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Quantification of regulating ecosystem services provided by weeds in annual cropping systems using a systematic map approach

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Summary

Ecosystem services have received increasing attention in life sciences, but only a limited amount of quantitative data are available concerning the ability of weeds to provide these services. Following an expert focus group on this topic, a systematic search for articles displaying evidence of weeds providing regulating ecosystem services was performed, resulting in 129 articles. The most common service found was pest control and the prevailing mechanism was that weeds provide a suitable habitat for natural enemies. Other articles showed that weeds improved soil nutrient content, soil physical properties and crop pollinator abundance. Weeds were found to provide some important ecosystem services for agriculture, but only a small number of studies presented data on crop yield. Experimental approaches are proposed that can: (i) disentangle the benefits obtained from ecosystem services provisioning from the costs due to weed competition and (ii) quantify the contribution of diverse weed communities in reducing crop competition and in providing ecosystem services. Existing vegetation databases can be used to select weed species with functional traits facilitating ecosystem service provisioning while having a lower competitive capacity. However, for services such as pest control, there are hardly any specific plant traits that have been identified and more fundamental research is needed.

Keywords: agroecology, functional traits, literature review, pest control, pollination, soil nutrient content, soil physical properties, soil quality, weed management.

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Introduction

Weed research traditionally focuses on the adverse impact that weeds can have on economic, aesthetic or environmental aspects of any system and on the approaches used to limit this. Recently, special attention has been paid to ecosystem services that natural vegetation can provide to society, and this may include

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species that are often classified as weeds. Ecosystem services can be described as the benefits obtained by the human population from an ecosystem (MEA, 2003). The communities that form (agro)ecosystems can provide services to humankind in terms of habitat, food and other goods, and clean resources (Daily, 1997), thanks to the specific functional traits of the species. The diversity of species traits present in these communities can also provide an insurance against future changes by hosting organisms and genes that may become of fundamental importance to guarantee ecosystem processes under changing environmental conditions (Moonen & Bàrberi, 2008). For example, insurance could derive from beneficial insect populations tolerant to extreme weather or from genes that can be used to grow drought-resistant crops. The Common International Classification of Ecosystem Services contains three main types of ecosystem services: provisioning services, regulating and maintenance services (hereafter referred to as regulating services), and cultural services (Haines-Young & Potschin, 2011).

In the light of current EU agricultural policies, and more specifically Directive 2009/128/EC on the sustainable use of pesticides and the 2014–2020 CAP reform including numerous proposals for 'greening', it becomes increasingly more important to provide farmers with concrete data regarding the benefits they can obtain from mixed farming, reduced herbicide use, inclusion of semi-natural habitats on their farms and the use of cover crops. Agroecological farming approaches promote management of the weed community instead of its complete eradication inside cropped fields. Potentially, this could result in weed communities that do not negatively affect crop production, while providing regulating services to the agroecosystem (Petit *et al*., 2015). These approaches can be combined with other management strategies. The management of agrobiodiversity surrounding cropped fields (e.g. in semi-natural habitat) can contribute to the provision of regulating ecosystem services, such as increasing beneficial insects for pest control and pollination (e.g. Alignier *et al*., 2014; Sutter *et al*., 2017). However, the effect on actual pest control and crop yield is not often measured (Holland *et al*., 2016).

