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Supporting biodiversity by occasionally abstaining weed control?

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ABSTRACT

How much does weed biomass increase if one abstains weed control in a single year, and would that increase involve weed species that may be beneficial to pollinating insects? To answer these questions, data on weed biomass were analysed from untreated and chemically treated plots in nearly 2000 field experiments conducted in spring- and autumn-sown cereal crops in Sweden. About 50% of the weed biomass was of the 30 species classified as 'pollinator friendly' based on the amounts of pollen and/or nectar produced. Increases were slightly larger in autumn- than spring-sown crops. The increase in biomass varied somewhat geographically and due to soil type, while type of crop seemed less important. Most important for the increase was the overall abundance of weeds in a field. We conclude that applying a single-year no-treatment strategy would be most suited in fields with relatively low weed abundance. Considering the low cost, potential acreage covered and assumed biodiversity benefit, such a strategy might be a preferable environmental mitigation method. To further evaluate this potential mitigation methods, data on biodiversity and pollinator visits to weed flowers within arable fields would be welcome, as well as potential side effects, like weed control challenges in following years.

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Sweden; cereal crop; weed; pollinator

Introduction

Since the dawn of agriculture, control of undesired plants, i.e. weeds, has been an important part of crop production (Zimdahl & Basinger 2024). Since the introduction of widespread modern chemical control methods during the 1950s, amounts of undesired plants have been modest in conventionally grown fields (Stoate et al. 2001, Robinson & Sutherland 2002). Nevertheless, weed control remains an important part of cropping globally both in terms of direct costs and yield losses (Chauhan 2020, MacLaren et al. 2020).

On the other hand, weeds make up an important part of biodiversity on arable land and are of importance to other organisms like insects and birds (Chiverton & Sotherton 1991, Chiverton 1999, Shrubb 2003, Milberg et al. 2025). What is less clear is how important weeds on arable land are for pollinating insects like wild bees and hoverflies: some species are known to attract pollinators (e.g. Balfour & Ratnieks 2022), while other species self-pollinate and provide no reward for pollinators. Further, the low abundance of weeds today, created by decades of efficient weed control, suggests they may be relatively unimportant for pollinators. On the other hand, the large acreage of arable land, dominated by annual crops, might still suggest relevance for the landscape-level abundance of pollinators.

With the current decline in pollinator population in agricultural landscapes (LeBuhn & Luna 2021, Stout & Dicks 2022, Brunet & Fragoso 2024), there is currently interest in environmental mitigation in arable fields (Eigenbrode & Adhikari 2023), ranging from overall farming policy like organic farming (Hole et al. 2005, Langlois et al. 2020, Stein-Bachinger et al. 2021, Tscharntke et al. 2021) to sowing flower strips to enhance pollinators (e.g. McHugh et al. 2022, Blumgart et al. 2023), or intercropping flowers within fields (Boetzl et al. 2023). Some of these mitigations specifically target pollinators, while others benefit overall biodiversity in agricultural landscapes. Furthermore, there seems to be a re-consideration of the biodiversity value of weeds (Nicholls & Altieri 2013, Bretagnolle & Gaba 2015, Balfour & Ratnieks 2022, Chandrasena 2022, Esposito et al. 2023). Terms like 'benign weeds' (Aguilar et al. 2003, Esposito et al. 2023) and 'beneficial weeds' (Storkey & Westbury 2007) are further evidence of ongoing change in our view of the role of weeds in agroecosystems.

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In the current contribution, a new alternative, potential pollinator-boosting method is explored: 'Abstaining weed Control in a Single Year' (ACSY). That would allow weeds to temporarily flourish, but prevent a more long-term buildup of weed populations as chemical control methods would resume in the following year(s). This approach would build upon the currently low weed population densities (Andreasen et al. 1996, Andreasen & Streibig 2011), the fact that weed control is not always economically justified (Milberg & Hallgren 2004), and the assumption that a single year's seeding would not be sufficient to create an out of control weed situation.

In the current study, a first step to evaluate ACSY is taken by using data from a total of 1987 agricultural field experiments on weed control – with both chemically treated and untreated plots. Our aims were to:

(i) assess the potential increase in weed biomass under Swedish conditions if ACSY would be applied;
(ii) evaluate to what extent this increase involved weed species useful for pollinators;
(iii) the increase was evaluated according to geographic regions, soil types, crops and weed density, to identify potential situations that might result in large increases in weed biomass, and hence substantial buildup of weed populations and threat to crop yield.

Material and methods

Field experiments

The experiments were carried out (1969–1994) in cereal crops, mainly in the southern part of Sweden, and have been used in some previous publications (Hallgren 1996, Hallgren et al. 1999, Milberg et al. 2000, 2001, Milberg & Hallgren 2004). The experiments were often conducted by the regional Agricultural Societies on their farms or on fields belonging to contracted private farms. Experiments were not randomly or systematically allocated to fields, but were slanted towards large-scale farming in the main agricultural regions in Sweden, and towards well-run farm operations.

The experiments were conducted to evaluate new herbicides against dicotyledonous weeds in cereal crops in Sweden (Hallgren 1996). Each experiment consisted of four blocks with randomly distributed treatment plots within the blocks (Figure 2). Treatment plot size was 35–50 m^2. The number of treatments compared in experiments varied and involved different old and new herbicides, different doses, etc. All experiments had two treatments in common: an untreated control (no weed control) and a treatment with a standard herbicide (hereafter called 'treated'), allowing comparisons of efficacy over space and time. The standard herbicide during this time period was Oxitril, a mixture of (i) 300 g L^{-1} dichlorprop, (ii) 130 g L^{-1} MCPA, (iii) 58 g L^{-1} ioxynil and (iv) 9 38 g L^{-1} bromoxynil.

