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Fifth survey on weed flora in spring cereals in Finland

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Regular weed surveys provide information on changes in weed communities. The composition of weed flora in spring cereal fields was investigated in southern and central Finland during 2020–2022. The survey was conducted in 16 regions, 226 farms and 549 fields. The occurrence of weeds was assessed in the second half of July from 90 organically cropped and 459 conventionally cropped fields. The weed flora was dominated by broad-leaved species, representing 81% of the total number of 138 identified species. The average species number per field was 21 in organic fields and 12 in conventional fields. The most frequent weed species in organic fields were *Chenopodium album* 99%, *Erysimum cheiranthoides* 84%, *Viola arvensis* 83% and *Stellaria media* 82%. In conventionally cropped fields, the most frequent species were *Viola arvensis* 83%, *Stellaria media* 65%, *Galeopsis* spp. 59% and *Galium spurium* 59%. The two most common grass species in both production systems were *Poa annua* and *Elymus repens*. The frequency and density of *Poa annua* had increased substantially in conventional cropping since the previous survey in 2007–2009. The average density of weeds was 384 plants m^{-2} in organic fields and 147 plants m^{-2} in sprayed conventional fields. The average air-dry biomass of weeds was 678 kg ha^{-1} and 151 kg ha^{-1}, respectively. *Elymus repens* produced almost a quarter of the total weed biomass in both production systems. Changes in weed flora were minor in terms of frequency and density of the most common broad-leaved weed species. Increased infestation of *Poa annua* in conventional cropping calls for special attention. The dominance of *Elymus repens* decreased in both production systems since the previous survey.

Key words: biodiversity, species diversity, conventional farming, organic farming, *Elymus repens, Poa annua*

Introduction

Arable weed communities are of agronomic, economic and ecological interest. Changes in agricultural practices and environmental factors are reflected in weed abundance and species composition (Fried et al. 2008, Andreasen and Streibig 2011, Pinke et al. 2012, Salonen et al. 2013). Therefore, periodic updating of the information on weed communities is needed. This can be obtained by conducting regular weed surveys (Krähmer et al. 2020).

National weed surveys have been conducted in many countries, including among others Spain (Cirujeda et al. 2011), Hungary (Novák et al. 2012), Germany (De Mol et al. 2015), Denmark (Andreasen et al. 2018) and Slovakia (Májeková et al. 2019). The major aim of those surveys has usually been to get updated information on the species composition of weed communities and the affecting factors. However, the focus can also be on the effect of specific agricultural factors, such as conservation agriculture (Derrouch et al. 2022), crop diversification (Hofmeijer et al. 2021) or incidence of herbicide resistance (Loureiro et al. 2017, Kolářová et al. 2023). Monitoring weeds and delivering information on weed biology and their incidence in arable fields is helpful for developing weed management strategies (Van Acker 2009, Borger et al. 2012).

In Finland, four extensive surveys of weeds in spring cereal fields have been carried out since the 1960s, the first in 1961–1964 (Mukula et al. 1969), and thereafter in 1982–1984 (Erviö and Salonen 1987), in 1997–1999 (Salonen et al. 2001a) and in 2007–2009 (Salonen et al. 2011). Responding to an increasing interest in organic production, organically cropped fields were included in the survey protocol from the 1990s survey onwards (Salonen et al. 2001b). Weed surveys in spring cereal fields in Finland are important in terms of crop dominance because spring cereals account for more than half of the total cropped area of around 2 million hectares (Luke 2023). The updated information on weed occurrence and diversity will be utilized by farmers, advisory services, authorities and industry as well for scientific communication.

In each decade, a special focus has been included in the weed surveys in Finland. During the latest two surveys, the development of production systems and cropping methods have been twofold regarding weed flora. Increase in the area of organic cropping has extensified production, leading to promotion of weed flora, both in terms of diversity and abundance (Rydberg and Milberg 2000, Hyvönen et al. 2003, Romero et al. 2008, Wortman et al. 2010). The area of organic production (incl. two-year transient period) in Finland has steadily increased from 170 876 ha in 2010 to 339 460 ha in 2022, corresponding to the increase in the proportion of cultivated

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area from 7.5% to 15.0% (Ruokavirasto 2022). On the other hand, reduced tillage and direct drilling have partly replaced ploughing in the 2000s, followed by an increase in the use of glyphosate, leading to reduction of *Elymus repens* (Salonen et al. 2013). Common use of herbicides has brought new challenges such as resistance in *Stellaria media* against sulfonylureas, as reported in Denmark already in the early 1990s (Kudsk et al. 1995) and in Finland in 2013 (www.weedscience.com).

In this study, we report the results of the fifth weed survey of Finnish spring cereals, conducted during 2020–2022. The present composition of weed flora is reported by focusing both on biodiversity and agronomic aspects of weed occurrence.

We expected the above-described trends in cropping practices to affect the species composition of the weed flora and the level of weed occurrence. Therefore, a divergent effect was expected regarding organically and conventionally cropped fields. In both production systems, long-term impacts are of interest because the current trends have been evident for decades.

Material and methods

Study regions, farms and fields

The weed survey was carried out in southern and central Finland in 2020–2022 (Fig. 1). The highest proportion of fields (N = 306, 56%) was studied in southern Finland (Table 1), where spring cereals are grown on more than 50% of the arable area and annual spring-sown crops predominate (Luke 2023). The number of study fields decreased towards the cattle farming regions in the east and north, where spring cereals account for less than 50% of the cultivated area and grassland is often included in the crop rotation. The number of farms visited was 226, of which 189 were engaged in conventional and 37 in organic production. We aimed at including 10–15% organically grown fields in all survey regions. This corresponds to 16% of all studied fields and is close to the proportion of organically cropped field area (15%) in Finland in 2022 (Ruokavirasto 2022).