In most reviews concerning weeds and ecosystem services, weeds are considered as pests (e.g. Oerke, 2006; Shennan, 2008). In others, potential benefits that weeds can have on ecosystem processes and functioning are discussed. These reviews focus on the role that weeds have in hosting beneficial arthropods (Petit *et al*., 2011), whether they be pollinators (e.g. Nicholls & Altieri, 2013; Bretagnolle & Gaba, 2015) or natural enemies of crop pests (e.g. Hillocks, 1998; Norris & Kogan, 2000). Weeds can exert an indirect effect on pest control by attracting beneficial insects that serve as crop pest predators. The effect of these beneficial insects on pest control and yield loss reduction is often difficult to establish and explanations for the lack of response can be similar to the ones hypothesised by Tscharntke *et al*. (2016), regarding the role of natural habitats in sustaining beneficial insects. On the other hand, weeds exert a direct effect on pest regulation by diverting certain pest species away from crops (Capinera, 2005), by reducing the attractiveness of a crop (Altieri & Whitcomb, 1979), or by making the crop less noticeable to the pest (Root's (1973) resource concentration hypothesis). Another mechanism through which weeds can reduce crop pest infestation is by creating an associational resistance within the crop. This occurs when weeds interact with a crop plant and increase the crop's resistance to pest infestation (Ninkovic *et al*., 2009).

The aforementioned review articles, however, are descriptive and present little quantitative data on the services provided by weeds. Assumptions extrapolate the role 'vegetation' plays in general in ecological processes, to the role 'weeds' may play. Based on discussions during a meeting of weed scientists interested in weed diversity conservation (Meeting of the Weeds and Biodiversity Working Group of the EWRS in Pisa, Italy, held from 18–20 November 2014), it was hypothesised that, in reality, little scientific evidence quantifying the services provided by weeds exists. Through a subsequent systematic literature mapping approach, quantitative information was extracted on regulating services provided by weeds (e.g. data on pest control enhancement) in arable or vegetable cropping systems. The search was restricted to regulating services, in order to have a manageable number of articles in the search result, and coherent and quantitative results for analysis. At least in theory, it should be easier to quantify how weeds interact with ecosystem processes than to quantify their cultural services, which is a rather subjective matter. The objective of this work was to quantify the amount of empirical data available on weeds providing ecosystem services to identify perspectives for future research aimed at agroecological weed management by (i) giving a bibliometric overview of the articles that provided scientific evidence of regulating services (directly and indirectly) provided by weeds and (ii) identifying the weeds providing ecosystem services and quantifying the effect on crop yield.

Materials and methods

Literature search

The systematic map approach consisted of conducting a systematic review and collecting existing evidence on a broad topic (Haddaway *et al*., 2016). This approach allows for a more objective and transparent review compared with the traditional narrative review (Collins & Fauser, 2005). It requires performing an initial search to define the relevant keywords in relation to the research topic. These terms are then used to perform a final search in an online database. The systematic map approach differs from a meta-analysis in that it gives an overview on a research topic, as opposed to answering specific hypotheses. This tool has recently become popular in environmental sciences (e.g. Bernes *et al.*, 2015; Fagerholm *et al.*, 2016).

We followed a similar protocol to previously performed systematic map approaches (e.g. Holland *et al.*, 2016). The online database Scopus® was used for searching articles. This search engine contains articles dating back to 1960. No year restriction was placed on the search. However, results were restricted to those in the field of 'agriculture and biological sciences', 'environmental science', and 'earth and planetary sciences'. The search was made on the 16 January 2015. Preliminary searches were carried out to determine the terms associated with the research question. The search string used circumscribed the search results to papers focussing on plant species defined as weeds by including 'weed*' as a search term. Papers were then limited to studies relevant to arable or vegetable crops in the open field by including the terms 'agr*', 'field*' and 'crop*'. Finally, search terms that were included aimed at extracting papers focussing on at least one of the four key regulating ecosystem services: pest control, crop pollination, soil physical quality and nutrient cycle regulation. Therefore, at least one of the following terms had to be present in the articles: 'ecosystem service*', 'ecological service*', nitr*, carbon, pollination, preda*, 'natural enem*', 'pest control', biocontrol, 'biological control', erosion, 'soil organic matter', 'temperature regulation', microclimate, 'nutrient cycle'.

