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Reviewing change in the arable flora of Europe: a meta-analysis

N RICHNER*, R HOLDEREGGER†‡, H P LINDER§ & T WALTER*

*Agroscope Institute for Sustainability Sciences ISS, Zurich, Switzerland, †WSL Swiss Federal Research, Birmensdorf, Switzerland, ‡Department of Environmental Systems Sciences, Universitätsstrasse 16, Zurich, Switzerland, and §Institute of Systematic Botany, University of Zurich, Zurich, Switzerland

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Summary

Changing agricultural practices have dramatically altered the arable flora of Europe since the Second World War. We conducted a meta-analysis of the available literature to assess the dynamics of species richness and species traits in the arable flora across Europe during this time period. We found a total of 32 publications, yielding 53 data sets with an average number of 252 studied plots per data set. Average species number per plot of arable plants across all data sets declined by about 20%. However, twelve data sets showed an increase in average species number per plot, including all studies starting after 1980. Plant species preferring nutrient-rich sites, neophytes and monocotyledons generally increased since 1980, while characteristic or threatened species of arable weed communities further declined. This temporal development of the European arable flora suggests that the changes happening in agricultural management since the 1980s, such as organic farming and reduced pesticide input, may have helped slow the decline of the arable flora in terms of species number, but not in terms of characteristic or threatened arable weeds. Hence, more specific measures are necessary to stop decline of the latter, making sure that these measures are advantageous for rare and characteristic arable species, but not for harmful weeds.

Keywords: biodiversity, conservation, functional traits, species decline, temporal development, weed.

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Introduction

Agricultural land covers about 40% of the land area of Europe (Georgieva & Martins, 2012) and is thus one of the largest biomes in Europe. Humans have been cultivating land since about 5000 years ago, which has led to a remarkably rich arable flora. This arable flora was assembled from both indigenous and introduced species (along with new crops from transcontinental commerce and migration) from all over the world, but mostly from the Middle East and the Mediterranean (Willcox, 2012). Generally, the pool of arable species increases from northern Europe to the Mediterranean (e.g. Finland: 120 weed species; Italy: more than 450 weed species; Lososová *et al.*, 2004; Glemnitz *et al.*, 2006).

Agricultural practices in Europe have changed dramatically since the Second World War. Although these changes affected all aspects of agriculture, the increase in inputs of industrial fertiliser, pesticides and other chemicals were especially dramatic (Robinson & Sutherland, 2002). In addition, the timing of sowing

Correspondence: Nina Richner, Agroscope ISS, Reckenholzstrasse 191, 8046 Zurich, (CH) Switzerland. Tel: (+41) 443777290; Fax: (+41) 3777201; E-mail: nina_richner@hotmail.com

has shifted from spring to autumn for many crops, and a variety of new crops have become widespread, while many traditional crops and crop varieties almost disappeared (Andreasen & Streibig, 2010). As effective seed cleaning processes have been implemented, seeds of arable weeds are no longer spread onto fields via crop seed in the same amounts as historically (Van Elsen, 1994). Agricultural practices have also altered, due to changes in political settings, for example in many countries of Eastern Europe (Bouma *et al.*, 1998; Májeková *et al.*, 2010), where farmers now have greater flexibility in regard to farm management than they had before due to the changes in the political system. Since the 1930s, field sizes increased together with a general impoverishment of structural elements (e.g. hedgerows) in arable landscapes (Kienast, 1993). As a consequence of all these changes, many characteristic arable weed species adapted to traditional, less mechanised and small-scale agricultural systems have become rare and are now red-listed in various European countries. In individual countries, up to 77% of the arable flora is threatened, and across the whole continent, a total of 582 species are endangered (Andreasen *et al.*, 1996; Storkey *et al.*, 2012). Typical traits of weeds characteristic for traditional agricultural management include late-flowering period, large seeds and preference for sites with high light and moderate nutrient supply (Storkey *et al.*, 2010). At the same time, weeds adapted to modern field management optimised for higher crop yields, such as species tolerating higher nutrition levels, less acidic soils and higher herbicide input, increased substantially in abundance and distribution (Kutzelnigg, 1984). In the 1980s, several European countries set up schemes to financially compensate farmers for conservation measures to protect biodiversity on arable land. Among these measures were schemes to leave field margins unsprayed or to establish ecological compensation areas (Kleijn & Sutherland, 2003). Furthermore, stricter pesticide management, farming with reduced tillage, organic farming and farming systems that implemented integrated production methods were introduced (ECC Regulation 797/85, 1985, European Parliament Council, 2009). However, few studies have assessed the influence of these recent agri-environmental measures on the plant diversity of arable fields (e.g. Kleijn *et al.*, 2011).

Surveying the flora of arable fields has a long tradition in Europe, starting at the end of the nineteenth century. The first investigations into changes in the flora of arable fields due to changes in agricultural practice were published in the 1960s (Meisel, 1966; Bachthaler, 1968), with many further publications appearing in the 1980s. The recent increase of reports on changes in arable species diversity (Storkey *et al.*, 2012) shows that this topic has not lost its importance. However, most of these studies were restricted to a single region or country, and no formal European-wide review of the changes in the arable flora is available. We, therefore, undertook a meta-analysis to comprehensively assess in what way the arable weed flora changed across Europe since the Second World War. We concentrated on changes in the number of species per plot and tested the following three hypotheses: (i) the number of arable plant species per plot declined all over Europe, (ii) the change in the number of arable plant species per plot differs in different time periods and (iii) the spectrum of weed-specific functional traits has changed, with traits associated with weeds characteristic for traditional arable farming declining.