In autumn-sown crops, the herbicide was applied at 4.5–5.0 L ha^{-1} when growth commenced in the spring while in spring-sown crops, 2.5–3.0 L ha^{-1} was applied when the crop had 3–4 leaves. This herbicide and these rates are effective against most annual dicot weed species. Less successful control occurs for grass species, perennial species, *Viola arvensis* and *Fumaria officinalis*.

As these trials were set up to study the control of annual dicotyledonous weeds, perennial weeds were rarer than expected as were annual grass weeds. Many trials had few weeds (Milberg & Hallgren 2004), which indicate an overall aim to apply and test new herbicides under conditions typical for south Swedish conventional agriculture at the time. Hence, the untreated plots represent a reasonable sample of what would be expected under ACSY in southern Sweden.

In late June – early July weeds were collected, sorted to species and their fresh weight measured in at least two sample plots (each of 0.25 m^2) per treatment plot. According to the sampling protocol for the experiments, the sample area should be sufficiently large to include at least 20 plants or shoots of the most frequent species within untreated plots. The occurrence of a species in an experiment was only noted when there were $\geq$5 plants per square metre. Species with fewer individuals were grouped together in an 'other weeds' category (10.7% of the total weed biomass recorded).

In the present study, only weed biomass data from untreated and treated plots were used. These data were transcribed from full paper records to a digital format around 1990 (the paper record has since been discarded). Weed biomass data is based on several sample plots, and here used as the average per square metre of the four replicated treatment plots (n.b. that the data also contained numbers per square

metre). Hence, from each experiment there was one species-wise biomass value for the untreated plots and one for the treated plots.

The geographic location of an experiment was noted as the county (the exact position is not known), which was too detailed for the current purposes, so the Swedish NUTS 2 regions were used instead (Figure 1) that merges counties (https://ec.europa.eu/eurostat/web/nuts/maps). These regions span mainly over a south/north gradient of decreasing temperature and also over a west/east gradient of decreasing precipitation. There were 1064 experiments in autumn-sown and 923 in spring-sown cereals. Soil type was assessed by soil samples taken and noted as one of seven different types: Sandy, Fine sand, Silty, Loamy, Silty clay loam, heavy clay soil, organogenic (soil data was missing from 242 experiments). Weed abundance in treated plots was used to construct quartiles, i.e. the experiments with 25% lowest abundance, etc. Treated plots were preferred, as they correspond to fields under normal production, and it also represent the view a farmer gets when potentially deciding on a mitigation strategy. Consequently, each experiment was given a score between 1 and 4, from the lowest to highest quartiles.

Species attributes

Information on pollinator usage of arable weeds is hard to come by, but floral rewards might constitute a proxy. Therefore, a recent compilation of Swedish plant species' attributes was used (Tyler et al. 2021), where the production of both nectar and pollen is considered. Species are put into one of the following categories (Tyler et al. 2021):

(1) no nectar production (0 g sugar m^{-2} $year^{-1}$) and no collectable pollen;
(2) nectar production insignificant (<0.2 g) or absent but with low but significant amounts of collectable pollen;
(3) nectar production small (0.2–5 g) or lower but with copious collectable pollen;
(4) nectar production modest (5–20 g);
(5) rather large (20–50 g);
(6) large (50–200 g);
(7) very large (>200 g).

The compilation by Tyler et al. (2021) lacked information on three weed species in the data. Therefore, corresponding values were extracted from Baude et al. (2016; *Taraxacum* coll., *Pilosella* coll.) and Ouvrard & Jacquemart (2018, *Fumaria officinalis*). 'Pollinator-friendly weeds' were defined as those belonging to 4–6 (no weed in our study belonged to 7) following Milberg et al. (2024, 2025).

Statistical evaluation

The difference in biomass between untreated plots and treated plots was calculated as this would represent the increase in biomass per square metre expected if applying ACSY.

First, the sum of biomass per square metre of all pollinator-friendly weeds (index 4–6) and of other weeds (1–3) was calculated separately. The 'increase' was then calculated by subtracting the treated plots from the untreated ones. Hence, each experiment contributed one data point.

To achieve normality, the increase data was square-root transformed.

Second, a number of factors could potentially explain the variation in biomass increase among experiments. There was no conscious 'design' involved: crops were not randomly distributed among regions or soil types, and soil types in themselves were not random within regions, etc. Given these limitations in data, an 'estimation statistics' approach was chosen focusing on estimating effect sizes (Cumming 2009, Claridge-Chang & Assam 2016, Cumming & Calin-Jageman 2016). Consequently, mean differences with 95% confidence intervals for five different types of combinations of experiments was calculated:

(i) autumn- vs spring-sown experiments;
(ii) weed abundance (in treated plots): 4 different classes;
(iii) geographic region: NUTS 2 regions;