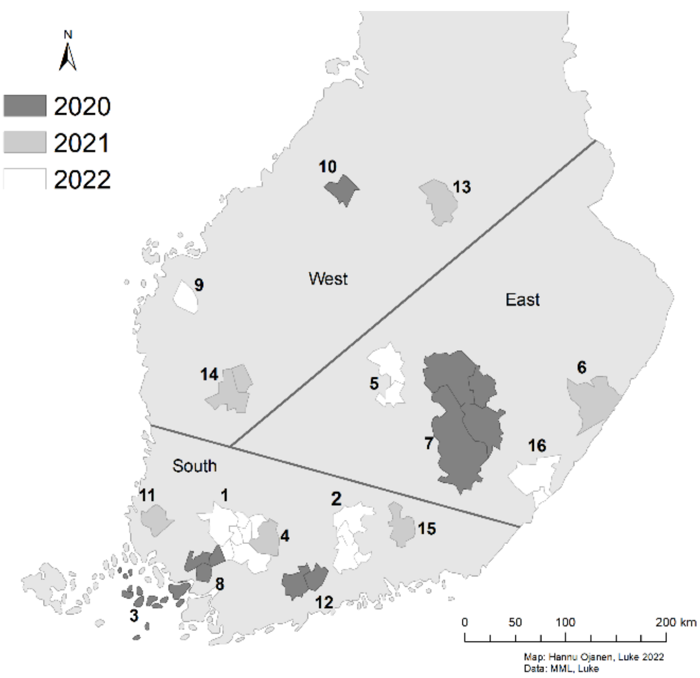

Fig 1. Weed survey regions (1–16) in three zones in 2020–2022. Key to region numbers: 1 = Jokioinen, 2 = Lammi, 3 = Nauvo/Korppoo, 4 = Tammela, 5 = Laukaa/Toivakka, 6 = Kitee, 7 = Mikkeli, 8 = Lieto/Paimio, 9 = Laihia, 10 = Nivala, 11 = Laitila, 12 = Nurmijärvi, 13 = Vieremä 14 = Kihniö/Parkano, 15 = Iitti, 16 = Imatra/Ruokolahti

One to seven spring cereal fields were examined on each farm, giving a total of 549 fields: 218 under barley (*Hordeum vulgare* L.), 183 under oats (*Avena sativa* L.), 112 under wheat (*Triticum aestivum* L.), 33 under oat/pea (*Pisum sativum* L.) mixture, 2 spring-sown triticale (× *Triticosecale* Wittmack) and one previously studied field which was now under maize (*Zea mays* L., excluded from biomass results). Cover crops, mainly pure Italian ryegrass (*Lolium multiflorum* L.) or mixed with white clover (*Trifolium repens* L.), were sown in 18 fields (20%) under organic production and 31 fields (7.5%) under conventional production.

Table 1. Number of fields surveyed by region, production system and cereal species

	Number of fields							
	Region			Production system		Cereal species[7]		
Year/ Municipality	No	Zone[5]	Total	Conventional[6]	Organic	Barley	Oat	Wheat
2020								
Nauvo/Korppoo	3	S	25	23 (18)	2	6	14	5
Mikkeli[1]	7	E	25	17 (17)	8	7	7	4
Lieto/Paimio[2]	8	S	44	40 (36)	4	10	13	20
Nivala	10	W	27	21 (20)	6	11	14	2
Nurmijärvi	12	S	41	38 (38)	3	22	7	12
2021								
Tammela	4	S	42	31 (31)	11	18	16	7
Kitee	6	E	26	21 (21)	5	12	8	6
Laitila	11	S	41	36 (35)	5	20	15	5
Vieremä	13	W	25	21 (21)	4	14	4	1
Kihniö/Parkano	14	W	26	21 (21)	5	8	18	0
Iitti	15	S	28	24 (22)	4	9	12	7
2022								
Jokioinen[3]	1	S	45	35 (35)	10	14	14	12
Lammi[4]	2	S	40	35 (33)	5	9	15	16
Laukaa/Toivakka	5	E	37	30 (29)	7	16	17	3
Laihia	9	W	42	37 (37)	5	27	3	8
Imatra/Ruokolahti	16	E	35	29 (27)	6	15	6	4
Total			549	459 (441)	90	218	183	112

[1] = incl. Joroinen, Juva, Pieksämäki, Mikkeli, Pertunmaa; [2] = incl. Lieto, Marttila, Paimio, Tarvasjoki; [3] = incl. Humppila, Jokioinen, Forssa, Koski Tl, Loimaa, Somero, Ypäjä; [4] = incl. Hämeenkoski, Kärkölä, Mäntsälä, Pukkila; [5] = key to zone abbreviation: S = South, E = East, W = West; [6] = number of sprayed fields in parentheses; [7] = added to this 33 fields with cereal/pea mixture, 2 triticale and 1 maize

Altogether 459 study fields were cultivated conventionally and 90 organically. Most of the organic fields (82%) had been ploughed, whereas in conventional fields reduced tillage (43%) and direct drilling (18%) were more common. The average area of the study fields was 6.9 ha (range 0.3–51.2 ha) and the area of surveyed fields was in total 3 786 ha. In the largest fields, the investigated area was restricted to a maximum of 21 ha and in some fields the surveyed field area was adjusted according to previous surveys. The same 16 regions were surveyed in two previous studies and altogether 275 out of the 549 surveyed fields were the same as in 2007–2009 (Salonen et al. 2011).

Permission to investigate weeds in survey fields was asked from farmers only in early July, with the aim that all cropping measures influencing the weed infestation, including tillage, the level of fertilization and weed control, were realized according to their normal practices. Information on cropping measures was recorded by interviewing the farmers afterwards.

Herbicides had been applied in 441 out of 459 conventionally cultivated fields. Pure MCPA (4-chloro-2-methylphenoxyacetic acid) was used in 4% of treated fields, products containing phenoxy acid mixtures (18%), pure sulphonylurea products (33%), sulphonylureas as tank mixture with other active ingredients (33%) and the rest of fields were treated with various tank mixtures of 2–3 commercial products. Six fields (1%) were treated with spring-glyphosate only. Chemical control of wild oat (*Avena fatua* L.) had been carried out in 39 fields (9%), in most cases with pinoxaden products.

Weed sampling

The weed survey was carried out during a 3-week period starting in mid-July (weeks 28/29), by which time spring cereals had reached their heading stage in the majority of survey fields and in most cases around one month had elapsed since herbicide treatment. The growth stage of cereals varied most in 2021 due to rainy weather conditions which extended the sowing period and later an exceptional drought hampered the growth of crops and weeds.

The weed sampling protocol was exactly the same as applied since the survey in 1997–1999 (Salonen et al. 2001a). The occurrence of weeds was assessed from 10 sample quadrats (1.0 m^2) randomly placed in each field. In advance, the positions of sample quadrats in each field were split into a 10 × 10 cell grid using a random number calculator. On the spot, each sample grid was placed in the field according to the area and shape of each field. The distance from the field edge was noted for each quadrat.