Meta-analysis is a useful tool to summarise the results from numerous studies, as it calculates the average effect across all included studies, but it also has some disadvantages (Gurevitch & Hedges, 1999). First, meta-analyses are only as good as the data on which they based. Studies without significant results are seldom published and thus introduce publication bias into meta-analyses (Borenstein *et al.*, 2009). Moreover, varying plot sizes and different survey methods complicate combining the results. Furthermore, poor data reporting and studies not replicated in a strict statistical way (Gurevitch & Chester, 1986) can confound critical data interpretation. This is confounded by attempting to combine studies from different biogeographical regions. Despite these deficits, meta-analyses can reflect large-scale trends more comprehensively and more objectively than single studies or traditional reviews.

Methods

Data set on species number per plot

We compiled studies which report on changes of numbers of weed species per sampling plot at two or more points in time. We considered articles published before December 2012. We searched ScienceDirect, Web of Knowledge, JStor and Google Scholar using the following search terms: chang* AND weed* AND ('arable' OR 'seget*'), ('change*' AND 'weed*') AND ('arable' AND 'segetal*') AND communit*. We also consulted the reference lists of the articles located. Additionally, we used Google to search for articles in German or French and considered articles if they contained the above-mentioned terms (or their equivalents in German and French) in the titles. To provide a broad data basis, the grey literature, such as governmental reports or Masters theses, was included.

Articles meeting the following criteria were considered: (i) the study site was in Europe, (ii) it provided data on species number per plot (in the text, tables or figures), (iii) the study was not designed to show differences between farming systems and (iv) the time period between consecutive surveys was at least 5 years. Experimental studies from common garden environments were not included. We found a total of 32 relevant publications. Several publications reported results for more than one crop type and/or more than two points in time. In these cases, all comparisons between two points in time were included as independent entries in the data set. This procedure resulted in 53 entries in the complete data set. An additional 30 publications might have met the above criteria, but we failed to access them (old and grey literature). The 32 publications covered the time period of 1939 to 2011. The average number of plots per data entry was 252. The entire data set contained a total of more than 10000 plots.

From the 32 publications, we extracted information on crop type, the area of sampling plots and the size of the study region. Crop type was included, because root crops usually have a lower number of associated weed species than cereals (Braun-Blanquet, 1928). Plot area was recorded, as small-sized plots might only reflect small-scale variation in species number, rather than long-term changes in the weed flora. This is a consequence of the uneven distribution of weeds in a field (Rew & Cousens, 2001). The size of the study region was included, as large study regions might contain subregions with different temporal developments of the arable weed flora. Furthermore, sampling densities are often higher in smaller than in larger study regions, which might lead to a better estimate of average species number in smaller study regions.

We recorded the longitude and latitude, because we wanted to test whether latitude and longitude have an influence on average species number per plot. This is predicted, as the species pool of arable weeds decreases from the Mediterranean to Northern Europe (Lososová *et al.*, 2004; Glemnitz *et al.*, 2006). It is known that the mean annual precipitation varies significantly among biogeographical regions, so we included it as an environmental factor. Mean annual precipitation of study regions was taken from http://www.klimadiagramme.de/. All information extracted from the 32 relevant publications is given in Table 1. Unfortunately, information about tillage or other farming practices were rarely available from the studies included in the analysis. Therefore, we could not test for explicit changes in agricultural practices.

Analysis of change in species number

Meta-analysis was calculated with METAWIN (Rosenberg *et al.*, 2007) and the packages 'metafor' (Viechtbauer, 2010) and 'bootES' in R (Gerlanc & Kirby, 2013). Generally, in meta-analyses, an effect size and a variance for each study are needed and a weighted mean of effect sizes is computed from these values, with more precise effect sizes weighted more than less precise effects. The variance of an effect size is based on the standard deviation, but standard deviations (or comparable measurements of variation) around the average species number per plot were only available for 14 of the 32 publications included. Consequently, we used the response ratio as an effect size, as this can be calculated without knowing standard deviations. Total species number should not be directly compared between different studies, because species number is affected by local species pools and this varies among regions (Shmida & Wilson, 1985). The response ratio is defined as the ratio of the average number of species per plot of historic and recent studies (Borenstein *et al.*, 2009) and is usually reported as the natural logarithm of the ratio denoted as lnRR. Bootstrapping was used to calculate 95% confidence intervals by resampling the mean of the response ratio 1000 times. If the confidence interval included zero, the effect size was considered to be non-significant. Using a response ratio has the additional advantage of avoiding the effects of plot size variation (Hedges *et al.*, 1999). We calculated the response ratio for several data sets: (i) for the entire data set, (ii) for data sets grouped by crop type (cereal, root crop or undefined) and (iii) for data sets grouped by study design. For the entire data set, we only dealt with relative changes in the number of arable weed species per plot, as it is not possible to perform meta-analyses based on means without standard deviations (Hedges *et al.*, 1999). The variable design was split into two groups, namely random and repeated study designs. In the first group, plots had been randomly distributed across a study region and were not paired in time, and surveys were not conducted on the same plot twice (21 data entries). In the second group, surveys had been repeated at the same location, yielding two points in time (32 data entries). Random studies with only a small number of plots result in less accurate estimation of the change in average species number than repeated studies (Borenstein *et al.*, 2009). We built general linear models (GLM) using the Gaussian family, with latitude and longitude, crop type, study design, precipitation and time period as explanatory variables and the response ratio as response variable. As the precision of the estimation of means improves with increasing sampling effort, we used the ratio of the number of samples per area of the study region as a weighting factor in GLMs.