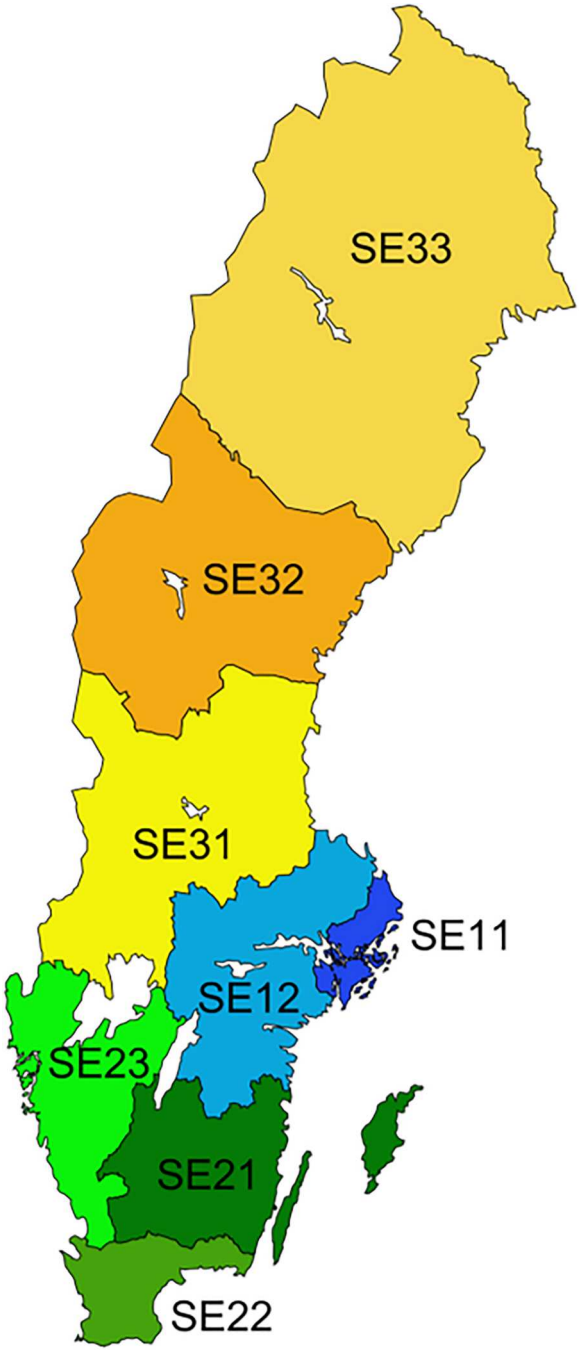

Figure 1. Swedish NUTS regions used in the current study.

(iv) soil types: seven different types;
(v) crop species: winter wheat, winter rye, winter barley (autumn-sown), and spring wheat, spring barley and oats (spring-sown).

For (ii)–(v), we present estimates for autumn- and spring-sown cereals separately. Third, to provide an overview of the data, and the relative importance of each group of variables, plus 'year', we conducted variance component analyses with Type II sum of squares using Statistica 13 (TIBCO Software Inc.).

Fourth, for individual species the average per square metre (with $CI_{95\%}$) in the treated plots over all experiments was calculated (i.e. their abundance in chemically treated Swedish fields). Furthermore, the increase (untreated minus treated) was also averaged (i.e. their abundance if applying ACSY).

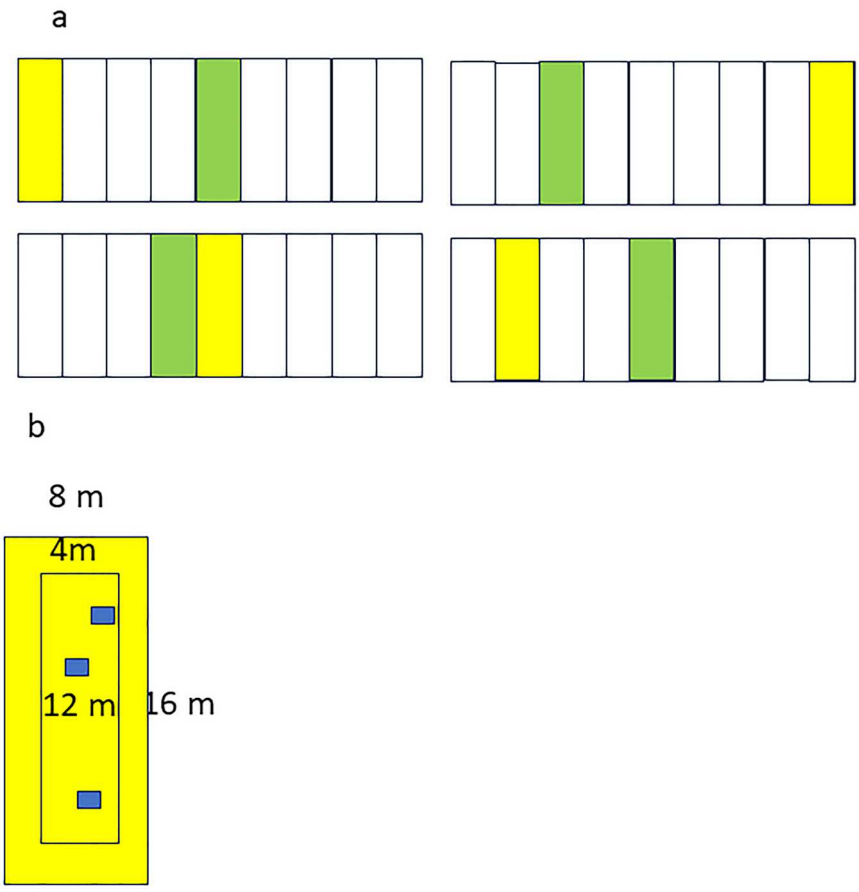

Figure 2. An example of one of the 1987 field experiments; in this case comparing nine weed control treatments: (a) the four blocks, each with nine treatment plots. Yellow indicates the untreated control plots, green the treated plots (oxitril), while white were other treatments not considered in the present study. (b) A treatment plot showing the inner harvested area and three sample plots where weeds were harvested. N.b. That (i) the layout of the blocks varied due to the local conditions in a field, (ii) the number of treatments compared varied, (iii) treatments were randomly allocated to treatment plots within blocks, (iv) the number of sampling plots were adapted after the weed abundance in a treatment plot, with a minimum of two when weeds were abundant, and more when scarce.