Weed density was determined by counting the number of plants or shoots of grass weeds by species in a rectangular frame measuring 0.1 m^2 (25 cm × 40 cm), which was a corner area within a larger quadrat measuring 1.0 m^2 (1.0 m × 1.0 m). The larger quadrat was used only for observations on the total number of species on a presence/absence scale. The results presented in the tables and figures derive from data collected from the small 0.1 m^2 quadrats and pooled over the 10 samples in each field. A complete list of the additional weed species found in the presence/absence observation (1 m^2) is given by survey region in the Appendix as a supplement to the 40 most frequent species presented in Tables 3 and 5.

In four out of ten small sample quadrats, weeds and cereals were cut at the soil surface. The biomass for *Elymus repens*, other weed species in total and for cereal crop were weighed after the samples had been dried in an air-flow dryer at 40 °C for several days. The air-dry biomass results are presented in kg ha^{-1}. The biomass of cover crops and undersown grasses and clovers were weighed separately and added to the cereal biomass to represent the pooled biomass of sown crops in certain calculations. Appraisal of herbicide resistance was based on visual observation of vigorous growth linked with the information about the applied herbicide.

Nomenclature and data analysis

All weed species found in sampling areas were assessed. Afterwards, some genera/taxa, e.g. *Galeopsis* spp. and *Lamium* spp., were pooled because they could not be unequivocally identified to species level at the seedling stage.

The plant species nomenclature follows Hämet-Ahti et al. (1998), and the abbreviations of species names are according to the code system by European and Mediterranean Plant Protection Organization (EPPO) available on the EPPO website (gd.eppo.int). The full scientific names with attribution are given to the 40 most frequent species (Tables 3 and 5).

The frequency of occurrence over studied fields (hereafter 'frequency') refers to the proportion of fields where a species was found indicating distribution of weed species. Differences in frequency values between production systems were tested with Fisher's Exact Test (Table 4). For each field, the total weed density and biomass indicating weed infestation level were summed, and the averages and median values of abundance are presented by 16 survey regions. Differences between the regions were tested with log-transformed values using the MIXED procedure of SAS 9.2 (SAS Institute Inc., Cary, NC, USA). In the linear mixed model, region, production systems and their interactions were considered as fixed effects and farm as a random effect. If not mentioned otherwise, the specific results concerning the weed occurrence in conventional production derive from the 441 fields treated with herbicides, i.e. the 18 non-sprayed conventional fields were excluded.

Differences in the weed species diversity between two production systems were determined by calculating Shannon's diversity (H') and evenness (E) indices (Shannon and Weaver 1949) and Simpson's diversity index (Simpson 1949) based data collected on species number and weed densities in small quadrats (see e.g. Magurran 2013 for the further information on the indices). The Shannon diversity index values (H') were calculated for both production systems as follows: $H' = -\sum_i p_i \ln(p_i)$ where p_i is the proportion of total individuals in the *i*th species in the fields of production system and the Shannon evenness (E) as follows: $E = H' / \ln(S)$ where H' is the Shannon diversity index and S is the total number of species in the production system. The Simpson index was calculated as follows: $D = 1-\sum n(n-1)/N(N-1)$ where n = number of individuals of each species in the production system and N = total number of individuals of all species in the production system.

Results

Species diversity

In total, 138 weed species were found in the large (1.0 m^2) sampling quadrats and 115 in the small (0.1 m^2) quadrats (see Appendix for the species recorded in large quadrats but not included in the list of 40 most frequent species). Out of the 138 observed species, 62 were annual and 76 perennial species. The majority (i.e. 98 species) of the observed species occurred in less than 5% of the fields studied and 67 species of them in less than 1% of fields.

Altogether 95 species were observed in organically cropped fields (N = 90) and 124 species in conventionally cropped, herbicide-treated fields (N = 441). The majority of the species (59%) was shared with cropping practices, whereas 43 species (31%) were unique for conventional and 14 species (10%) for organically cropped fields. Indices describing weed species diversity were very similar between production systems (Table 2).

The average observed species number per field was higher in organically farmed fields, 21 (SD = 4.0, min 12, max 33), than in conventionally farmed sprayed fields, 12 (SD = 5.0., min 1, max 31).

Table 2. Comparison of weed diversity between production systems using Shannon index for diversity (H´) and evenness (E) and Simpson's index for dominance (1/D) calculated using density values for a total number of observed weed species (S)

	Production system	
Index	Conventional (N=441)	Organic (N=90)
Diversity (H´)	2.82	2.87
Evenness (E)	0.62	0.69
Dominance (1/D)	10.98	11.35
Species number (S)	124	95

Frequency of weed species

The occurrence of the 40 most frequent weed species in the small 0.1 m^2 sample quadrats is presented by region (Tables 3 and 5) and the remaining species observed from the larger 1.0 m^2 quadrats are listed by region (Appendix). Only nine weed species exceeded the frequency of 50% in large quadrats.

The most frequent weeds were primarily broad-leaved species. *Viola arvensis*, *Stellaria media* and *Chenopodium album* were the only species with overall frequency above 50% (Table 3), and they were frequently found both in conventionally and organically cropped fields. Nevertheless, there were evident differences in the ranking list of predominant weed species and their frequency levels between conventionally and organically cropped fields (Table 4). *S. media* was the only weed species judged to be herbicide resistant, with a low frequency of four sprayed fields.

With a frequency of 42%, *Poa annua* was the most common grass weed before *Elymus repens* (40%) (Table 3). Other grass species were found at much lower frequency; *Alopecurus geniculatus* (5%), *Phleum pratense* (1%) and *Poa* spp. (1%). Altogether, 26 grass species, including volunteer cereal species, were identified in the sample quadrats (1.0 m^2, see Appendix).

Highly productive perennial broad-leaved weed species occurred more frequently in organic than in conventional production; *Sonchus arvensis* had a frequency of 58% in organic and 28% in conventional fields and *Cirsium arvense* 51% and 19%, respectively. Typical weed species in grassland rotations, such as *Achillea millefolium* 18% vs. 0.5% and *Ranunculus repens* 43% vs. 6%, were more frequent in organic than in conventional production.

