegetation shall be examined in later phenological stages of the crop or the survey is focused on a precise estimate of weed species diversity. Having large parts of the field with no chemical weed control is unpopular with farmers and thus can complicate the search for fields to be sampled. Frequently, this could be overcome by installing plots with no herbicides, although this method restricts the survey site to small parts of the fields. Sampling after herbicide application is unproblematic in this regard and appropriate when the overall effect of farming systems reflecting the impact of all typical agronomic practices is to be examined (Leeson et al. 1999; Pinke et al. 2011, 2012). A time-consuming but informative alternative is to compare the weed flora in sprayed and unsprayed parts of the fields (Sutcliffe and Kay 2000) or before and after herbicide application (Saaverda et al. 1990; Hidalgo et al. 1990; Fried et al. 2008).

3.3 Assessments of abundance

The most commonly used measure of abundance is the estimation of weed cover (Mueller-Dombois and Ellenberg 1974; Poggio et al. 2004) as percentages or by assignment to cover classes (e.g. Pyšek et al. 2005; Aavik et al. 2008) which differ slightly between different existing schemes (McCune and Grace 2002) and usually are transformed into the midpoints of the ranges for further analysis. While weeds were traditionally scored following the scale of Braun-Blanquet (1964), any other scoring scale, existing and citable (e.g. Londo 1976) or self-created, can be used.

Fig. 3 Late spring weed flowering aspect of a wheat field in Germany

Fig. 4 Some weed species (e.g. *Geranium* sp.) difficult to distinguish as seedlings can be determined at the species level when assessed late in the season

The popularity of cover estimation is accounted for by its quickness whilst found to be an effective surrogate for direct biomass measurement (Hermy 1988; Andújar et al. 2010). Disadvantages include the potential for bias between observers (Sykes et al. 1983); however, Andújar et al. (2010) found that visual cover assessment by humans tends to overestimate the weed cover, but they did not report constraining differences between observers. Another issue worth to mention here is the usual need for transformation of cover data and scores before statistical analysis. While this step is required to obtain serious statistical results, understanding plotted or tabulated transformed data demands for a trained mathematical imagination power. Counting individual weeds (plant density) or parts of them (e.g. shoot numbers) within the sampling unit results in precise numerical data ready for statistical analysis but usually means tedious sampling unless weed numbers are estimated according to density classes (Barralis 1976; Chancellor and Froud-Williams 1984; Potts et al. 2010). However, this applies even more to direct weed biomass measurement as done by Hallgren (1996), Hallgren et al. (1999) or Hyvönen et al. (2003). Counting density, estimating cover or measuring biomass assesses different traits of the weed vegetation. Counted individuals are most suitable to be connected to processes which are mainly investigated on a single plant base, while cover and biomass deliver more realistic values for the competitive effects of the weeds. In some situations, counting of individuals is not possible (many monocotyledonous weeds). For perennial weeds, the 'individual' plant can often not be assigned. Parameters like weed cover, number of plants and weed biomass change quickly during the season and consequently require a high level of human resources in order to conduct a weed survey across a larger area within a short period of time. Repeated measurements within one season are rare (Table 1); however, if they are scheduled, the dynamic of the measured variables has to be carefully addressed. When financial limitations are an issue and only a few people are available for sampling, frequency analyses are more suitable to yield data that are comparable throughout the sampling season. Measuring weed frequency as the proportion or percentage of sample units (within a field) in which a weed species occurs (Raunkiaer 1934; Andreasen and Stryhn 2008; Lutman et al. 2009) is fast to score, sensitive to infrequent species and also contains information about spatial distribution. However, it is known to be highly dependent on the size of the sample units (McCune and Grace 2002). The simplest way of sampling weeds is to just record the presence or absence of a species. This is very effective in large-scale studies as it will carry most of the information in heterogeneous sample areas but fails to detect more subtle or local differences. Another kind of measuring weed vegetation is to combine traits directly in the assessment, in such a way that importance of a species is weighted. An advantage of importance values or other combined values of visual scoring is that they yield one (continuous) variable for analysis though taking into account several aspects of weed occurrence, e.g. dominance, relative height and cover (Qiang 2005) or density and cover (Miloanova et al. 2007). However, just these various possible combinations often hamper the interpretation and even more the comparison with other studies (McCune and Grace 2002).