To analyse the effect of temporal changes on the number of arable species, we split the 32 publications

Table 1 Information on studies used in meta-analysis. Design: studies, where plots were either repeated at the same location as the historic ones or taken from random plots across a study region. Crop types were split into root crops or cereals. If the two crop types were not distinguished in the respective study, crop type was set to 'several'. Plot area: size of plots as reported in the respective study

Reference	Start of study	End of study	Country	Annual precipitation [mm/a]	Longitude [°]	Latitude [°]	Design	Crop type	Area of the study region km^2	Number of historical relevés	Number of recentrelevés	Plot area [m^2]	Historical average species number	Recent average species number	Standard deviation (or similar measure)	Information about functional traits
Andreasen and Stryhn (2012)	1987	2004	Denmark	600	56	10	random	all	43094	157	167	0.1	3.13	4.53	yes	no
Andreasen *et al.* (1996)	1967	1989	Denmark	600	56	10	random	cereal	43094	139	213	0.1	6.28	2.63	yes	yes
Andreasen and Stryhn (2008)	1987	2004	Denmark	600	56	10	random	cereal	43094	213	240	0.1	2.63	4.28	yes	yes
Bachthaler (1982)	1950	1980	Germany	789	51	10	random	all	70552	25	32	–	97.4	81.1	yes	yes
Bachthaler (1985)	1948	1965	Germany	789	51	10	random	cereal	70552	653	662	–	26.6	22.3	no	no
Bachthaler (1985)	1948	1980	Germany	789	51	10	random	cereal	70552	–	–	–	26.6	14.1	no	no
Bachthaler (1985)	1948	1965	Germany	789	51	10	random	root	70552	761	650	–	25.6	15	no	no
Bachthaler (1985)	1948	1980	Germany	789	51	10	random	root	70552	–	–	–	25.6	15.4	no	no
Baessler and Klotz (2006)	1959	1979	Germany	789	45	11	random	all	4	120	115	100	20	14	no	no
Baessler and Klotz (2006)	1979	2000	Germany	789	45	11	random	all	4	115	220	100	14	15	no	no
Braun (1988)	1965	1974	Germany	789	49	8	repeated	all	75.3	42	42	–	17.4	12.9	no	no
Braun (1988)	1966	1971	Germany	789	49	12	repeated	all	93.6	37	37	–	16.9	12.7	no	no
Braun (1988)	1971	1980	Germany	789	49	12	repeated	all	93.6	37	37	–	12.7	11.5	no	no
Braun (1988)	1974	1985	Germany	789	49	8	repeated	all	75.3	42	40	–	12.9	11.5	no	no
Bunce *et al.* (1999)	1978	1990	Britain	850	54	3	random	all	–	124	124	–	6.69	5.08	no	no
Cirujeda *et al.* (2011)	1976	2007	Spain	300	41	1	random	cereal	–	21	138	2000	9	3	no	yes
Davy (2006)	1978	2002	Britain	850	51	1	repeated	all	2.52	22	22	100	7.6	7.7	no	no
Dessaint *et al.* (2007)	1968	2006	France	825	47	5	repeated	all	8763	757	315	2000	16.5	9.3	yes	yes
Fried *et al.* (2009)	1970	2000	France	825	51	1	repeated	all	6000	158	158	2000	16.5	9.28	yes	yes
Hilbig and Jage (1984)	1970	1980	Germany	789	51	12	random	all	770	–	–	–	–	–	no	yes
Köck (1984)	1967	1979	Germany	789	51	13	random	all	60.67	45	67	–	22.56	20.4	yes	yes
Kohlbrecher *et al.* (2012)	1960	2011	Germany	789	51	11	repeated	all	1035	–	–	–	24	13	yes	no
Kojic (1978)	1952	1977	Serbia	500	44	21	repeated	cereal	–	5	5	–	25.4	10.6	yes	no
Kojic (1978)	1952	1977	Serbia	500	44	21	repeated	root	–	5	5	–	15	16.6	yes	no
Kropàc (1984)	1954	1962	Czechia	450	50	13	repeated	cereal	3	40	40	100	62	57	yes	no
Kropàc (1984)	1962	1972	Czechia	450	50	13	repeated	cereal	3	40	40	100	57	55	yes	no
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	cereal	14000	28	28	100	34	28	yes	yes
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	cereal	14000	28	28	100	33	25	yes	yes
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	cereal	14000	28	28	100	31	26	yes	yes
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	cereal	14000	28	28	100	34	27	yes	yes
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	cereal	14000	28	28	100	32	30	yes	yes
Kropàc (1984)	1972	1977	Czechia	450	50	13	repeated	cereal	3	40	40	100	55	54	yes	no
Kropàc (1984)	1977	1981	Czechia	450	50	13	repeated	cereal	3	40	40	100	54	49	yes	no