Table 3. Frequencies (%) of 40 most frequent weed species by regions

	Year / Region[1]																Average
Species / Taxon	2020					2021						2022					2020–2022
	3	7	8	10	12	4	6	11	13	14	15	1	2	5	9	16	
Achillea millefolium L.	8	4	0	0	5	5	8	0	16	12	4	0	0	3	0	0	3
Alopecurus geniculatus L.	0	8	0	0	0	14	8	0	20	15	0	2	0	14	0	0	5
Artemisia vulgaris L.	4	24	5	0	5	7	4	29	0	8	0	7	8	0	5	11	7
Bidens tripartita L.	4	0	2	0	5	2	0	0	0	0	0	4	3	11	0	0	2
Brassica rapa L. ssp. *oleifera* (DC.) Metzg.	8	20	2	4	2	5	8	0	4	27	18	0	3	3	0	6	6
Capsella bursa-pastoris (L.) Medik.	44	20	18	19	15	24	42	34	32	15	11	22	23	51	19	26	26
Cerastium fontanum Baumg.	4	0	0	0	7	7	0	0	0	0	0	2	8	0	0	0	2
Chenopodium album L.	92	48	70	93	27	48	54	46	60	23	36	67	38	54	38	54	52
Cirsium arvense (L.) Scop.	16	24	27	33	27	29	4	10	32	15	36	27	20	41	17	26	24
Elymus repens (L.) Gould	12	56	30	37	10	33	58	46	72	73	29	38	25	68	33	49	40
Epilobium L. spp.	0	16	0	4	0	7	8	2	8	0	7	0	0	5	2	6	4
Equisetum arvense L.	40	12	27	4	37	17	4	22	8	8	39	33	13	24	10	29	21
Erysimum cheiranthoides L.	36	40	23	44	15	26	19	15	24	23	21	27	23	38	14	23	25
Fallopia convolvulus (L.) À. Löve	28	24	43	56	34	33	19	20	12	12	32	56	65	32	36	51	36
Fumaria officinalis L.	56	48	39	30	63	19	23	20	16	23	29	56	45	43	26	69	38
Galeopsis L. spp.[a]	20	36	57	52	27	36	23	22	32	35	25	53	70	70	48	40	42
Galium spurium L.[b]	92	12	77	22	88	62	8	24	4	23	50	62	45	62	52	46	49
Gnaphalium uliginosum L.	0	36	0	0	0	50	50	29	48	77	7	9	35	68	12	40	28
Lamium L. spp.[c]	92	28	86	4	63	31	0	37	0	0	54	60	23	35	31	57	40
Lapsana communis L.	72	84	41	4	78	48	35	54	0	23	57	40	75	49	21	89	49
Matricaria matricarioides (Less.) Porter	0	28	0	4	2	19	35	15	48	46	0	13	30	38	19	17	19
Myosotis arvensis (L.) Hill	20	64	30	15	5	26	15	5	8	15	14	24	38	43	36	43	25
Persicaria lapathifolia (L.) Gray	20	28	32	37	10	43	15	27	28	31	21	27	48	49	7	51	30
Plantago major L.	20	32	9	4	12	12	38	17	12	12	18	11	18	35	10	34	18
Poa annua L.	4	56	11	59	34	55	35	37	80	65	36	29	30	76	50	29	42
Polygonum aviculare L.	28	20	27	22	22	38	46	32	36	38	29	51	43	65	36	37	36
Ranunculus repens L.	4	0	5	15	2	12	23	2	24	19	11	11	10	30	10	23	12
Sonchus arvensis L.	60	44	34	41	20	26	8	17	52	50	43	27	33	49	14	43	33
Sonchus asper (L.) Hill	16	0	11	0	2	5	0	12	0	0	11	13	13	0	10	0	6
Spergula arvensis L.	32	36	32	41	12	38	46	27	44	42	29	31	38	57	31	34	35
Stachys palustris L.	0	0	0	0	5	0	0	0	0	0	14	2	8	3	0	3	2
Stellaria media (L.) Vill.	72	68	77	67	49	48	27	39	28	31	43	78	78	68	74	60	58
Taraxacum Weber spp.	8	20	43	0	12	33	31	7	8	4	25	16	8	24	17	23	18
Thlaspi arvense L.	8	12	5	4	12	17	4	2	0	12	4	7	15	11	7	0	8
Trifolium L. spp.[d]	16	12	7	7	2	14	4	0	28	8	7	4	13	38	2	11	10
Tripleurospermum inodorum (L.) Sch. Bip.	80	12	34	26	39	36	4	44	0	15	39	47	35	35	21	40	33
Tussilago farfara L.	0	4	0	0	0	2	8	0	12	4	4	2	0	8	0	9	3
Veronica L. spp.[e]	8	16	5	0	44	24	12	41	0	0	36	4	28	3	2	29	17
Vicia L. spp.[f]	24	12	7	15	7	21	12	15	12	27	11	13	18	11	10	20	14
Viola arvensis Murray[g]	80	100	59	74	51	69	81	76	84	62	46	78	90	89	88	86	75

[1]Key to regions given in Figure 1 and Table 1. [a]= mainly *G. bifida* and *G. speciosa*; [b]= incl. *G. aparine*; [c]= mainly *L. purpureum;* [d]= mainly *T. repens;* [e]= mainly *V. agrestis*; [f]=mainly *V. cracca*; [g]=incl. *V. tricolor*

Table 4. Frequency of ten most common weed species in two production systems and the change in frequency-% from 2007–2009 to 2020–2022

	Sprayed conventional (N = 441)			Organic (N = 90)		
Rank	Weed species	%	Change	Weed species	%	Change
1	*Viola arvensis*	73	–10	*Chenopodium album*	99*	+3
2	*Stellaria media*	52	–13	*Erysimum cheiranthoides*	84*	–2
3	*Galium spurium*	50	–9	*Viola arvensis*	83*	–11
4	*Poa annua*	48	+15	*Stellaria media*	82*	–12
5	*Lapsana communis*	47	–10	*Galeopsis* spp.	81*	–7
6	*Chenopodium album*	41	–11	*Elymus repens*	79*	–10
7	*Lamium* spp.	39	–3	*Spergula arvensis*	74*	–15
8	*Fumaria officinalis*	37	–11	*Persicaria lapathifolia*	59*	–9
9	*Galeopsis* spp.	33	–26	*Vicia* spp.	59*	+9
10	*Polygonum aviculare*	33	–15	*Sonchus arvensis*	58*	–3
	Erysimum cheiranthoides#	12	–13	*Galium spurium*#	40	+1
	Elymus repens	32	–18	*Lapsana communis*	56	–4
	Spergula arvensis	26	–12	*Poa annua*	11*	–4
	Persicaria lapathifolia	24	–6	*Lamium* spp.	41	+16
	Vicia spp.	5	–4	*Fumaria officinalis*	49*	–9
	Sonchus arvensis	28	–7	*Polygonum aviculare*	50*	–22

* = indicates significant difference in species frequencies between production systems (’Fisher’s Exact Test, p<0.05); # = Cross-comparison to the species in another production system

Some weed species were characteristic of certain regions in Finland; *Galium spurium, Sonchus asper, Tripleurospermum inodorum* and *Veronica* spp. were most frequently found in southern survey regions, whereas the frequency of *Elymus repens*, *Gnaphalium uliginosum, Matricaria matricarioides,* and *Poa annua* increased towards the east and north. Two common species, *Lamium* spp. and *Lapsana communis*, were missing or rare in some regions (6, 10, 13, 14).