In the preliminary searches, a high number of articles that did not contain information on weeds providing ecosystem services were found. Therefore, the following strategy was used to improve the focus of the search. Articles were excluded when the title, abstract or keywords contained the terms orchard*, forest*, tree*, as the habitat of interest was annual crops. Also, many unwanted articles appeared because the authors referred to 'weed control' as 'pest control', and therefore, 'pest control' was not intended as an ecosystem service provided by weeds. By excluding the terms 'chemical control', 'mile-a-minute weed', and knapweed in the title, abstract, or keywords and the term herbicide* in the title, we were able to avoid collecting numerous articles that did not contain information on regulating ecosystem services in the final search. Finally, articles containing 'seed predat*' in the title, abstract or keywords were excluded as well because these articles focussed on the predation of weed seeds and did not contain information on weeds providing regulating ecosystem services. We did not extract data on the effect of scale on ecosystem provisioning, as articles often did not contain such data and some reviews have already provided this information, although they did not focus on weeds (e.g. Mitchell *et al.*, 2013; Veres *et al.*, 2013; Malinga *et al.*, 2015).

Screening of the search result

In the second phase, abstracts of all retained articles were screened based on four predefined inclusion criteria. Firstly, the document should provide a quantitative result on at least one regulating ecosystem service provided by weeds. Secondly, the studied system should include arable or vegetable crops for human consumption. Thirdly, the document should be written in English, so that, in the event of an incongruent entry in the map, the article could be analysed by another author. Lastly, the result(s) of the study should not be obtained through the use of modelling, as primary data were required to obtain values for the ecosystem services provided.

The abstracts of all the articles in the search result were scanned by the lead author to see whether they met the set criteria. Whenever it was unclear whether an article met all the criteria, the article was treated as if it did. Those that met the criteria were randomly distributed among the authors and read in full. Information was transcribed into the systematic map, a table constructed by the authors with issues deemed relevant to the research topic (*Supporting information*). Information retrieved was related to country of origin, type of experimentation (on-farm, on-station, controlled environment), ecosystem service targeted, weed species involved, ecosystem service measured, presence of other organisms benefitting from weed presence such as predators or pests, and comparison of crop yield in situations with and without weeds. Review articles that met the criteria were not included in the literature map. Instead, citations in the reviews that were related to the search topic but not yet included in the systematic map were collected. They then underwent the same process as the documents from the search result. Due to the wide variety of services presented, combined with the lack of uniform quantitative data, not all effect sizes could be analysed quantitatively. Pest control was the most abundant regulating service for which the range of minimum and maximum percentage values could be calculated. In 30 studies, the effect of weeds on yield was reported; however, in only seven of these was it possible to calculate the log response ratios (lnR) as an estimation of the effect size of the presence of weeds on crop yield.

Results

In total, 4449 results were found in the literature search. The abstracts were scanned for the presence of empirical results on the relation between weeds and regulating ecosystem service. This yielded 189 articles. A second more thorough evaluation of the results led to the retention of 129 articles, 60 of which did not contain detailed enough information to compile the systematic literature map, despite the positive wording in the abstract.

Ecosystem services

The ecosystem service most often referred to was pest control (Fig. 1A). In all, 91 articles (71%) contained examples of weeds supporting pest control. Weeds were found to contribute to nutrient cycling in 28 articles (22%). In seven articles (5%), weeds were shown to improve soil physical properties. Finally, benefits of weeds in enhancing crop pollination were only found in five articles (4%), while three articles were found showing evidence of weeds providing regulating services that were not directly targeted by the search (e.g. reduction in greenhouse gas emissions).