Table 1. (Continued)

Reference	Start of study	End of study	Country	Annual precipitation [mm/a]	Longitude [°]	Latitude [°]	Design	Crop type	Area of the study region km^2	Number of historical relevés	Number of recentrelevés	Plot area [m^2]	Historical average species number	Recent average species number	Standard deviation (or similar measure)	Information about functional traits
Kropàc (1984)	1954	1962	Czechia	450	50	13	repeated	root	3	40	40	100	55	53	yes	no
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	root	14000	30	30	100	31	21	yes	yes
Kropàc (1988)	1962	1985	Czechia	510	50	15	repeated	root	14000	30	30	100	35	33	yes	yes
Kropàc (1984)	1962	1972	Czechia	450	50	13	repeated	root	3	40	40	100	53	51	yes	no
Kropàc (1984)	1972	1977	Czechia	450	50	13	repeated	root	3	40	40	100	51	45	yes	no
Kropàc (1984)	1977	1981	Czechia	450	50	13	repeated	root	3	40	40	100	45	57	yes	no
Kulp and Preuschhof (1985)	1950	1983	Germany	789	53	9	repeated	all	419	190	190	25	18.6	13.5	no	no
Kutzelnigg (1984)	1950	1981	Germany	789	51	7	random	all	200	106	106	500	17.6	12	yes	yes
Maire (1999)	1975	1996	Switzerland	1458	46	8	repeated	all	51.55	15	34	–	21.1	25	no	no
Májeková *et al.* (2010)	1949	2006	Slovakia	650	48	17	random	all	1000	347	121	100	14.7	17.7	no	yes
Meisel (1979)	1945	1977	Germany	789	52	9	random	all	1	72	50	–	30	10	no	yes
Mittnacht (1980)	1948	1978	Germany	789	48	10	random	cereal	16	–	–	100	21.9	16.2	no	no
Otte (1990)	1951	1986	Germany	789	49	11	repeated	all	357104	6	6	75	33.7	41.4	no	no
Pàl (2004)	1969	2003	Hungary	550	46	18	random	all	–	161	5	50	35	22.5	no	no
Potts *et al.* (2010)	1968	2005	Britain	850	51	0	repeated	cereal	62	106	106	1	1.03	1.79	yes	no
Šilc and Čarni (2005)	1939	2002	Slovenia	1000	46	15	random	all	50	–	–	–	22	26	yes	no
Toth *et al.* (1997)	1949	1996	Hungary	550	47	20	random	all	93030	202	202	25	86.4	37.8	yes	no
Toth *et al.* (1997)	1949	1996	Hungary	550	47	20	random	all	93030	202	202	25	37.8	69.2	yes	no
Trzcinska-Tacik (1991)	1947	1988	Poland	662	50	20	repeated	cereal	4000	38	40	–	48.5	39.75	no	no
Tyser *et al.* (2009)	1975	2005	Czech	510	50	15	repeated	all	52065	7	–	100	32.86	17.71	no	no
Xylander (1987)	1967	1985	Germany	789	51	12	repeated	cereal	150	42	42	100	9.95	10.1	yes	yes

into the following three groups: (i) studies ending before or in 1980, (ii) studies beginning before and ending after 1980 and (iii) studies beginning in or after 1980. We choose 1980 as a threshold, because from 1980 onwards, less intensive agricultural management, such as decreasing use of pesticides or more extensive farming, started in many European countries (ECC Regulation 797/85, 1985, Kleijn & Sutherland, 2003).

Because meta-analysis of data with standard deviations is more precise than an analysis of data for which standard deviations are lacking, we separately analysed the 24 data entries, belonging to 14 publications that provided standard deviations (Table 1). This allowed us to verify the results of the analysis of the entire data set. Following Borenstein *et al.* (2009), we calculated an average response ratio weighted by the variance of the effect size, so that data with smaller variance had a higher weight in the analysis. We then assessed the homogeneity of the effect sizes across studies using Q and I^2 values according to the standard procedure of meta-analysis (Borenstein *et al.*, 2009). Q tests for significance, and I^2 estimates what proportion of the observed variance is real. We included the same factors in the mixed-effect model programmed in R as we used for the entire data set, namely latitude and longitude, crop type, study design, precipitation and time period (Viechtbauer, 2010).

Publication bias

To check for publication bias, we used Rosenberg's fail-safe N (Rosenberg, 2005) and funnel plots. The fail-safe N represents the number of data entries without a significant result, which had to be included in the analysis to change the outcome of the analysis. A funnel plot is a scatterplot of standard error against effect size. If data entries are not symmetrically distributed, there is publication bias (Borenstein *et al.*, 2009).

Data on functional traits

Of the 32 publications, only 20 reported on plant functional traits or species identity. For the 21 mentioned traits, we noted whether the percentage of the trait on the species pool was increasing or decreasing during the study period (Table 2). In addition to reproductive and life-strategy traits, we also included information on 'indicator species', which are characteristic for different site and management conditions under traditional arable farming (Braun-Blanquet, 1928). As the number of publications reporting on plant functional traits was small and diverse, we did not analyse the corresponding data statistically.