Results

In total, 66 taxa were recorded as weeds in the experiments, with 30 being classified as pollinator friendly (Table 1). Most of the species were annual weeds s.s. while and two were self-sown crops (*Trifolium pratense* and *Brassica rapa/Brassica napus*).

Increase in weed biomass under ACSY

As expected, plots where weeds had not been chemically treated ('untreated') had more weed biomass than herbicide treated plots ('treated'). Hence, abstaining weed control led to an increase in weed biomass. For most species it involved a 10-fold increase, but with large differences among species (Table 1). For example, biomass of *Equisetum arvense* doubled on average, while *Sinapis arvensis*, *Capsella bursa-pastoris* and *Thlaspi arvense* increased more than 100-fold (Table 1).

Overall, the pollinator-friendly weeds made up about 50% of the increase, and most often they increased to the same degree as the other weeds (Figures 3 and 4).

The larger increase occurred in autumn-sown crops, where also a larger proportion of the biomass increase was made up of pollinator-friendly weeds (Figure 3).

Variables affecting the increase

Of the variables considered, weed abundance explained most of the variation in biomass increase, followed by region, crops, soil types and years (Table 2).

Table 1. Weeds recorded in the weed control experiments, their average biomass as (95% confidence interval within parenthesis) in treated plots, and the increase when not subjected to chemical weed control.

		Autumn-sown		Spring-sown	
Species	Family	Biomass (g/m^2)	Biomass increase (g/m^2)	Biomass (g/m^2)	Biomass increase (g/m^2)
POLLINATOR INDEX 6					
Stachys palustris L.	Lamiaceae			0.030 (0.036)	0.063 (0.085)
Trifolium pratense L.	Fabaceae			0.0016 (0.0031)	0.0082 (0.016)
Achillea ptarmica L.	Asteraceae			0	0.014 (0.028)
Taraxacum officinale (L.) Weber ex F.H. Wigg.	Asteraceae	0.13 (0.18)	0.27 (0.31)		
SUM		***0.13***	***0.27***	***0.03***	***0.09***
POLLINATOR INDEX 5					
Galeopsis speciosa Mill./*Galeopsis tetrahit* L./*Galeopsis bifida* Boenn.	Lamiaceae	1.81 (0.77)	15.4 (5.4)	5.4 (2.2)	38.5 (7.8)
Fallopia convolvulus (L.) Á. Löve	Polygonaceae	0.160 (0.061)	0.45 (0.69)	0.24 (0.085)	4.2 (1.1)
Centaurea cyanus L.	Asteraceae	0.28 (0.18)	10.8 (7.7)		
Brassica rapa L./*Brassica napus* L.	Brassicaceae	0.0085 (0.0108)	0.64 (0.92)	0.37 (0.23)	16.9 (5.0)
Cirsium arvense (L.) Scop.	Asteraceae	0.55 (0.63)	0.40 (0.97)	0.77 (0.35)	5.1 (2.6)
Erysimum cheiranthoides L. ssp. *cheiranthoides*	Brassicaceae	0.0065 (0.0087)	0.011(0.055)	0.041 (0.033)	2.5 (1.4)
Anthemis arvensis L.	Asteraceae	0	0.10 (0.20)		
Anchusa arvensis (L.) M. Bieb.	Boraginaceae			0	0.054 (0.106)
SUM		***2.82***	***27.81***	***6.71***	***67.25***
POLLINATOR INDEX 4					
Tripleurospermum inodorum (L.) Sch. Bip.	Asteraceae	7.7 (1.7)	84.6 (14.1)	0.33 (0.14)	4.4 (1.4)
Myosotis arvensis (L.) Hill	Boraginaceae	2.67 (0.67)	10.8 (2.3)	0.44 (0.18)	3.0 (1.0)
Lamium purpureum L./*Lamium hybridum* Vill./*Lamium amplexicaule* L.	Lamiaceae	1.18 (0.49)	3.8 (1.8)	0.47 (0.17)	3.4 (1.1)
Matricaria chamomilla L.	Asteraceae	0.42 (0.26)	3.0 (2.0)	0.040 (0.033)	1.4 (2.0)
Buglossoides arvensis (L.) I. M. Johnst.	Boraginaceae	0.12 (0.12)	0.88 (0.89)	0.024 (0.034)	0.19 (0.18)
Sinapis arvensis L.	Brassicaceae	0.041 (0.057)	1.04 (1.34)	0.035 (0.037)	4.1 (1.9)
Vicia cracca L.	Fabaceae	0.075 (0.147)	0.045 (0.12)		
Sonchus arvensis L.	Asteraceae	0.12 (0.23)	−0.20 (0.40)	1.26 (0.75)	3.9 (2.3)
Ranunculus repens L./*R. acris* L.	Ranunculaceae	0	0.091 (0.18)	0	0.020 (0.031)
Sonchus oleraceus L.	Asteraceae			0.25 (0.29)	0.75 (0.52)
Brassica rapa L.	Brassicaceae			0.0044 (0.0048)	0.91 (0.65)
Barbarea vulgaris R. Br.	Brassicaceae			0.00052 (0.00102)	0.049 (0.080)
Convolvulus arvensis L.	Convolvulaceae		0.00060 (0.00117)	0.029 (0.033)	
Raphanus raphanistrum L.	Brassicaceae			0	0.74 (1.39)
Bidens tripartita L.	Asteraceae			0.0021 (0.0042)	0.20 (0.37)
Silene latifolia Poir.	Caryophyllaceae		0.0011 (0.0022)	0.027 (0.053)	
Euphorbia helioscopia L.	Euphorbiaceae		0.0036 (0.0070)	0.00074 (0.00144)	
Silene noctiflora L.	Caryophyllaceae		0	0.017 (0.034)	
SUM		***12.34***	***103***	***2.87***	***23.18***
POLLINATOR INDEX 3					
Stellaria media (L.) Vill.	Caryophyllaceae	12.8 (3.8)	60.9 (10.4)	1.93 (0.52)	19.9 (4.8)
Viola arvensis Murray	Violaceae	5.7 (1.6)	5.8 (3.0)	1.76 (0.45)	8.1 (2.0)
Veronica arvensis L./*Veronica agrestis* L./*Veronica persica* Poir.	Plantaginaceae	1.78 (0.64)	9.7 (2.9)	0.070 (0.058)	0.53 (0.29)
Polygonum aviculare L.	Polygonaceae	0.31 (0.13)	1.5 (0.78)	0.129 (0.076)	0.98(0.40)
Capsella bursa-pastoris (L.) Medik.	Brassicaceae	0.075 (0.053)	3.3 (1.1)	0.014 (0.011)	1.49 (0.68)
Thlaspi arvense L.	Brassicaceae	0.069 (0.078)	1.66 (0.98)	0.015 (0.019)	3.1 (1.0)
Papaver dubium L./*Papaver rhoeas* L./*Papaver argemone* L.	Papaveraceae	0.36 (0.47)	3.9 (2.0)		
Consolida regalis Gray	Ranunculaceae	0.027 (0.027)	0.42 (0.53)		
Persicaria lapathifolia (L.) Delarbre	Polygonaceae	0.11 (0.14)	−0.012 (0.451)	0.73 (0.37)	18.6 (5.7)
Lapsana communis L.	Asteraceae	0.023 (0.019)	0.24 (0.26)	0.106 (0.075)	3.1 (1.7)
Fumaria officinalis L.	Papaveraceae	0.043 (0.038)	−0.16 (0.43)	1.23 (0.47)	2.54 (0.63)
Cerastium fontanum Baumg.	Caryophyllaceae	0.013 (0.015)	0.14 (0.16)		
Spergularia rubra (L.) J. Presl & C. Presl	Caryophyllaceae	0.013 (0.023)	0.12 (0.18)		
Odontites vernus (Bellardi) Dumort.	Orobanchaceae	0	0.020 (0.028)		
Viola tricolor L.	Violaceae	0.044 (0.086)	−0.00154		
Stellaria graminea L.	Caryophyllaceae	0.024 (0.048)	−0.028 (0.055)		
Valerianella locusta (L.) Laterr.	Caprifoliaceae	0.0010 (0.0020)	0.011 (0.022)		
Vicia tetrasperma (L.) Schreb./*Vicia hirsuta* (L.) Gray	Fabaceae			0.0098 (0.0158)	0.26 (0.40)
Gnaphalium uliginosum L.	Asteraceae			0	0.0065 (0.0108)
Hieracium/Pilosella	Asteraceae			0.039 (0.066)	0.18 (0.17)
SUM		***21.44***	***87.44***	***6.02***	***58.87***
POLLINATOR INDEX 2					
Galium aparine L.	Rubiaceae	1.12 (0.38)	20.7 (4.8)	0.46 (0.24)	3.5 (1.5)