3.4 Size and distribution of sampling units

The size of the smallest sampling unit used in the surveys varies to a very considerable extent. Although in many surveys it was decided to have sampling units of less than 1 m^2 (15 surveys, Table 1), the total range stretched to more than 1.000 m^2 (five surveys). Intermediate sampling unit sizes as they are traditionally used in vegetation science (e.g. 25 to 100 m^2) are also found frequently (12 surveys). Two surveys reviewed by us did not report about any repeated sampling per field.

Mulugeta et al. (2001) calculated species–area curves, which can be derived if a range of sampling unit sizes was conducted or combined. Though these authors found that an area of 1 m^2 contains less than half of the total observed species richness of a field, it is generally recommended to choose many small sample units instead of a few large ones and to include more fields rather than investigate more plots within a field. In this way, one obtains not only a higher level of reproducibility for the same cost (Henderson 2003) but also reasonable estimates of the occurrence of weed species on a large scale in different crops (Andreasen and Skovgaard 2009).

The measure of weed abundance also interacts with the size and design of the sample area/unit. Pollnac et al. (2009) give examples for these interactions. While highly accurate measures like weed density and biomass restrict the size of sampling units and are rarely applied to areas larger than 1 m^2, estimation of weed cover and visual scoring can easily be applied to whole fields (Miloanova et al. 2007; Goerke et al. 2007) or even to sampling units including several adjacent fields (Qiang 2005). For those methods not considering the entire field, quadrat sampling is a common practice. Usually, the square sample units are either placed randomly (Hanzlik and Gerowitt 2011; Mehrtens et al. 2005), arranged along transects (Lutman et al. 2009; Hawes et al. 2010; Potts et al. 2010) or form a 'w' pattern within a field (Thomas 1985; Leeson et al. 2000, details in Table 1). Larger sample units are usually walked until no more new species are found (Fried et al. 2008; Poggio et al. 2004). Due to known field edge effects (Marshall and Arnold 1995), the placement of sample units close to field boundaries and headland areas should be avoided except when this is part of the objective.

3.5 Collecting data for potential explanatory variables

Considering additional information on site properties, management options and environmental influences is indispensable for the interpretation of weed vegetation data. Spatial unit of most explanatory variables is the field, in case that several sites per field were included, site properties can have a subfield spatial scale. A variety of parameters that proved to be possible explanatory variables is collected in Table 1. While site and environmental data like soil type, exposition, longitude, and latitude can often be obtained from official databases or maps, management data can only be collected with the help of farmers. Typical management data considered as background information of surveys characterise crop rotation, soil cultivation, fertilisation and pesticide use.

3.6 Conclusions

How and where in the single fields the vegetation is recorded is strongly influenced by the available resources for the survey. Moreover, tying the current survey to former ones determines how variables are recorded. For agronomic purpose, we recommend to assess abundances rather than presence only; these can be densities, cover, biomass or scores. If logistically achievable, assessments of the weed vegetation in herbicide free plots deliver valuable information for agronomic purposes. To collect sound explanatory data, demands for robust contacts with land owner and/or farm managers.

4 Interpretation and statistical analysis of survey data

Large-scale surveys entail incredibly large data sets. Usually several sampling years, hundreds to thousands of sampled fields, containing numerous species and sometimes also a large set of potentially useful explanatory variables have to be handled. Thus, one of the main questions when dealing with weed survey data is how to proceed to concentrate the information.

4.1 Depending weed variables and explanatory variables

Based on the observed weed attributes (counted density, estimated cover, scores, measured biomass), dependent variables can be directly used as observed (e.g. density, cover) or deduced from the recorded vegetation attributes (e.g. number of species, frequencies, EIV). There are many possible ways of combining, deriving and deducing dependent variables to describe the species composition, the species number and further species-related information (Table 1).

Most surveys referred to in this review used explanatory variables in order to analyse and describe the chosen dependent 'weed variable'. In Table 1, we bulked the explanatory variables into the complexes 'environment', 'site' and 'management' (Table 1). If accounted for, it is most popular to include all three bulks of explanatory variables or at least 'site' and 'management'.

4.2 Mapping and analyses of single species

When the geographical distribution or spreading of a species shall be examined, this is commonly done by means of maps. Mapping is a simple method to transfer field observations data records into spatial explicit points on a geographical map. To draw maps is an established method for processing weed survey data. We therefore include it, although it is not in the central focus of this review, because geographic maps mainly refer to single species (Kolářová et al. 2013; Hanzlik and Gerowitt 2012; Novák et al. 2009).