Pest control

More than half of the articles contained examples of the presence of weeds benefitting pest control, although the mechanism through which this service was provided differed. In 38% of the studies documenting pest control, it was possible to acquire values for the reduction in pest abundance. An increase in the predation or parasitism of pests was calculated for 10% of the articles. Most commonly, however, studies calculated an increase in the abundance or diversity of natural pest enemies due to the presence of weeds (41% of studies). None of the above information was provided in 29% of the articles. In most cases, this was because the effects of weeds were not statistically tested, either due to a lack of control or weeds not being directly investigated in the study. In other cases, the benefits of weeds were studied in a laboratory or in glasshouse experiments measuring the time beneficials spent foraging on flowers or by analysing their preference for flowers of specific species. For example, Belz *et al.* (2013) found a preference of *Microplitis mediator* Haliday for *Iberis amara* L. and *Cyanus segetum* Hill over *Fagopyrum esculentum* Moench and *Ammi majus* L. Griffin and Yeargan (2002) demonstrated the preference of the lady beetle *Coleomegilla maculata* DeGeer to deposit eggs on *Abutilon theophrasti* Medik. over eight other broad-leaved annual weeds (*Acalypha ostryaefolia* Riddell, *Acalypha virginica* L., *Amaranthus hybridus* L., *Chenopodium album* L., *Galinsoga ciliata*

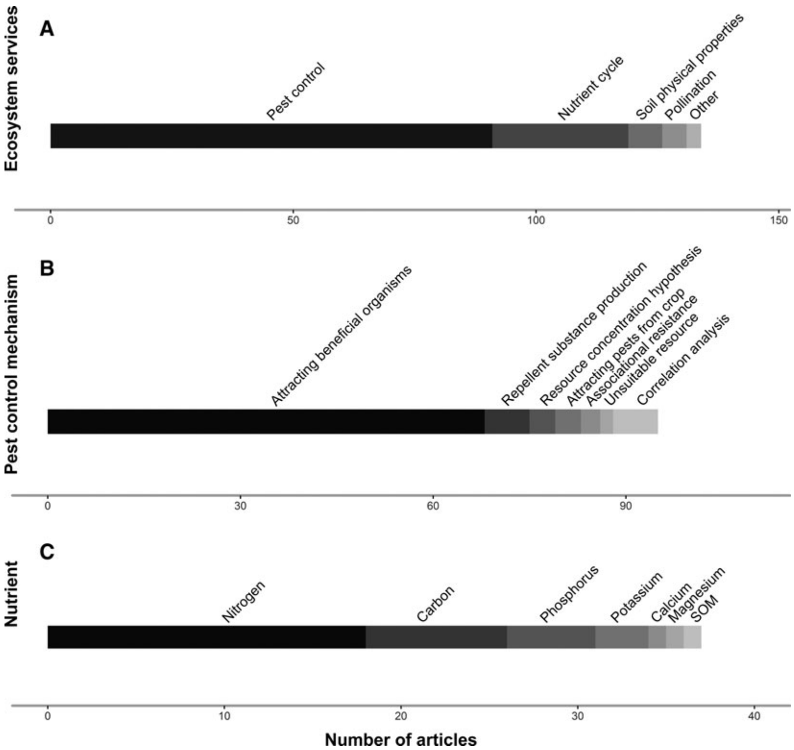

Fig. 1 Partition of articles based on (A) ecosystem service type, (B) pest control mechanism type and (C) soil nutrient type. In (A), 'Others': regulating ecosystem services that were not targeted by the search. In (B) 'Correlation analysis': no explanation was provided in the manner which weeds provided pest control.

Ruiz & Pav., *Sida spinosa* L., *Solanum ptychanthum* Dunal, *Xanthium strumarium* L.). In two cases, the presence of weeds was shown to decrease the number of damaged crop plants (Frank & Barone, 1999; Gill *et al*., 2010). A few studies were based on mere correlation analysis. For example, Green (1980) showed that skylark predation on sugarbeet (*Beta vulgaris* L.) seedlings decreased with increasing abundance of weed seeds having a dry weight over 1 mg (e.g. *Polygonum* spp.). The mechanisms that explained how pest control was provided differed among studies (Fig. 1B). By far, the most common means was by diverting natural enemies of pests (75% of the articles relating to pest control) by offering them a resource in or around cultivated fields. An increase in natural enemy abundance or diversity does not, however, necessarily mean that there is a reduction in pest abundance or, eventually, an increase in crop yield. Often, this information was not provided. In seven cases (8%), weeds repelled pests by producing chemical substances (e.g. Glinwood *et al*., 2004). In three studies, weeds contributed to pest control through associational resistance (e.g. Ninkovic *et al*., 2009). Two studies found that weeds did not offer suitable resources to pests, which reduced their numbers (e.g. Alexander & Waldenmaier, 2002). Four studies referred to the resource concentration hypothesis to explain an increase in pest control (e.g. Gill *et al*., 2010). In four other articles, weeds contributed to pest control by diverting pests away from crops (i.e. weed acting as a trap crop) (e.g. Green, 1980). In seven articles, the mechanism with which weeds contributed to pest control was not explained and data were obtained from correlation analysis.