(*Continued*)

Table 1. Continued.

Species	Family	Autumn-sown		Spring-sown	
		Biomass (g/m^2)	Biomass increase (g/m^2)	Biomass (g/m^2)	Biomass increase (g/m^2)
Erodium cicutarium (L.) L'Hér./*Geranium pusillum* L.	Geraniaceae	0.054 (0.094)	0.13 (0.22)	0.0027 (0.0054)	0.10 (0.14)
Spergula arvensis L.	Caryophyllaceae	0.0054 (0.0079)	0.099 (0.155)	1.21 (0.59)	5.3 (1.9)
Myosurus minimus L.	Ranunculaceae	0.0058 (0.0081)	0.12 (0.19)		
Galium mollugo L.	Rubiaceae	0.0071 (0.0103)	0.081 (0.093)		
Draba verna L.	Brassicaceae	0.00094 (0.00184)	0.0019 (0.0037)		
Arabidopsis thaliana (L.) Heynh.	Brassicaceae	0	0.027 (0.053)		
Atriplex patula L.	Amaranthaceae		0.0099 (0.0194)	0.0075 (0.0146)	
SUM		***1.19***	***21.11***	***1.68***	***8.97***
POLLINATOR INDEX 1					
Chenopodium album L./*Chenopodium suecicum* Murr/*Lipandra polysperma* (L.) S. Fuentes, Uotila, & Borsch	Amaranthaceae	0.13 (0.12)	1.51 (1.18)	0.64 (0.24)	34.4 (6.2)
Poa annua L.	Poaceae	2.3 (2.3)	−1.83 (1.99)	0.29 (0.27)	0.014 (0.327)
Apera spica-venti (L.) P. Beauv.	Poaceae	2.6 (1.4)	−1.17 (1.72)	0.024 (0.047)	−0.019 (0.037)
Equisetum arvense L.	Equisetaceae	0.38 (0.25)	−2.05 (1.88)	0.42 (0.39)	0.69 (0.47)
Elytrigia repens (L.) Desv. ex Nevski	Poaceae	0.76 (0.67)	−0.61 (0.78)	2.5 (1.0)	0.12 (0.55)
Aphanes arvensis L.	Rosaceae	0.0037 (0.0073)	−0.020 (0.039)		
Plantago major L.	Plantaginaceae		0	0.0054 (0.0106)	
Lysimachia arvensis (L.) U. Manns & Anderb.	Primulaceae			0	0.0054 (0.0106)
SUM		***6.2***	***−4.16***	***3.88***	***35.2***

Weed biomass in treated plots. As expected, experiments with more weeds (in chemically treated control plots), manifested larger increases in weed biomass in unsprayed control plots (Figures 4a and b). In the two quartiles with the least weeds (i.e. 0–50% of the experiments), increases were 50–90 g/m^2 (Figures 4a and b). The 50–75% quartile had twice as much weed while the experiment with the highest weed biomass (quartile 75–100%) had four to five times more (Figures 4a and b).