The number of fields with observed wild oat infestation was 36 in total (6.5% of all fields), all of them under conventional production. In the previous survey 2007–2009 the proportion of infested fields was almost 30%, but this figure was based on the information from farmers and therefore direct comparison is not possible.

Weed density

The average density of weeds in all fields surveyed was 189 plants m^{-2} (SD = 196, median = 123, N = 549) (Table 5). However, the difference between the two production systems was considerable; the average density of weeds in organic production was 384 plants m^{-2} (SD = 248, median = 347, N = 90), in sprayed conventional fields 147 plants m^{-2} (SD = 153, median = 97, N = 441) and in unsprayed conventional fields 261 plants m^{-2} (SD = 251, median = 177, N = 18). The total weed densities were lowest in conventional production in the regions 10 (74 plants m^{-2}) and 15 (86 plants m^{-2}), differing significantly ($p < 0.05$) from the regions 1, 2, 3, 5, 7, 8, 13 and 16. Regional differences in organic fields were not found.

Ranking of the most abundant species differed between the cropping systems both in terms of species composition and the level of weed density (Fig. 2). The three most abundant weed species in organic fields were *Chenopodium album* (on average 73 plants m^{-2} vs. 10 in sprayed conventional fields), *Spergula arvensis* (50 vs. 3) and *Elymus repens* (48 vs. 7). Correspondingly, the three most abundant weed species in sprayed conventional fields were *Poa annua* (25 vs. 1), *Viola arvensis* (24 vs. 19) and *Stellaria media* (18 vs. 26). In conventional fields, the average density of *E. repens* had a decreasing trend from 12 plants m^{-2} in 2007–2009 to 7 plants m^{-2} and likewise in organic fields from 68 plants m^{-2} to 48 plants m^{-2}.

Table 5. Weed density (plants m^{-2}) by regions. + indicates Mean < 1 plant m^{-2}

Species / Taxon	Year / Region[1]																Average 2020–2022
	2020					2021						2022					
	3	7	8	10	12	4	6	11	13	14	15	1	2	5	9	16	
Achillea millefo/ium L.	+	1	0	0	+	+	1	0	+	1	+	0	0	+	0	0	+
Alopecurus geniculatus L.	0	+	0	0	0	1	+	0	1	+	0	+	0	+	0	0	1
Artemisia vulgaris L.	+	+	+	0	+	+	+	1	0	+	0	+	+	0	+	1	+
Bidens tripartita L.	+	0	+	0	+	+	0	0	0	0	0	+	+	+	0	0	+
Brassica rapa L. *ssp. oleifera* (DC.) *Metzg*	+	1	+	+	+	+	+	0	3	2	2	0	+	+	0	+	+
Capsella bursa-pastaris (L.) *Medik.*	6	2	2	+	1	3	2	2	2	1	1	1	+	2	+	3	2
Cerastium fontanum Baumg.	+	0	0	0	+	+	0	0	0	0	0	+	+	0	0	0	+
Chenopodium album L.	56	41	11	17	6	19	58	9	8	3	3	76	30	16	5	13	23
Cirsium arvense (L.) Scop.	+	1	1	1	1	1	+	1	2	1	1	1	+	1	1	1	1
Elymus repens (L.) Gould	6	19	19	20	2	12	21	11	11	25	7	9	3	26	2	37	14
Epilobium L. spp.	0	+	0	+	0	+	+	+	+	0	+	0	0	+	+	+	+
Equisetum arvense L.	2	1	1	+	2	+	+	1	+	+	2	2	+	+	+	1	1
Erysimum cheiranthoides L.	2	3	1	5	2	1	+	2	3	4	2	3	4	4	1	1	2
Fallopia convolvulus (L.) À. Löve	1	1	5	2	1	2	2	+	+	+	+	3	8	4	3	4	3
Fumaria officinalis L.	4	5	2	2	9	1	+	+	+	1	1	8	4	2	4	13	4
Galeopsis L. spp.[a]	2	13	4	2	2	11	4	1	1	1	2	6	22	4	10	3	6
Galium spurium L.[b]	38	2	14	1	30	10	+	2	+	4	3	11	6	3	5	4	9
Gnaphalium uliginosum L.	0	5	0	0	0	17	15	8	9	25	+	+	8	24	7	3	7
Lamium L. spp.[c]	34	2	19	+	12	2	0	5	0	0	17	26	2	2	7	10	9
Lapsana communis L.	7	12	2	+	23	4	3	9	0	1	5	3	18	7	+	15	7

Table 5 continues

Matricaria matricarioides (Less.) Porter	0	7	0	+	+	2	2	1	5	3	0	+	2	7	3	4	2
Myosotis arvensis (L.) Hill	+	9	+	1	+	3	1	+	+	+	+	1	2	4	3	3	2
Persicaria lapathifolia (L.) Gray	2	1	3	1	1	3	6	3	4	3	5	7	5	6	+	6	3
Plantago major L.	1	3	+	+	1	2	4	1	2	+	1	1	1	6	3	5	2
Poa annua L.	+	50	7	10	10	16	9	10	84	27	13	18	14	61	17	8	21
Polygonum aviculare L.	1	+	+	1	1	1	1	1	1	1	1	2	2	3	2	1	1
Ranunculus repens L.	+	0	+	1	2	1	+	+	2	2	+	+	+	4	+	2	1
Sonchus arvensis L.	3	2	2	5	1	3	1	2	4	5	3	1	2	4	+	11	3
Sonchus asper (L.) Hill	+	0	1	0	1	1	0	+	0	0	+	+	2	0	1	0	+
Spergula arvensis L.	6	15	9	57	2	6	9	3	13	37	17	3	7	12	1	10	11
Stachys palustris L.	0	0	0	0	+	0	0	0	0	0	1	+	+	+	0	+	+
Stellaria media (L.) Vill.	35	14	55	11	15	5	2	2	2	1	13	44	40	12	32	5	20
Taraxacum Weber spp.	1	1	1	0	+	1	1	+	+	+	1	+	+	1	+	1	1
Thlaspi arvense L.	1	2	+	+	1	1	+	+	0	+	+	+	1	+	2	0	+
Trifolium L. spp.[d]	2	+	+	+	+	1	3	0	3	+	+	+	1	2	+	+	1
Tripleurospermum inodorum (L.) Sch. Bip.	6	1	4	2	5	3	+	2	0	+	1	5	2	2	1	7	3
Tussilago farfara L.	0	+	0	0	0	+	+	0	1	+	+	+	0	+	0	1	+
Veronica L. spp.[e]	+	3	+	0	20	1	+	9	0	0	9	1	9	1	+	4	4
Vicia L. spp.[f]	1	+	1	2	1	1	+	2	1	1	1	1	1	1	+	1	1
Viola arvensis Murray [g]	7	33	5	12	12	18	19	27	16	32	6	24	66	25	34	25	23
Mean total, plants m^{-2}	228	251	171	153	163	154	167	121	178	193	122	260	263	263	153	205	189
Median total, plants m^{-2}	175	209	111	64	101	96	84	87	123	131	76	128	231	225	113	153	123