Table 2 Traits and the number of times a particular trait was mentioned to positively or negatively influence changes in the numbers of arable weeds in the literature

Trait	Positive	Negative
Indicator species		13
Tolerant to extreme pH		8
Large seeds		2
Nutrient loving	14	
Monocotyledon	8	
Herbicide resistance	7	
Neophyte	6	
Ubiquitous plant	4	
Tolerant to minimum tillage	2	
Wind dispersed	2	
Long flowering time	2	
Ruderal	2	1
Rare plant	2	6
Short-living seeds	1	1
Long-living seeds	2	1
Shade tolerance	7	3
Moisture loving	6	1
Small size	2	2
Summer annual	3	3
Temperature loving	3	1
Winter annual	1	1

Results

The 32 publications detected were unequally distributed across Europe. Few data were from Mediterranean areas (Fig. 1), where arable fields historically had the richest arable weed flora (Shmida & Wilson, 1985). Additionally, we did not find data for some northern countries. More than one-third of the studies were located in Germany, and the majority of studies that included the year 1980 were from the Czech Republic.

Analysis of the entire data set

The meta-analysis of the entire data set showed that the mean effect size per data entry varied between −1.099 and 0.605. The overall mean effect size was lnRR = −0.208 (95% confidence interval (CI): −0.1126, −0.3070). Hence, the average species number of arable weeds per plot declined by about 20% from an overall mean of 33.5 to an overall mean of 27.5, rejecting the null hypothesis of no change. The average species number per plot increased in 13 data entries, while it decreased in 40 data entries. Analysing temporal subgroups, we found a significant decline in average species number for studies conducted before 1980 (lnRR = −0.242; CI: −0.356, −0.122) and for those studies beginning before and ending after 1980 (lnRR = −0.245; CI: −0.409, −0.077). For studies beginning after 1980, however, we found a tendency

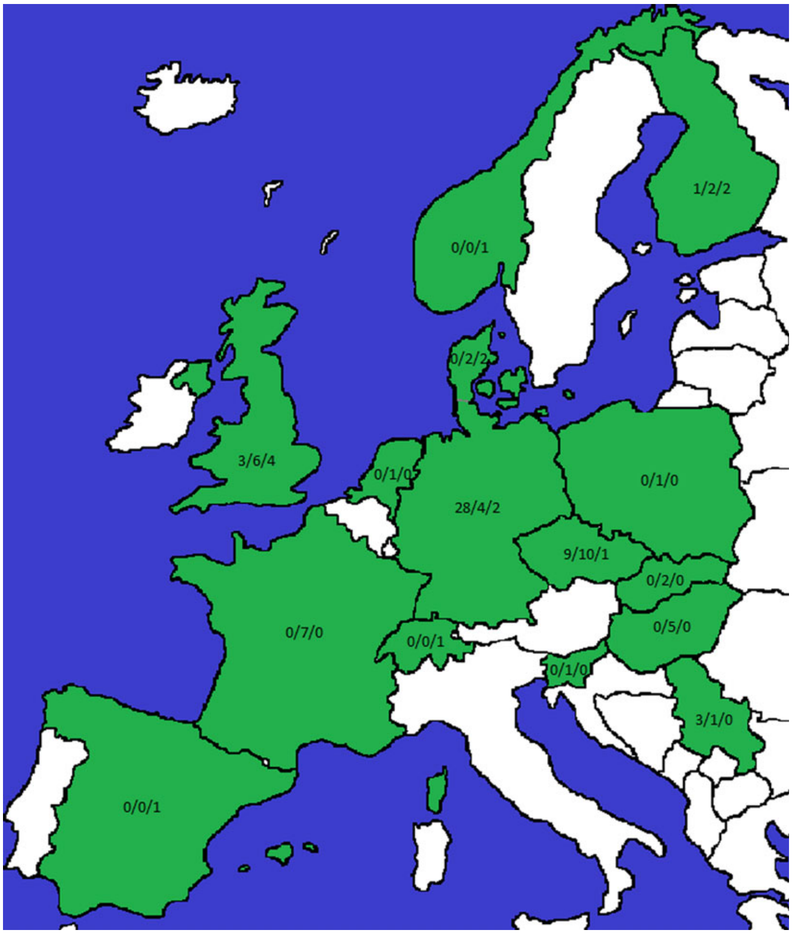

Fig. 1 Map showing the number of data entries in the entire data set on changes in arable weeds per European country (ending before 1980/including 1980/beginning after 1980).

for increasing species number with lnRR = 0.133, but this trend was not significant (CI: −0.092, 0.357). There was no influence of study design or crop type on mean effect size (Table 3).

In GLMs, crop type, study design, geographic latitude and precipitation showed no significant effects on average species number per plot (Table 4). Longitude had a significantly positive effect on mean effect size, indicating that the average species number per plot declined less in Eastern than in Western countries (Table 4).