Regional differences. Weed biomass increase varied among regions. But when comparing spring- and autumn-sown crops, regional differences in weed biomass increase were inconsistent. A striking results was that the two southernmost regions mainly favoured non-pollinator-friendly weeds (Figures 4c and d). This was particularly so in autumn-sown cereals (Figure 4d). Further north, however, pollinator-friendly weeds were favoured (Figures 4c and d).

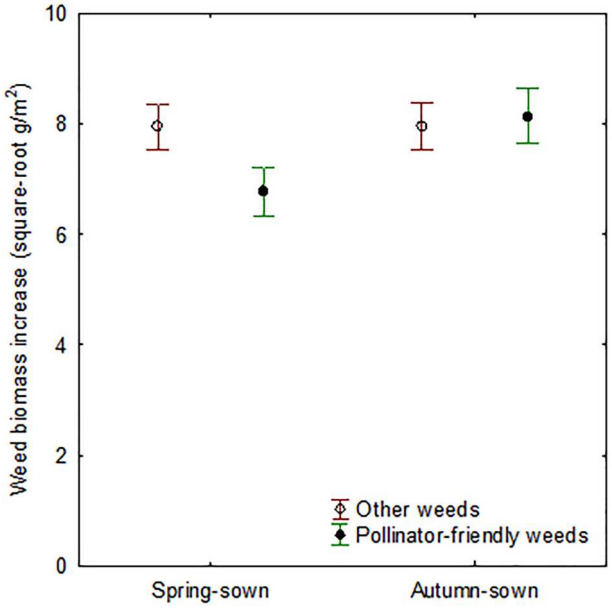

Figure 3. Increase in weed biomass ($CI_{95\%}$) when abstaining weed control. Data from numerous weed control field trials in Sweden, with weeds classified as pollinator-friendly or not. Weed biomass data has been square-root transformed.