The range of values obtained for pest control varied considerably (Table 1). The highest value for pest reduction in the field was obtained from Atakan (2010) in which it was shown that infestation of the western flower thrips (*Frankliniella occidentalis* Pergande) on faba bean (*Vicia faba* L.) was reduced by a maximum of 98% due to weedy margins that hosted beneficial insects. For pest predation, the highest value was obtained in a laboratory experiment by Araj and Wratten (2015), in which they demonstrated that the predation of cabbage aphids *Brevicoryne brassicae* L. on *Capsella bursa-pastoris* L. increased by 255%. Powell *et al*. (1985) found that the rove beetle *Philonthus cognatus* Stephens was 1721% more abundant in plots containing weeds than in weed-free plots. As for natural enemy diversity, Albajes *et al*. (2009) reported that pest enemy diversity rose by a maximum of 213% in the presence of weeds.

Table 1 Range of values for all pest control measurements obtained in 90 articles retrieved. Negative values indicate a negative effect on pest control measures

Pest control measurement	Mean lower range ± SD (in %)*	Mean upper range ± SD (in %)*
Reduction in pest abundance	19.4 ± 66.32	61.4 ± 29.39
Increase in predation/parasitism	49.9 ± 79.32	72.1 ± 74.16
Increase in pest enemies' abundance	93.6 ± 211.97	423.3 ± 563.38
Increase in pest enemies' diversity	15.0 ± 21.21	131.5 ± 115.26

*Mean lower/upper range ± SD: the average of all the minimum/maximum percentages of pest control enhancement reported in each study.

Soil nutrients

Twenty-three articles in the literature map provided information on weeds increasing the amount of nutrients in the soil. In 18 of these (78%), weeds were found to help improve both available and total nitrogen stock in agricultural soils (Fig. 1C), often as a consequence of their capacity to reduce nitrogen leaching by erosion control (available N) and by active N uptake and fixation (total N), which stabilised N levels in soil organic matter. For example, the presence of broad-leaved weeds (*Amaranthus viridis* L., *Richardia scabra* L., *Indigofera hirsuta* L.) led to less microbial immobilisation of mineral N than grass weeds, which resulted in faster net release of mineral N in the following crop (Promsakha Na Sakonnakhon *et al*., 2006). Also, Ariosa *et al*. (2004) found that cyanobacteria in the common rice weed *Chara vulgaris* L. significantly improved soil fertility through their capacity to fix nitrogen in the weed biomass. Eight studies (35%) demonstrated that weed biomass increased carbon inputs in the soil (e.g. Arai *et al*., 2014). The same was shown to occur for phosphorus (e.g. Ojeniyi *et al*., 2012), as well as for potassium (e.g. Das *et al*., 2014), soil organic material (De Rouw *et al*., 2015), calcium and magnesium (Swamy & Ramakrishnan, 1988).

In seven of the 13 articles, no values were given for the increase in nutrients due to weeds. In some cases, this was because there was no treatment factor without weeds (e.g. Ariosa *et al*., 2004). Mazzoncini *et al*. (2011) used correlation analysis to demonstrate the effect of weeds on soil organic carbon and soil total nitrogen. De Rouw *et al*. (2015) used carbon isotopes as a proxy for plant contribution to the soil organic pool. In these cases, it was not possible to accurately measure the contribution of weeds in providing ecosystem services.