[1]Key to regions given in Figure 1 and Table 1. [a]= mainly *G. bifida* and *G. speciosa*, [b]= incl. *G. aparine*, [c]= mainly *L. purpureum,* [d]= mainly *T. repens,* [e]= mainly *V. agrestis*, [f]=mainly *V. cracca*, [g]=incl. *V. tricolor*

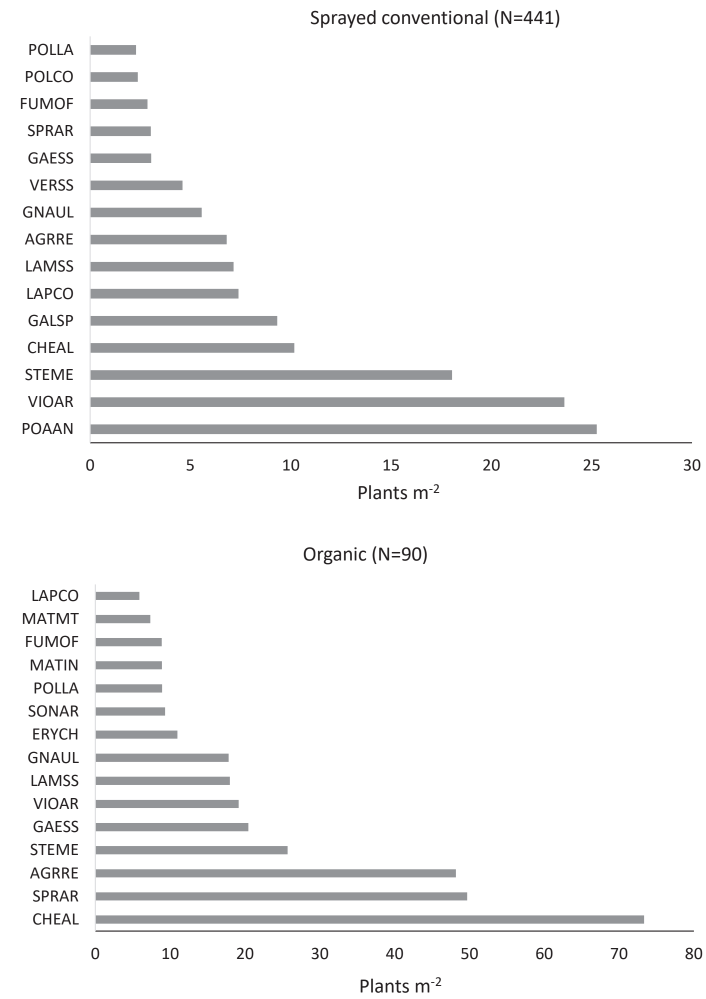

Fig. 2. Average weed density (plants m^{-2}) of most abundant weed species in sprayed conventional and organically grown spring cereal fields. EPPO codes for weed species available at https://gd.eppo.int/. Note different scale on x-axis.

Weed biomass

The average biomass production of weeds was 246 kg ha^{-1} (SD = 377, median = 98, N = 547) (Table 6). The difference between production systems was as clear as in the case of weed densities, in that for organic fields the average weed biomass was 678 kg ha^{-1} (SD = 568, median = 538, N = 90), being more than four times higher than the quantity of 151 kg ha^{-1} (SD = 243, median = 70, N = 440) grown in sprayed conventional fields. In unsprayed conventional fields the corresponding value was 399 kg ha^{-1} (SD = 327, median = 338, N = 17). The deviant total biomass in the region 7 (593 kg ha^{-1}) was due to substantially high biomass of *Chenopodium album* some organic fields and high biomass of *Poa annua* in both production systems.

Table 6. Weed biomass (kg ha^{-1}) by regions.

Category	Year / Region[1]																Average
	2020					2021						2022					2020–2022
	3	7	8	10	12	4	6	11	13	14	15	1	2	5	9	16	
Elymus repens (L.) Gould	22	123	36	82	6	49	79	44	103	151	8	27	10	101	15	98	54
Other weeds in total	258	471	126	100	134	209	268	196	234	232	102	154	163	184	137	246	191
Mean total, kg ha^{-1}	280	593	162	182	141	258	347	240	337	383	110	181	173	285	152	344	246
Median total, kg ha^{-1}	163	368	38	90	53	74	105	98	158	224	49	64	74	173	78	168	98

[1] Key to regions given in Figure 1 and Table 1

There was a marked difference in the air-dried biomass of cereal crops between production systems, being on average 3 180 kg ha^{-1} (median = 3 139) in organic fields and 5 675 kg ha^{-1} (median = 5 639) in sprayed conventional fields. The proportion of weed biomass relative to total vegetative biomass (crop + weeds) was relatively low (mean = 2.7%) in sprayed conventional fields, but considerably higher (mean = 21%) in organic fields (Fig. 3). Furthermore, the proportion of sprayed fields remained high, 96% of studied conventional fields, and the proportion of weeds out of the total biomass of crop stand was below 5% in 83% of sprayed fields, whereas it was more than 10% in 68% of organic fields.