Analysis of data sets for which standard deviations were provided

In the meta-analysis, the weighted mean effect size of the data sets for which standard deviations were provided was lnRR = −0.126 (CI: −0.249, −0.002,

Table 3 Mean response ratio (lnRR; ratio of change in average species number per plot) with 95% confidence interval. Plots were either randomly distributed or repeated at the same location. Crop types were either cereals, root crops or undefined (several crops). Studies were beginning after 1980, ending before 1980 or including the year 1980. The last row shows the results of the null model without additional factors (i.e. entire data set included). Significant changes are marked with asterisks

	Entire data set analysed with R using bootstrap	Data set with standard deviation analysed with MetaWin	Data sets with standard deviation analysed with R using bootstrap
Random	−0.28 (−0.48, −0.10)*	−0.08 (−0.33, 0.17)	−0.08 (−0.39, 0.24)
Repeated	−0.16 (−0.26, −0.06)*	−0.15 (−0.34 0.03)	−0.14 (−0.32, 0.04)
Cereal	−0.23 (−0.41, −0.033)*	0.03 (−0.12, 0.06)	−0.10 (−0.40, 0.20)
Root	−0.15 (−0.31, 0.02)	0.01 (−0.21, 0.23)	0.03 (−0.09, 0.14)
All crops	−0.22 (−0.37, −0.07)*	−0.26 (−0.33, −0.20)*	−0.21 (−0.49, 0.06)
Before 1980	−0.24 (−0.36, −0.12)*	−0.13 (−0.27, 0.02)	−0.12 (−0.27, 0.03)
Overlapping 1980	−0.25 (−0.42, −0.08)*	−0.25 (−0.65, 0.15)	−0.16 (−0.69, 0.36)
After 1980	0.13 (−0.11, 0.37)	0.43 (0.31, 0.54)*	0.43 (0.35, 0.51)*
Null	−0.21 (−0.31, −0.12) *	−0.13 (−0.24 −0.011) *	−0.12 (−0.29, 0.05)

Table 4 General linear model for the entire data set including crop type (cereal, root, undefined = several), time period (beginning after 1980, ending before 1980, including 1980), latitude, longitude, precipitation and design (random, repeated; see Table 2) on the log response ratio weighted with the area of the study

Coefficients	Estimate	SE	*t*-value	*P*-value
Intercept (all, after 1980, random)	−1.065	1.031	−1.034	0.307
Cereal	0.101	0.128	0.791	0.433
Root	0.176	0.160	1.101	0.277
Before 1980	−0.620	0.196	−3.163	0.003
Overlapping 1980	−0.507	0.198	−2.556	0.014
Latitude	0.010	0.019	0.526	0.602
Longitude	0.025	0.012	2.153	0.037
Precipitation	0.001	0.000	1.876	0.067
Repeated	0.190	0.106	1.789	0.080

$z = -1.988$, $P = 0.047$; Fig. 2). This translates into a decrease in average species number per plot of about 13% through time. Heterogeneity between studies was significant (Q_{tot}: 3299.3, df = 23, $P < 0.001$, $I^2 = 99.3$), indicating that most of the observed variance was real. We found no significant change in mean effect size caused by study design or crop type (Table 3). However, there was a significant increase in mean effect size from the group 'before 1980' to the group 'after 1980' (Fig. 2). Therefore, while average species number per plot decreased in studies ending before 1980, it increased in studies beginning after 1980. In the mixed-effect models, neither precipitation, longitude, latitude, area of study region, crop type nor time period had a significant effect on the change in average species number per plot (Table 5).

Publication bias

We found no evidence for publication bias. The funnel plot was symmetric and 6.3×10^{13} studies without significant results would have to be added to change the outcome of the results.

Trends in functional traits

In the ten publications providing data on species identity, we found eleven functional traits that were associated with arable weeds that either changed positively or negatively in frequency. Six traits were linked to species that have increased in frequency and ten traits were associated with species that have become rarer (Table 2).

Declining species either belonged to arable weed communities characteristic of traditionally managed fields (e.g. *Adonis aestivalis* L. or *Agrostemma githago* L.) or were species growing under extreme pH conditions (e.g. *Ajuga chamaepitys* (L.) Schreb. or *Scleranthus annuus* L.). These arable weeds are currently rare and threatened. Species that became more common preferred nutrient-rich sites (e.g. *Polygonum lapathifolium* L.) were monocotyledons or herbicide-resistant (e.g. *Alopecurus myosuroides* Huds.), wind-dispersed (e.g. *Senecio vulgaris* L.) or neophytes (e.g. *Nicandra physalodes* (L.) Gaertn.). Only in Slovakia and the Czech Republic did some species of arable weed communities characteristic for traditional management increase in numbers (e.g. *Lathyrus tuberosus* L., *Silene noctiflora* L.; Kropàc, 1984; Májeková *et al.*, 2010).

Discussion

In this study, we showed that the average number of arable weeds per plot generally declined by about 20% across Europe since the Second World War. This result is in line with other studies from different agricultural systems reporting on species decline (Conn *et al.*, 2011; Wesche *et al.*, 2012). However, the species decline in agricultural land in Europe of 23% (de Heer *et al.*, 2005) is still lower than the 30% decrease observed across all ecosystems worldwide (Butchart *et al.*, 2010).