Weeds were also shown to provide benefits to the nutrient cycle by promoting arbuscular mycorrhizal fungi (AMF). The presence of AMF in fields can facilitate nutrient acquisition in crops (Azaizeh *et al.*, 1995). Vatovec *et al.* (2005) found that some weed species (e.g. *Ambrosia artemisiifolia* L.) were strong hosts to AMF and could potentially increase AMF abundance and diversity in an agricultural field. A correlation between weed diversity and spore numbers was also found (Miller & Jackson, 1998). In another article, weeds were found to promote rhizobacteria and, in turn, positively affect crop plant growth (Arun *et al.*, 2012).

Soil physical properties

Weeds were found to enhance soil physical properties in seven articles. Most commonly, weeds had a positive effect by reducing soil loss and run-off (43%) (e.g. Pannkuk *et al.*, 1997) or by reducing bulk density (29%) (e.g. Yagioka *et al.*, 2014). In some cases, it was unclear whether the positive effect on soil structure was caused by reduced tillage or by the increase in weeds often observed following reduced tillage (e.g. Arai *et al.*, 2014). Weeds were also reported to benefit water storage in soil (e.g. Ojeniyi *et al.*, 2012), while Kabir and Koide (2000) showed an increase in the proportion of water-stable aggregates due to weeds hosting mycorrhizal fungi.

Crop pollination

In all five articles related to pollination, the effect that weeds had on crop pollination was not directly investigated. Instead, the movement of pollinators to dicotyledonous species was demonstrated (e.g. Hawes *et al.*, 2003). Therefore, the extent to which weeds enhanced crop pollination remains unclear. All these studies were observational and were carried out on real farms. Pollinators belonged mostly to the insect family Hymenoptera. In some studies, pollinators from the orders Coleoptera, Diptera, Lepidoptera and the suborder Heteroptera were counted as well (Carvalheiro *et al.*, 2011).

In three articles, weeds positively affected pollinator diversity (e.g. Carvalheiro *et al.*, 2011) by offering a food resource and Hoehn *et al.* (2008) reported a positive impact of pollinator diversity on crop yield. Pettis *et al.* (2013) found that bees visited surrounding weeds, as well as crops. Crop pollination increased near field margins where weeds offered the majority of alternative forage to pollinators (Gemmill-Herren & Ochieng, 2008).

Other regulating and maintenance ecosystem services

Weeds can also play a part in reducing emissions linked to climate change. In rice paddy fields, weeds can reduce the emission of methane (CH_4) by improving the stimulation of CH_4 oxidation, as well as by reducing methanogenesis rates compared with rice (Holzapfel-Pschorn *et al.*, 1986). Yagioka *et al.* (2015) reported that weed cover mulching had a reduced net global warming potential compared with conventional tillage practices, due to a greater soil organic carbon accumulation. Furthermore, they found that weeds altered the microclimate by increasing relative humidity.

Weed identity

In 23 studies, the focus was on one individual weed species. In small assemblages of less than five species, the ecosystem service provision was attributed to each of the species. For bigger assemblages, no single weed species effect was indicated. In 44 articles analysed (34%), the services were provided by a plant assemblage containing weeds, but the main species were not specified. In these studies, the identity of the plant was not important. High plant diversity or the presence of vegetation was deemed to enhance the delivery of ecosystem services. Table 2 shows the list of weed species most often cited as providing an ecosystem service. *Chenopodium album* was the most frequently cited species, often in relation to enhanced pest control through offering resources, for example oviposition sites to natural enemies (Smith, 1976). Ninkovic *et al.* (2009) demonstrated that barley (*Hordeum vulgare* L.) exposed to volatiles from *C. album* reduced plant acceptance by aphids. Another study found that *C. album* dead mulch released nitrogen more quickly during the following growing season compared with the grass weed *Setaria faberi* Herrm. (Lindsey *et al.*, 2013).