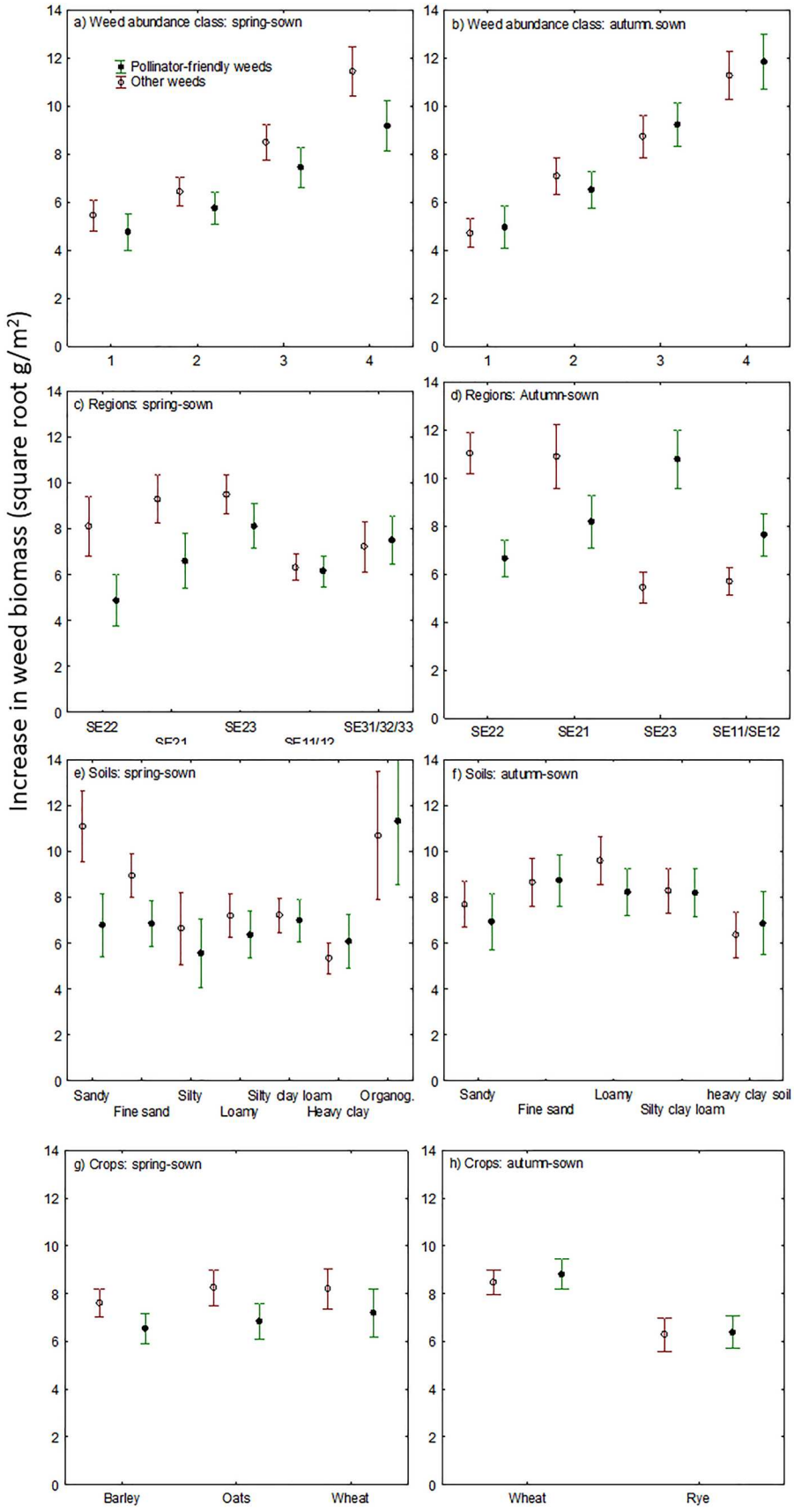

Figure 4. Increase ($CI_{95\%}$) in weed biomass when abstaining weed control according to (a, b) weed abundance; (c, d) geographic region (see Figure 1); (e, f) soil types and (g, h) crops. Data from Swedish field trials on weed control (biomass in untreated plots minus biomass in standard herbicide plots). Only crops, regions and soils with >20 trials are shown. Weeds classified as pollinator-friendly (solid symbol) or not (empty symbol). The data had been square-root transformed.

Table 2. Variance component analysis of the increase in biomass data, using Type II sum of squares, and broken down by spring and autumn-sown crops and pollinator-friendly and other weeds.

			Pollinator-friendly weeds		Other weeds	
	df	Df	*F*	*p*	*F*	*p*
AUTUMN-SOWN						
Weed abundance	3	882	40.533	**>0.00001**	30.826	**>0.00001**
Region	4	882	11.815	**>0.00001**	26.300	**>0.00001**
Crops	2	882	6.996	**0.00097**	9.931	**0.00005**
Soils	6	882	1.194	0.30694	2.575	**0.01769**
Year	25	882	2.627	**0.00003**	2.630	**0.00003**
SPRING-SOWN						
Weed abundance	3	785	10.479	**>0.00001**	28.774	**>0.00001**
Region	4	785	3.992	**0.00326**	1.928	0.10388
Crops	2	785	0.169	0.84431	0.605	0.54655
Soils	6	785	2.874	**0.00892**	4.185	**0.00038**
Year	21	785	1.421	0.09952	1.403	0.10750

Soil types. Soil types also affected the increase in weed biomass, with fine sand, silty and loamy soils having larger increases (Figures 4e and f). At the same time, there were no consistent differences in the increase of pollinator-friendly weeds and other weeds (Figures 4e and f).

Crops. Crop differences were apparent only in autumn-sown crops, with rye showing smaller increases in weed biomass than winter wheat (Figures 4g and h).

Discussion

The current study, that was based on nearly 2000 Swedish weed field experiments, reached four findings relevant to ACSY. First, the expected weed biomass increases varied among species from 2- to 100-fold (Table 1). Part of this variation was likely caused by different susceptibility to the herbicide used. Second, there were only small differences among pollinator-friendly weeds and other weeds (Figures 3 and 4). Hence, a substantial part of the increase would be potentially beneficial to pollinators. Third, the increase was often largest in autumn-sown cereals that often involved a higher proportion of pollinator-friendly weeds (Figure 3). It was expected that the longer growth season of autumn- than spring-sown crops would produce more weed biomass (Milberg et al. 2000), but not how much of such an increase would potentially benefit pollinators. Fourth, there were only modest differences in weed increase due to geographic region, soil type or crop species, but experiments with an abundance of weeds (in treated plots) resulted in a larger increase in biomass (Figures 4a and b). It is encouraging that the response seems unaffected by most agricultural factors, and hence that these can be ignored if implementing ACSY. What cannot be ignored, however, is the abundance of weeds in a field, and the challenge is to find a cut-off over which ACSY should be avoided.

A few caveats should be considered. First, the data were collected some years ago and environmental conditions (climate) and agricultural practices have changed since. For example, spring-sown crops have decreased in use while autumn-sown have slightly increased (SOS 2020). Such a shift is unlikely to substantially change the composition of the weed flora, but it is worth pointing out that grass weeds have become more prominent (Milberg & Andersson 2006). Herbicides used historically are no longer sold (like Oxitril, the standard herbicide used in these experiments), while new have been introduced. To what extent this affects the conclusions presented below remain a matter of opinion. Second, this study is using biomass increase as a proxy for the increase in amount of floral resources. Although there is a likely positive relationship between fecundity and biomass, it is not universal (Younginger et al. 2017). Third, this study does not consider the larger spatial scales central to the potential success of ASCY, i.e. to what extent pollinator densities increase on a landscape level. That is likely, however, mainly to depend on the potential future prevalence of the method.

A successful ACSY rests on a few assumptions, of which only the first is tested in the current study. First, that abstaining weed control in a single year will increase the amount of flowers of weeds that are useful to pollinators. With about half of the biomass increase being of weed species classified as pollinator-friendly, this assumption seems to hold. Second, that weeds in arable field are visited by pollinators. In recent Swedish studies, many bumble bees searched both conventionally and organically grown fields

(Sidemo-Holm et al. 2021) and more than 100 species of pollinating insects were caught in colour pan traps placed within arable fields (Milberg et al. 2025). Third, that the weed situation does not get out of control in the short as well as longer term by abstaining weed control in a single year: 'letting the genie out of the bottle'. This cannot be assessed from the current data, so future research would be needed. But by choosing fields with relatively small amounts of weeds, the expected increases would in most cases be modest. Fourth, that the increase in weeds, due to a single year without weed control, can easily be treated in the following year(s). Unless one deals with weeds particularly difficult to control, like grass weeds, and herbicide-tolerant weeds, this seems manageable in current Swedish agriculture, an assumption that should be assessed under field conditions. Also, weed control later in the ACSY season might be an option to prevent weed population buildup (Fogelfors 1981, Olfert et al. 1991, Walsh et al. 2017, Glasner et al. 2019). Future studies might find a balance, at the landscape scale, between (i) yield loss, (ii) proportion of fields under ACSY in a particular year, (iii) the temporal recurrence of ACSY to a field and (iv) the biodiversity benefits, especially regarding pollination services.