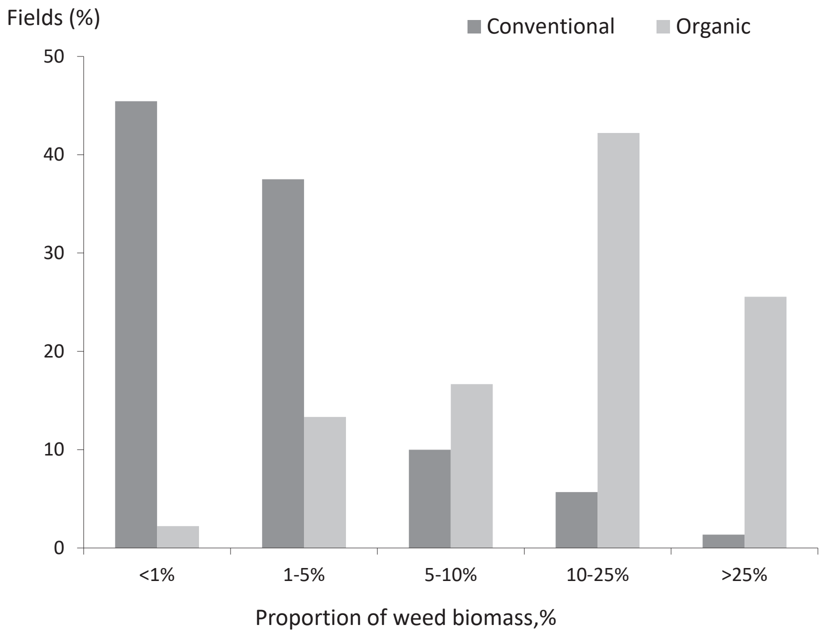

Fig 3. Relative number of fields (%) in different weed biomass classes in two production systems. Weed biomass is proportioned to total vegetative biomass (crop + weeds).

The average biomass of *Elymus repens* in organic fields was 160 kg ha^{-1}, accounting for 24% of the total weed biomass pooled over all organic fields and correspondingly the average biomass 34 kg ha^{-1} accounted for 22% in sprayed conventional fields.

Discussion

We found only minor changes in weed species diversity compared with the previous weed survey in 2007–2009 (Salonen et al. 2011). However, changes in the total occurrence of single species were dependent on production system.

The number of weed species, 115, found in small sample quadrats (0.1 m^2), was slightly lower than in previous survey when 148 species were recorded (Salonen et al. 2011). In the larger (1.0 m^2) quadrats, the number of observed species was now 138 versus 175 species, respectively. However, the average number of weed species per field remained the same in both production systems compared with the previous survey. The most probable reason for the reduction in species diversity is that the total number of surveyed fields was lower (549 vs. 595) (cf. Pollnac et al. 2009) but the decline can also be regarded as a consequence of agricultural intensification (Cirujeda et al. 2011, Richner et al. 2015, Chamorro et al. 2016, Andreasen et al. 2018). In comparison, Mukula et al. (1969) recorded 304 weed species in the first national weed survey in Finland, and 188 species were recorded in the larger quadrats of our weed survey in the 1990s (Salonen et al. 2001a).

The total number of weed species was found to be higher in conventional than in organic fields, a similar finding with the earlier weed survey (Salonen et al. 2011). This was likely due to five times higher sampling effort of conventional than organic fields. Despite of differences in the total weed species number between production systems, the differences in diversity and evenness indices were minor. A similar result has earlier been found in the comparisons of weed species diversity between production systems (Hyvönen and Salonen 2002).

Only 34 weed species exceeded the overall frequency level of 5%. Moreover, the list of 40 most frequent species was dominated by broad-leaved species and only three grass species were included. Although we found more perennial than annual species, only 16 perennial species out of 76 recorded ones were included in the list of 40 most frequent species.

In all, the frequencies of occurrence for the most common weed species were significantly higher in organic cropping than in conventional cropping. Characteristic species of organic production, *Chenopodium album, Erysimum cheiranthoides* and *Spergula arvensis*, were effectively controlled with herbicides in conventional production. *Viola arvensis* continues to be a characteristic species of cereal fields, as reported in other surveys (Andreasen and Stryhn 2008, Májeková et al. 2019, Hofmeijer et al. 2021). Only four weed species out of ten were the same in the list of the most frequent species in both production systems. Competitive perennial species *Cirsium arvense* and *Sonchus arvensis* were especially associated with organic production both in terms of frequency and density.

Concerning apparent changes among the common weed species, *Poa annua*, (+11% units increase since 2007–2009), and *Veronica* spp. (+8), have become more frequent, whereas *Myosotis arvensis* (–23), *Taraxacum* spp. (–21), *Polygonum aviculare* (–16) and *Elymus repens* (–16) have become less frequent since 2007–2009 (Salonen et al. 2011). There were three newcomers in the list of 40 most frequent species: *Bidens tripartita, Stachys palustris* and *Tussilago farfara*, which replaced *Juncus bufonius* L.*, Phleum pratense* L. and *Poa pratensis* L.

The increased occurrence of *Poa annua* is noteworthy because its frequency (42%) significantly increased since the two previous surveys, having been 31% in 2007–2009 (Salonen et al. 2011) and only 12% in 1997–1999 (Salonen et al. 2001a). However, *P. annua* was characteristic only in conventional production in terms of frequency (48%) and average density (25 plants m^{-2}) compared with organic production (11% and 1 plant m^{-2}). The success of *P. annua* is in line with observations in the Nordic and Baltic countries (Tørresen et al. 2006, Andreasen and Stryhn 2008, Nečajeva et al. 2018) linked with moist soil conditions, adaptation to compact soil, successful over-wintering and substantial phenotypic and genotypic variability (Warwick 1979). Increased area of reduced tillage in survey fields since the 1990s has likely favoured *P. annua*, as reported earlier in Norway (Tørresen et al. 2003).

The abundance of weeds remained at the same level in conventional but declined in organic production since the previous survey in 2007–2009 (Salonen et al. 2011). The decline in total weed biomass in organic production was primarily due to *Elymus repens*, with 34% lower biomass than in 2007–2009. *E. repens* is still the most harmful weed species for spring cereals in Finland, producing on average 23% of total weed biomass in both production systems compared with an average of 29% in the earlier survey. In conventional production, the declining trend of *E. repens* biomass began in the late 1990s (Salonen et al. 2013) as a consequence of common use of glyphosate, which has been the most sold herbicide in Finland for more than two decades (Tukes 2023). In comparison, a similar decline in *E. repens* was observed earlier in Denmark (Andreasen and Stryhn 2008) and Latvia (Nečajeva et al. 2018), and also associated with increased use of glyphosate.

The benefit of using herbicides in reducing weed competition against crop is clearly demonstrated by comparing weed biomass results from sprayed and unsprayed conventional fields. Weed management in conventional production of spring cereals has relied on herbicide use in Finland, as well as in 96% of conventional fields in this survey. This has resulted in relatively low total abundance of weeds and a declining trend in *Elymus repens* infestation. The scenario for the future is strongly dependent on the registration of glyphosate (EC 2022) and the actions to reduce the overall use and risk of chemical pesticides by 50% by 2030 in the EU (EC 2020).