Crops and yield

The most commonly studied crop was maize (*Zea mays* L.) (26% of studies), followed by wheat (*Triticum* spp.) (18%) and barley (11%) (Table 3). Cereals were the most studied crop type in the articles documenting improvement in soil nutrient and soil physical quality. However, legumes were more studied than cereals in pest control.

Of all the articles included in the literature map, only 30 (23%) measured the effect of weeds on crop yield. In 13 (43%) of these articles, the effect of weeds on yield was significantly negative, in nine (30%) no significant change in yield was reported, while eight (27%) demonstrated a positive effect of weeds on yield. There was no relation between the effect on yield and crop type and the relation with weed species could

Table 2 Number of articles reporting the provision of ecosystem services by weed species

	Pest control	Nutrient cycle	Soil physical properties	Others	Total articles
Chenopodium album L.	5	2	0	0	7
Ambrosia artemisifolia L.	3	2	0	0	5
Cirsium arvense L.	4	1	0	0	5
Acalypha ostryaefolia Riddell	4	0	0	0	4
Amaranthus retroflexus L.	2	2	0	0	4
Capsella bursa-pastoris (L.) Medik.	4	0	0	0	4
Sinapis arvensis L.	4	0	0	0	4
Abutilon theophrasti Medik.	2	1	0	0	3
Echinochloa crus-galli (L.) Beauv.	2	0	0	1	3
Elytrigia repens (L.) Desv. ex Nevski	3	0	0	0	3
Solanum nigrum L.	2	1	0	0	3
Ageratum conyzoides L.	2	0	0	0	2
Bidens pilosa L.	2	0	0	0	2
Brassica rapa L.	2	0	0	0	2
Cirsium vulgare (Savi) Ten.	2	0	0	0	2
Commelina benghalensis L.	2	0	0	0	2
Imperata cylindrica (L.) Räusch.	1	1	1	0	2*
Lamium amplexicaule L.	2	0	0	0	2
Leersia hexandra Sw.	2	0	0	0	2
Sonchus oleraceus L.	2	0	0	0	2
Taraxacum officinale F.H.Wigg.	1	0	1	0	2
Urtica dioica L.	2	0	0	0	2

**Imperata cylindrica* was reported to have provided two different ecosystem services in one article.

not be analysed because all the studies contained different species (*Supporting information*). The log response ratios (lnR) representing an estimation of the effect size of the presence of weeds on crop yield are shown in Fig. 2 (15 cases provided by seven articles). No clear pattern of the effect size distribution emerged. However, we found more effect sizes with positive values than with negative values.

Gaps in knowledge and future perspectives

The number of articles retained in the systematic map was low considering that the original search yielded 4449 results. This reduction is in line with results from other reviews based on the systematic map approach, such as Holland *et al*. (2016) who found 2252 references of which only 152 were retained in the final map. The systematic map has clarified the amount of scientific evidence that is available on regulating ecosystem services provided by weeds. Data retrieved in the map also allowed for the quantification of the services provided and, in some cases, gave an indication of the effects weeds had on crop yield. However, the list of articles found containing information on regulating ecosystem services provided by weeds is not exhaustive. This is partly due to the methodology that prescribes only one literature search. Furthermore, the search was inevitably restricted to articles in which the authors considered the plant providing the regulating ecosystem service as a weed. For example, Smith *et al*. (2009) demonstrated that *Bassia hyssopifolia* (Pall.) Kuntze attracted natural enemies to various species of tumbleweed. Although *B. hyssopifolia* is often considered a weed, the authors did not refer to it as a weed. Furthermore, our search was restricted to the English language but there are articles written in other languages that contain evidence of weeds providing regulating ecosystem services (e.g. Cochereau, 1976).