Chorological maps, where a species' presence or absence is recorded anywhere in a grid square of 10×10 km, are generally available in European countries. However, these maps do not differentiate between segetal, ruderal and occurrences in other habitats and thus are not suitable for detailed analyses of arable weed vegetation (Holzner and Immonen 1982). In contrast, distribution maps from surveys on arable land indicate whether a species occurs as a weed in a specific region. This information is not to be underestimated as it is known that there are numerous species which are common weeds in their areas of origin (mostly the Mediterranean) but towards the borders of their geographic ranges are first outcompeted to poorer arable sites and finally restricted to ruderal habitats (Holzner and Immonen 1982). Furthermore, maps from weed surveys can be supplemented with additional information, such as the species abundances (Mehrtens et al. 2005; Goerke et al. 2008; Novák et al. 2009; Hanzlik and Gerowitt 2012), total weed infestation or species richness at the sampled sites, for a better illustration of regional differences or even be used to predict the probability of species occurrences by means of interpolation and spatial smoothing (Firbank et al. 1998).

There exists a multitude of (descriptive and univariate) statistical methods to compare and interpret abundance data of single weed species. Interesting examples include different indices of population change between successive weed surveys (Hyvönen et al. 2003; Fried et al. 2009; Potts et al. 2010; Storkey et al. 2010).

4.3 Measurements of diversity

When weed survey data shall be used for the analysis of weed diversity, it is essential that many species are represented in the dataset. One of the central questions is whether the sampling effort has been sufficient to adequately characterise the weed assemblage. A simple and commonly used approach to

answer this question is a species accumulation curve. It is produced by plotting the cumulative number of found species against a measure of sampling effort (sampling units/sites) and becomes an asymptotic curve provided sufficient samples have been taken (Henderson 2003; Hawes et al. 2010). Species–area relationship can also be used to deal with data sets where the size of sample units is inconsistent (Rosenzweig 1995). Also common and easy is the calculation of several diversity indices taking into account the number of species and their abundances in each sample unit (in detail e.g. Magurran 2004) which then can be used as dependent variables for further analysis. An advantage of using such indices for statistical analysis is that—in contrast to abundance measures—they contain information about the entirety weed vegetation of the field. Moreover, these indices are suitable to apply common univariate statistics like general linear models (GLM) (Potts et al. 2010; Šilc et al. 2008), generalised additive models (GAM) (Potts et al. 2010) or analysis of variance (ANOVA).

The classification of diversity according to Whittaker (1972) into the three type alpha (α), beta (β) and gamma (γ) diversity provides many possible applications for large-scale weed surveys. While ß diversity is most obvious as a measure of the extent of change in species along a gradient or between regions (Lososová et al. 2004; Šilc et al. 2009; Fried et al. 2008; Poggio et al. 2004), the large spatial extent of such surveys enables the examination and comparison of all three types, alpha (α), beta (β) and gamma (γ) diversity at or between different spatial scales within the same data set. This hierarchical partitioning of diversity was described in detail by Gabriel et al. (2006) and applied to larger sets of weed vegetation data by Hawes et al. (2010). Pollnac et al. (2009) use species–area curves to calculate diversity on different scales—in their case not for survey data but for comparison of farming systems with the help of selected fields and trials.

4.4 Multivariate statistics

It is known that the occurrence of weeds and the composition of weed communities are determined by a large number of factors that are partly interrelated (Kenkel et al. 2002; Murphy and Lemerle 2006). The identification of complex patterns in the data requires statistical approaches that master the simultaneous observation and analysis of more than one depending variable and therefore are called multivariate statistics. Weed survey data are very suitable for multivariate statistical techniques; thus, 26 of the reviewed 43 survey were analysed with this technique, 20 of them together with univariate methods. While 16 surveys are analysed with univariate statistics, in one survey, no information of the analysing methods is given.

The main differentiation between multivariate techniques is whether their purpose is to assign objects to a number of more or less homogenous groups (classification) or to order species along gradients to find out which species are commonly found associated with each other and what are the factors that structure the community (ordination).