The main aim with ACSY would be to increase floral resources in agricultural landscapes, assuming this would lead to increased populations sizes of wild pollinators. There are at least two caveats regarding ACSY and pollinators that future studies need to resolve. First, solitary bees that nest in soil (Antoine & Forrest 2021) might be tempted by increased floral resources, to nest within fields. Annual tillage and harrowing might destroy nest sites, potentially turning the field into an population sink. Second, bumblebees might be sensitive to within-season variation in floral resources (Requier et al. 2015, Timberlake et al. 2019, Guezen & Forrest 2021, Jachuła et al. 2021, Ammann et al. 2024). Would ACSY increase or decrease resource fluctuations for pollinators? At the field level, there might be larger fluctuation between years in floral resources if introducing ACSY. On larger spatial and temporal scales, the frequency of ACSY would influence the stability of floral resources.

It is worth stressing that decades of careful weed control, resulting in low weed densities, represent a long-term investment that should be carefully curated. Enhancing biodiversity in agroecosystems by ACSY means using part of this investment. In the balance sheet, expected yield loss is of importance when evaluating environmental mitigation in arable fields. In fact, many fields with low yield loss might be below the short-term economic threshold for weed control and hence being prime candidates for ACSY. Using a model presented elsewhere (Milberg & Hallgren 2004), the estimated yield loss in the experiments that belonged to the lowest quartile were 1.8% and 5.7% for spring- and autumn-sown crops, respectively. If considering the two lower quartiles (0–50%), corresponding values were <9.2% and <18.9%, respectively. It is difficult to pinpoint an economic threshold (Coble & Mortensen 1992, Jones & Medd 2000), as both costs and income can vary tremendously. A previous estimate place this at a yield loss of 2.5% in the current experiments (Milberg, unpublished), suggesting money saved by ACSY in some fields.

All environmental mitigation strategies in an arable landscape have their pros and cons. Flower strips cover a small area, that is temporarily taken out of production, and involves establishment costs and contains a limited set of plant species. Enhancing biodiversity in crop and field borders (Fischer & Milberg 1997, Vickery et al. 2009, Zamorano et al. 2020) sometimes involves a direct investment and would also affect only a modest acreage. Organic farming involves not only large acreage but also a loss of productivity (e.g. Batáry et al. 2015, Tscharntke et al. 2021). ACSY, if applied cautiously would cover a relatively large acreage (whole fields), involve numerous weed species, and carry no investment cost. Yield loss is likely modest (Milberg & Hallgren 2004), but whether there will be an increased cost for control in the years to follow, remains to be clarified.

Which species to promote?

Not all species are equal, and the target species within ACSY are those that (i) have high pollinator index, (ii) are abundant and widespread, (iii) are relatively weak competitors (i.e. benign weeds), and (iv) are easy to control in the year(s) following ACSY. Hence, a balance between least harm and most benefit. In practice, it will be very difficult to differentially benefit only a single species, but still some species would be more welcome than others. Selecting, or avoiding, fields depending on species composition is clearly an option.

It is apparent in the current data that the most pollinator-friendly species (indexes 6–7) are absent from or rare in most arable land in Sweden, so let us consider the abundant species with the index 5. In the current

study, *Galeopsis* spp., *Fallopia convolvulus*, *Centaurea cyanus* and the perennial *Cirsium arvense* all score high on most of the criteria. But especially *Galeopsis* spp. is associated with high yield losses (Boström et al. 2003). *Cirsium arvense* is a special case, often being considered of particular importance to pollinators (Balfour & Ratnieks 2022). The hypothesis is that perennial species with deep root systems are much less sensitive to drought, and hence of particular importance for pollinators in dry years. On the other hand, *Cirsium arvense* was historically an important weed (Adolfsson 1996) and it remains so in organic farming today (Donald 1994, Rydberg & Milberg 2000, Graglia et al. 2006). Although easy to control with herbicides, it might still be a species to be avoided if selecting a field for ACSY (but see Balfour & Ratnieks 2022).

If considering pollinator index 4, some abundant species come in focus. *Tripleurospermum inodorum* is one of the most widespread and abundant weeds in Scandinavian agriculture (Hallgren 1996, Reiss et al. 2018) and must therefore be considered relatively difficult to control, which is further supported by numerous reports of herbicide resistance (Hull et al. 2014, Šuk et al. 2023). Hence, this might be a species to be avoided within ACSY. The other annual species – *Myosotis arvensis*, *Lamium* spp., *Matricaria chamomilla* – seem less likely to cause post-ACSY problems, nor does the perennial *Sonchus arvensis*.

Conclusion

A substantial part of weed biomass on Swedish arable land is made up of species that provide nectar and/or pollen for pollinators. By abstaining weed control in a single season (ACSY) that biomass would increase. If fields with an abundance of weeds are avoided, yield loss caused would be modest. For a better understanding of the potential of ACSY, further research would be welcome regarding pollinator visits to weeds within arable field. Also, a thorough economic assessment is needed.

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Author contributions

Both authors designed the study and analysed the data. PM wrote a first draft, and both authors revised the MS.

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Data availability statement

The data is published in a data repository (*Zenodo* doi:10.5281/zenodo.15581422).

Notes on contributor

Per Milberg is an adjunct professor with research interests in the instersection of landuse, applied ecology and biodiversity Lars Westerberg is an associate professor researching spatial ecology.

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