Decline of arable weeds per plot

In accordance with our first hypothesis, the average number of arable species per plot declined by about 20% (13% based on data sets for which standard deviations were provided). However, this result does not report the cumulative decline in arable weeds across the last 75 years, as the duration of the studies included in the data set was much shorter. The actual decline since the Second World War is probably much higher. A cumulative review by Albrecht and Bachthaler (1990) from Germany found a much larger decrease in weed species of about 50% between 1930 and 1980. This discrepancy in outcome was at least partly explained by the influence of studies from the Czech Republic in our meta-analysis; in the Czech Republic, the decline in arable weeds was not as pronounced as in other countries (Kropàc, 1984, 1988). The change to more intensive agriculture in the Czech Republic took place after 1980 (Májeková *et al.*, 2010). Therefore, a more pronounced decrease in average species number per plot in the Czech Republic would be expected after this time, as confirmed by Tyser *et al.* (2009). These east–west differences are corroborated by the significant effect of longitude on effect size (Table 3). However, we did not find an effect of latitude, precipitation, different study design or crop type on

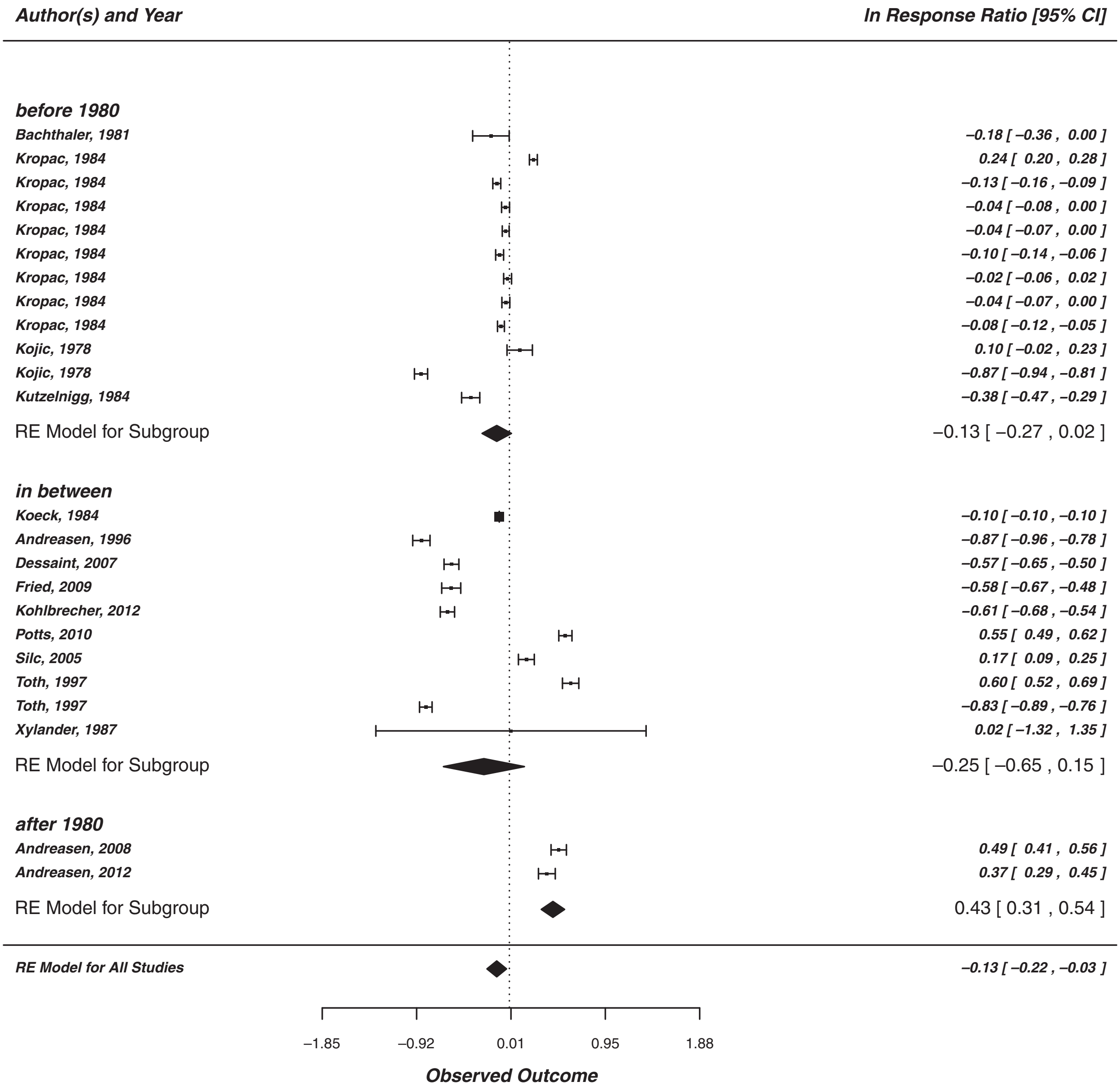

Fig. 2 Mean effect sizes (log response ratio of the average species number per plot; squares) of the 24 data entries in the data set with standard deviation (bars) and the respective grand means (diamond) for three time periods (beginning after 1980, ending before 1980, including 1980). Studies with bars crossing the dashed line reported a non-significant effect.

the change in average weed species number per plot. Additionally, we also did not find an influence of geographic location in the data set for which standard deviations were provided. We thus believe that there was no problem with the geographic distribution of studies in our data set (e.g. a lack of data in south-eastern Europe) and that the longitudinal difference we detected (Table 3) reflects ecologically meaningful differences among European regions. In summary, the observed decline in arable weed species seems to be a general trend across Europe, with only small differences between countries (Stoate *et al.*, 2001).