Kenkel et al. (2002) promoted the applicability of ordination methods for weed science. Hence, the use of these techniques, especially detrended correspondence analysis (DCA) (Hill and Gauch 1980) and canonical correspondence analysis (CCA) (Ter Braak 1987), has become quite common for the analysis of weed survey data (Table 1, column 'multivariate statistics'). The choice of a specific method depends on both the scientific purpose and the kind of data available (Table 2). Ordination techniques are either based on models assuming a linear response of variables along gradients or on those assuming a unimodal one. Provided the gradient in the data is long enough, most species show a unimodal response to environmental factors. Thus, unimodal models are often more suitable for ecological data sets (Lepš and Smilauer 2003). Indirect gradient analysis only uses a species by sites matrix, which means that the change in species composition alone is expected to indicate what the most important gradients are. Direct gradient analysis (also termed 'canonical methods'), in contrast, utilises external environmental data additional to the species data and provides information on whether and to which extent species composition is related to our measured variables. The interpretation of ordination results in indirect methods such as CA or DCA (abbreviations see Table 2) can be simplified by a posteriori and passively projecting the effects of explanatory variables onto the ordination diagram which is widely used (e.g. Cimalová and Lososová 2009; Šilc et al. 2009; Májeková et al. 2010). However, canonical methods go one step further as they include the possibility to compute the respective importance of environmental factors both as gross effect and, by applying partial ordination (e.g. pCCA or pRDA; for abbreviations, see Table 2), as net effect corrected for the portion of explained variation shared with other variables (Lososová et al. 2004; Fried et al. 2008; Pinke et al. 2010; Šilc et al. 2009; Hanzlik and Gerowitt 2011). Finally, variation partitioning is a procedure where the explained variation is disassembled into components represented by single or thematically grouped variables. A systematic order of partial ordinations (usually pCCAs, Table 2) is used to compute all unique effects of and shared effects between variables/groups in order to compare their impact on weed species composition. A detailed example of variation partitioning among four single factors is given by Hallgren et al. (1999), diagrammed examples including three groups of variables can be found in Schweiger et al. (2005) and Pinke et al. (2009). When applying variation partitioning, the defined groups should each contain a comparable number of variables to avoid bias due to the known positive correlation between the amount of explained variation and the number of included explanatory variables (Borcard et al. 1992;

Table 2 Most common
ordination methods
(abbreviations in bold) with their
properties and statistical
assumptions

	Indirect gradient analysis	Direct gradient analysis
Linear model	Principal component analysis, **PCA**	Redundancy analysis, **RDA**
Unimodal model	Correspondence analysis, **CA**	Canonical correspondence analysis, **CCA**
	Detrended correspondence analysis, **DCA**	Detrended canonical correspondence analysis, **DCCA**

Peres-Neto et al. 2006). A stepwise and demonstrative procedure to determine the underlying factors of spatial distribution of weeds has been described as 'adaptive analysis' by Cousens et al. (2006) and proved to be a helpful tool to analyse spatial data.

Though ordination techniques proved to be very valuable in community ecology, less experienced users of multivariate statistics often tend to be suspicious of this kind of data analysis and especially of how to decide on a specific method. A selective, non-statistical overview of ordination methods with applications for weed research can be found in Kenkel et al. (2002), whereas Hallgren et al. (1999) and McCune and Grace (2002) describe how to assess and enhance the reliability of ordination results and Onofri et al. (2010) give directions for the scientifically accurate publication of multivariate approaches.

Classification and clustering, as the second major approach in multivariate statistics, has been applied to weed survey data, e.g. to examine the extent of similarity between the weed vegetation of various crops (Andreasen and Skovgaard 2009) or to hierarchically subdivide the weed vegetation into homogenous weed communities for comparison with the phytosociological units of current taxonomical systems (Lososová et al. 2006a; Pinke and Pál 2008; Šilc et al. 2008). The clustering of weed species into functional groups according to a variety of species traits enabled Fried et al. (2009) to search for trait combinations that determine the success of a weed species under specific selection pressures. Other approaches that cluster management and environmental data rather than species data target the classification of farm management systems or eco-regions to be then related to weed vegetation (Leeson et al. 1999; Hanzlik and Gerowitt 2011). While in other scientific fields (e.g. molecular biology and medicine) the use of both hierarchical and partitioning cluster methods is common (Pollard and van der Laan 2005), in the analysis of weed survey data, hierarchical clustering by means of dendrograms clearly dominates. However, there is no overall disadvantage of partitional clustering methods like k-means clustering (allocating data between a number of a priori defined centroids) and their additional application is even recommended to test hierarchically clustered groups for their robustness (Fukami et al. 2005). An advantage of the non-hierarchical method partitioning around medoids (PAM) is that it allows clustering with respect to any specified distance

metric (Kaufman and Rousseeuw 1990; van der Laan et al. 2003) including those that are able to deal with quantitative variables, e.g. the general dissimilarity coefficient of Gower (1971) (example in Hanzlik and Gerowitt 2011).