As a newly observed challenge, increased infestation of *Poa annua* calls for rapid development of weed management strategies in conventional production. In contrast, the evolving risk of herbicide resistance in *Stellaria media* has been acknowledged and successfully taken into account among farmers who have adapted their herbicide use either by replacing or supplementing sulfonylureas with products with different modes of action.

Conclusions

As demonstrated in our survey, weed communities provide floral diversity to spring cereal fields but also represent a notable threat to cereal production not only in organic production but also in unsprayed conventional fields. Integrated cropping measures that promote crop competition as part of an integrated weed management strategy will become necessary to reach EU pesticide targets. Efforts to establish competitive crop stands and develop mechanical weed control methods are important for both production systems.

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Appendix

Frequency (% in descending order in each region) of additional weed species observed in survey fields (N=549) by region. EPPO codes for weed species available at https://gd.eppo.int/

1. Jokioinen (45 fields)		2. Lammi (40)		3. Nauvo/Korppoo(25)		4. Tammela (42)	
Weed	Freq-%	Weed	Freq-%	Weed	Freq-%	Weed	Freq-%
LTHPR	4	POLHY	5	EPHHE	36	IUNBU	14
BARVU	2	SECCE	5	CENCY	8	POLHY	14
CIRSS	2	ALOPR	3	GERSY	8	PHLPR	12
CRYCA	2	BARVU	3	SENVU	8	RORSY	12
EPHHE	2	LEBAU	3	ACHPT	4	AVESA	7
PHLPR	2	PHLPR	3	CHYLE	4	BARVU	7
PHRCO	2	PIEAB	3	LINVU	4	HORVS	7
POLPE	2	POAPR	3	MENAR	4	SENVU	7
RORSY	2	PTLAN	3	RAPRA	4	AGSTE	5
RUMSS	2	RUMSS	3	SONOL	4	LTHPR	5
URTDI	2	SENVU	3			RUMAA	5
						SALCA	5
						VIOSS	5
						ACHPT	2
						ANKSY	2
						ANRSY	2
						ATXPA	2
						AVEFA	2
						CIRSS	2
						DACGL	2
						FAGES	2
						MEDSS	2
						POAPR	2
						POATR	2
						RUBID	2
						RUMSS	2
						TRZAS	2
						URTDI	2

5. Laukaa/Toivakka (37)		6. Kitee (26)		7. Mikkeli (25)		8. Lieto/Paimio (44)	
Weed	Freq-%	Weed	Freq-%	Weed	Freq-%	Weed	Freq-%
RAPRA	16	RORSY	15	CRYCA	8	BRSNN	11
RUMSS	14	URTDI	15	LINVU	8	RUMSS	7
CRYCA	8	LINVU	12	AEOPO	4	PHLPR	7
CIRSS	5	LTHPR	12	APESS	4	PIUSI	5
DECCA	5	ACHPT	8	CENCY	4	CIRSS	2
EPICT	5	AVESA	8	HORVS	4	EPHHE	2
PRUVU	5	PHLPR	8	LTHPR	4	FESPR	2
URTUR	5	RUMAA	8	PHLPR	4	LOLSS	2
FAGES	3	ALCSS	4	POATR	4	LTHPR	2
LEBAU	3	HORVS	4	POLHY	4	PIEAB	2
PHLPR	3	IUNBU	4			SENVU	2
PHRCO	3	KNAAR	4			VICFX	2
PIBSA	3	LEBAU	4				
PIUSI	3	POLHY	4				
POAPR	3	RAPRA	4				
POLHY	3	TRZAS	4				
RORPA	3	VIOSS	4				
RUMAA	3						
SENVU	3						
SINAL	3						
URTDI	3						

9. Laihia (42)		10. Nivala (27)		11. Laitila (41)		12. Nurmijärvi (41)	
Weed	Freq-%	Weed	Freq-%	Weed	Freq-%	Weed	Freq-%
AVESA	14	HORVS	26	AVEFA	2	CRYCA	10
PIEAB	7	LEBAU	11	CHYLE	2	LOLSS	7
POLPE	7	RUMSS	7	EPHHE	2	LEBAU	5
HORVS	7	RUMAA	7	EPIAC	2	PHRCO	5
MEDSS	7	RORSY	4	PHLPR	2	POLPE	5
CVPTE	5	CENCY	4	SOLTU	2	SENVU	5
PHLPR	5	LTHPR	4	SONOL	2	ACHPT	2
PIUSI	5	POAPR	4			ANKSY	2
APESS	2	RORIS	4			AVESA	2
CIRSS	2	RUMAC	4			BARVU	2
LEBAU	2	URTDI	4			BRSNN	2
RORSY	2	VERLO	4			CIRSS	2
		VIOSS	4			CLMAR	2
						FESPR	2
						LINVU	2
						LTHPR	2
						PHLPR	2
						PIEAB	2
						PIUSI	2
						POLHY	2
						RUMSS	2
						SONOL	2
						URTDI	2

13. Vieremä (25)		14. Kihniö/Parkano (26)		15. Iitti (28)		16. Imatra/Ruoholahti (35)	
Weed	Freq-%	Weed	Freq-%	Weed	Freq-%	Weed	Freq-%
AVESA	24	HORVS	23	PTLAN	11	LINVU	11
LTHPR	16	CHYLE	15	EROCI	7	PHCTA	9
LEBAU	12	AVESA	12	LEBAU	7	CHYLE	6
RUMAA	12	POLHY	12	RUMAA	7	EROCI	6
HORVS	8	RANAC	12	TTTMM	7	PHLPR	6
PHLPR	8	ACHPT	8	ACHPT	4	PTLAN	6
PIUSI	8	FESPR	8	CRYCA	4	URTDI	6
RUMSS	8	LOLPE	8	LINVU	4	AEOPO	3
FESOV	4	LTHPR	8	LTHPR	4	CNISA	3
HIEJU	4	RUMAA	8	POLHY	4	HYPMA	3
LINVU	4	IUNBU	4	SAXSS	4	MENAR	3
LUPPO	4	LEBAU	4			PHRCO	3
PHCTA	4	MELRU	4			POAPR	3
PTLER	4	RUMSS	4			POATR	3
RORIS	4	SAIPR	4			RUBID	3
		URTDI	4			TRZAS	3