Early versus late trends in weed species numbers

The implementation of agri-environmental schemes increased across Europe from 1980 onwards. Before 1980, hardly any agri-environmental schemes or measures to protect the environment were implemented. We thus chose this year as a threshold. In fact, in our meta-analysis, the publications providing some measurement of variance and beginning after 1980 showed a significant increase in average species number. Similarly, in the entire data set, the same trend for increasing average species numbers of arable weeds was

Table 5 Mixed-effect model for the data set for which standard deviations are provided including crop type (cereal, root, undefined = several), time period (beginning after 1980, ending before 1980, including 1980), longitude, latitude, precipitation and design (random, repeated, see Table 2) on the log response ratio. Residual heterogeneity = 0.00, P = 1.00; test of moderators: = 2.41, P = 0.64

	Estimate	SE	*z*-value	*P*-value
Intercept (all, random, after 1980)	3.16	4.41	0.72	0.47
Cereal	0.30	0.31	0.97	0.33
Root	0.56	0.40	1.41	0.16
Before 1980	−0.77	0.46	−1.69	0.09
Overlapping 1980	−0.83	0.47	−1.78	0.08
Latitude	−0.05	0.07	−0.77	0.44
Longitude	−0.02	0.04	−0.55	0.58
Precipitation	0.00	0.00	0.21	0.84
Repeated	−0.27	0.38	−0.70	0.48

detected, but it was not statistically significant. Consistent with this, an increase in the average number of arable weeds per plot was reported in Denmark (e.g. Andreasen & Stryhn, 2012). These results were thus in line with our second hypothesis. Although our results only show tendencies, they indicate that the measures taken to protect the environment or to preserve biodiversity on agricultural land since the 1980s, such as stricter pesticide policy, organic farming, unsprayed field margins or wild-flower strips (Kleijn *et al.*, 2011; Andreasen & Stryhn, 2012), were effective, at least in terms of species numbers. Additionally, the change to management with reduced tillage could lead to higher species numbers on arable fields (Tuesca *et al.*, 2001). While it is impossible to confirm that agri-environmental schemes are the factor causing this increase in species number in our data set, our results are congruent with other studies inferring a positive effect of agri-environmental measures on species richness (Kleijn & Sutherland, 2003; Bengtsson *et al.*, 2005). It is possible that there is a basement level below which weed species number will not drop and that subsequent increases are to be expected because of an increasing abundance of agricultural problem species. However, the two studies in our data set that studied change in arable weeds after 1980 (Andreasen & Stryhn, 2008, 2012) not only found an increase in average species number per plot, but also documented increases in the regional species pool, more species gained than lost and more species increasing than decreasing in frequency. It would, therefore, be valuable to repeat surveys in areas that were included in studies in the 1980s (e.g. Bachthaler, 1985; Braun, 1988; Kropàc, 1988; Trzcinska-Tacik, 1991) to test whether the trend for increasing numbers of weed species persisted. Additionally, further investigations on the effect of management practices are needed, to identify those measures that increase arable weed species diversity.

One reason for the contrasting judgment on the effectiveness of agri-environmental schemes might be that species number does not reflect the occurrence of characteristic or endangered species *per se*. However, changes in the frequency of these less common species are difficult to detect (Andreasen & Stryhn, 2008), but it is precisely these species that are the focus of conservation management.

Plant functional traits

Unfortunately, most publications in our data set lacked a commented species list and only few directly reported on changes in plant functional traits. We can thus only speculate on the third hypothesis posed in this study, that is, the traits of the species that increased since 1980. These increasing species could either be the currently rare weeds characteristic of traditional arable farming, such as *Adonis* sp. or *Legousia* sp., or the more common species that are widely distributed or even problematic invasives?

The data set with standard errors (Table 5) indicated that increasing arable weeds are linked to high nutrient demand, herbicide resistance or a status as a neophyte. Such characteristics are often linked to species that are highly competitive and difficult to control. This suggests that weeds that are common or causing problems in agriculture increased in number and not the rare, threatened arable weeds characteristic of traditional management. These are usually short, have large seeds and flower late in the season (Storkey *et al.*, 2010). This finding is not surprising, given that arable lands are currently exposed to high nutrient and herbicide inputs (Robinson & Sutherland, 2002). This agricultural practice favours problematic weeds. However, our study suggests that also wind-dispersed species such as *Senecio vulgaris* L. or grasses were favoured. Potentially, this could be due to modern agricultural landscapes being less structured by trees, hedgerows or ruderal sites than previously. These structures were removed to simplify management. In modern landscapes, there may thus be fewer barriers to wind dispersal (José-Maria *et al.*, 2011). However, for most functional traits, we could not detect a clear pattern.

Conclusions and implications

The average number of arable species per plot has clearly declined since the Second World War, potentially due to the intensification of agricultural practices including the introduction of fertilisers and herbicides. Nevertheless, increases in average species number per plot after 1980 indicate that measures taken to protect the environment or conserve biodiversity in agricultural landscapes and arable fields seem to have a positive effect on plant species richness. However, it is likely that nutrient-loving widely distributed weeds profited most from these measures. In fact, most rare species will not spontaneously return to formerly intensively used agricultural landscapes, because regional or local species pools are now depauperate. As we could not investigate the influence of functional traits on losses and gains in arable weeds in a statistical framework, their effects remain enigmatic. Without such functional information, however, it is difficult to disentangle the processes behind species decline, although such knowledge would be essential to preserve biodiversity on arable land. While more information on the actual situation of individual arable weed species in different countries is clearly needed, this study gives valuable insight into the general magnitude and direction of change in arable weed numbers across Europe.

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