Usually, groupings found by clustering need some further verification in order to give ecological meaning to them. Especially the clustering of explanatory variables, e.g. to classify management effects within the data set, requires a subsequent procedure to examine whether the specific classification is of any significance for the weed vegetation. Indicator species analysis as described by Dufrene and Legendre (1997) is a robust tool to verify clustering results by determining the species whose presence and incidence best characterises the weed community of fields in different clusters. Phi-coefficient (Φ) and Ochiai index are other measures of fidelity that are commonly used by phytosociologists to quantify the preference of a species for a particular community in large sets of vegetation data (de Cáceres et al. 2008). Another less known but flexible and easily interpretable approaches to explore differences among groups of sites or species are classification and regression trees (CART) (McCune and Grace 2002; De'Ath and Fabricius 2000) which have been applied to survey data by Pyšek et al. (2005).

The described methods have been proven to be helpful in the reviewed analyses. However, there are more methods available, which could be checked by curious weed survey analysers for their additional value. Useful sources for the mathematical background to a multitude of both ordination and classification techniques are Legendre and Legendre (2008) and McCune and Grace (2002).

4.5 Conclusions

Survey data can be used to analyse and map single species or the diversity of species can be concentrated in coefficients. However, the amount of variables collected in large-scale surveys is best accounted for by multivariate approaches. From the variety of multivariate procedures, several have already proven to create extra value from weed survey data. We recommend weed scientists to apply these multivariate procedures, without discouraging them to explore others. Explanatory variables are of incredible importance for survey analyses to extract the background knowledge about the drivers of arable weed vegetation.

5 Summarizing survey results

Due to the number of weed surveys and the many different species and landscapes involved, it is impossible to treat their results in detail. However, as they all share the agronomic objectives, a short summary of main conclusions from recent weed surveys is attempted at this place.

The majority of surveys that targeted the species composition of weed communities found similar factors to be important. In different surveys across Europe (Andersson and Milberg 1998; Hallgren et al. 1999; Lososová et al. 2004; Fried et al. 2008; Cimalová and Lososová 2009; Šilc et al. 2009; Hanzlik and Gerowitt 2011; Pinke et al. 2012) and even on other continents (Tamado and Milberg 2000; Qiang 2005), weed species composition was most affected by the crop, edaphic factors (especially soil pH and soil texture), season, altitude and climate. However, rankings of these factors are highly inconsistent between studies. On the one hand, this could be due to the specificity of each region; on the other hand, there are at least some indications for general trends. Firstly, the relative importance of climatic variables and altitude was found to decrease with decreasing length of gradients and thus potentially decreases with smaller spatial scale of a study (Lososová et al. 2004; Cimalová and Lososová 2009). However, the same variables are also known to decrease in their relative importance towards southern Europe as they are generally more favourable for the weed vegetation there (Holzner and Immonen 1982; Šilc et al. 2009; Pinke et al. 2010, 2012). Another interesting fact is that variables representing a geographical position or region usually affect species composition much more when they are expressed as eco-region or phytogeographical region (Andersson and Milberg 1998; Hallgren et al. 1999; Leeson et al. 2000; Šilc et al. 2009) rather than purely as latitude and longitude (Fried et al. 2008; Hanzlik and Gerowitt 2011). This suggests strong interactions with climatic and edaphic variables rather than a significant net effect of geographical position. Similarly, at least in canonical correspondence analysis, the relative importance of the factor 'crop' tends to be influenced by the number of individual crops included in the analysis due to mathematical properties of this method (Hallgren et al. 1999; Fried et al. 2008; Šilc et al. 2009).

Research on large-scale patterns of diversity (beta (β) diversity) showed that weed vegetation varies less between fields. Under rather unfavourable environmental conditions, e.g. in higher altitudes, on sandy soils or under extreme soil reaction, this counts also within regions (Fried et al. 2008; Lososová et al. 2004; Šilc et al. 2008). No clear pattern was found for between-field differences due to crop type (Lososová and Cimalová 2009; Šilc et al. 2009) or farming system (Hawes et al. 2010).

There are also a number of weed surveys that aimed at examining changes in the abundance of weed species and/or the proportions of different species traits by comparing consecutive surveys of the same area (Table 1). While in Denmark and Finland the dominant weed species were largely the same in three consecutive surveys since the 1960s (Andreasen et al. 1996; Hyvönen et al. 2003; Andreasen and Stryhn 2008), in France, more than two thirds of the common weed species significantly changed their frequency rank status during the last 30 years (Fried et al. 2009). In contrast, for total weed abundance, a similar trend was observed in different parts of Europe. It shows a decreasing abundance and diversity of weeds from the beginning of wide applications of herbicides and levelling of site conditions until the 1980s but often increasing weed abundances during the last two decades due to herbicide reduction programmes, structural changes and a partial reversal of intensification (Andreasen et al. 1996; Hyvönen et al. 2003; Miloanova et al. 2007; Kapeluszny and Haliniarz 2007; Novák et al. 2009). However, this increase is rarely related to weed species of conservational value but usually involves higher proportions of problematic perennial and monocotyledonous species (Hyvönen et al. 2003; Novák et al. 2009; Potts et al. 2010; Pinke et al. 2011), higher abundances of generalist species that are common in all crops (Fried et al. 2010), nitrophilous weeds and weeds adapted to dense vegetation stands (Lososová et al. 2008; Šilc et al. 2009; Májeková et al. 2010).

Finally, the traditional phytosociological classification of weed associations was largely validated as it was found to coincide well with numerical classification by clustering of weed survey data (Lososová et al. 2006a; Šilc et al. 2008).

6 Conclusions

Despite the long history of weed surveys in arable situations, the plurality of sampling strategies is an issue in weed research, as is the exhaustive evaluation of survey data. With respect to different goals of and resources for surveys, we avoid to conclude an 'optimal' technic or protocol for all purposes; however, the increasing number of methodical approaches applied impedes comparisons and consolidations of different survey results. Strictly interpreted, the interaction of purpose and eligibility of survey data demand for specific approaches delivering data which exclusively answer the specific questions and is never used for any other purpose. However, times of widespread spatial modelling activities, accessible databases and biological data exploratories emphasise the opposite. With respect of the resources needed to obtain spatial data on arable weeds, it seems more rational to explore available data as much as possible and persuade users to do all analyses with caution and care.

Arable weeds are in general not the focus of national botanical surveying activities. Thus, long-term planned, repeated weed surveys organised by public authorities and done with

public support are exceptional. To our knowledge, in Europe, this only applies to Hungary, Finland and Denmark. At least for the latter two, continuation does not seem guaranteed. In France, a national database for arable weeds exists (Fried et al. 2007), but continuous surveys are not reported. For a more global perspective, we found no recent example for organised, repeated surveys of arable weeds.

Opposite to this trend, information coming out of weed surveys receives increasing interest. Scientific approaches dealing with the effects of management methods or land use changes require these data. The most urgent need for weed survey data probably originates from spatial modelling and the simulation of climate change effects on weeds. As arable weeds will react on climate change on various scales, serious predictions about weeds have to rely on data of different scale, including a large scale (Peters et al. 2014). Any space or time projection either for selected species or for weed communities depends on proper spatial data from the region on which the projection is based. The ongoing scientific debate on the importance of management versus environmental factors on species diversity and composition would surely profit from additional survey material. We make two proposals to overcome this discrepancy of engagement and requirements:

First, weed scientists should make as much scientific extra value out of existing survey data as possible. This review hopefully contributes to this proposal. Successful attempts to this goal will help to increase the attractiveness of weed surveys for public donors.

While any public engagement in surveying weeds would be welcome, other solutions using innovative ways of project organisation seem necessary. Therefore, our second proposal is to establish public–private partnerships for weed surveys. Private partners, coming, e.g. from the herbicide industries, have a distinct interest in an overview on weed species distributions, have locally experienced people and can arrange access to farmers and fields. Research institutions, as public partners, have the methodological expertise to design the studies, to train the observers and to analyse the data. As a matter of course, unconfined access to the data and freedom to operate is indispensable for both partners. If these requirements are treated with caution and no interest of one of the two partners is causing any bias in the survey, valuable contributions to agronomic purposes can be obtained. Two surveys or parts of repeated surveys included in this overview provide examples for such public–private partnerships. While private partners are mainly interested in general species overviews and the results of first steps in data analyses, not necessarily published internationally (Mehrtens et al. 2005; Goerke et al. 2008), public partners can create extra value through more innovative data analyses (Hanzlik and Gerowitt 2011; De Mol et al. 2015).

Finally, an agreed upon common protocol about the methods of assessment would assist all joint activities with survey data. For agronomical purpose, we recommend some general cornerstones. However, regarding the high diversity and national European traditions in weed survey methods, setting widely accepted standards is a challenge which requires an organised, supranational interest in the data, which has not yet been expressed officially.

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