Regulating ecosystems services

From this systematic map analysis, a substantial gap in knowledge emerged regarding two of the four key regulating services that are relevant to farmers: soil properties and crop pollination. Among the few articles dealing with weed effects on soil properties, over half of the studies were performed in Asia (see *Supporting information*). This may be due to the observed stagnation in crop production in that continent (Ray *et al*., 2012), which has been attributed to the depletion of nutrient pools (Bhandari *et al*., 2002; Manna *et al*., 2005). Soil erosion rates also tend to be higher in Asia than elsewhere (Pimentel *et al*., 1995; Lal, 2003). Similarly, not many articles were found to demonstrate the benefits of weeds in supporting crop pollination. As agricultural land often offers low amounts of nectar compared with other habitats (Baude *et al*., 2016), it stands to reason that the presence of weeds would diversify and augment nectar availability, which could

Table 3 Number of articles reporting ecosystem services provided by weeds for each crop

	Pest control	Nutrient cycle	Soil physical properties	Pollination	Others	Total
Maize	16	13	4	1	0	33*
Wheat	15	5	2	1	1	23*
Barley	10	3	0	0	0	13
Rice	6	5	0	0	1	12
Rapeseed	7	0	0	1	0	7*
Bean	5	1	0	0	0	6
Soyabean	6	0	0	0	0	6
Tomato	5	1	1	0	0	6*
Lettuce	3	2	1	0	0	5*
Brussels sprout	4	0	0	0	0	4
Cucumber	2	1	0	1	0	4
Beet	2	0	0	1	0	3
Collard	3	0	0	0	0	3
Daikon/radish	1	2	2	0	0	3*
Eggplant	2	1	0	0	1	3*
Oat	3	0	0	0	0	3
Okra	2	1	0	0	1	3*
Pepper	2	1	0	0	1	3*
Potato	2	1	0	0	0	3
Pumpkin/squash	2	1	0	1	1	3*
Allium fistulosum L.	1	1	1	0	0	2*
Cabbage	2	0	0	0	0	2
Faba bean	2	0	0	0	0	2
Pea	1	1	0	0	0	2
Rye	2	0	0	0	0	2
Strawberry	1	0	1	0	0	2
Sunflower	0	1	0	1	0	2
Watermelon	1	0	0	1	0	2

*Weeds in this crop were reported to have provided multiple ecosystem services in some articles.

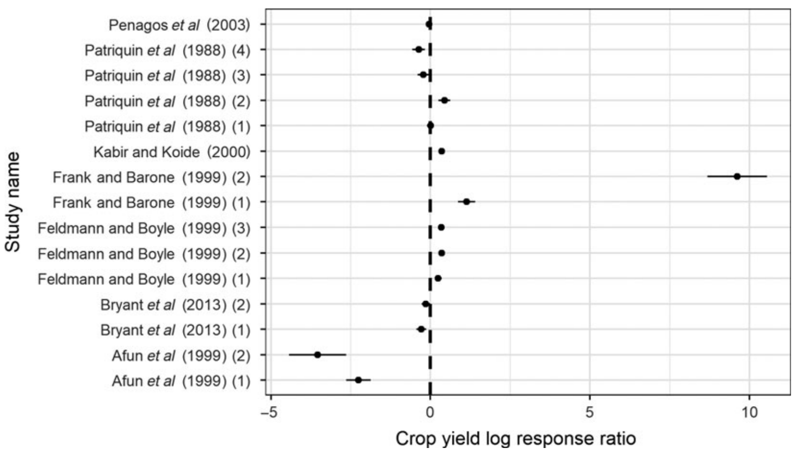

Fig. 2 Log response ratio (lnR) estimating the effect size of the presence of weeds on crop yield in different studies. Whiskers indicate 95% confidence intervals. The dashed vertical line indicates 0 effect. Some studies contain more than one entry due to multiple yield data (e.g. yield data for multiple years). A positive lnR indicates that crop yield was higher when weeds were present while a negative lnR indicates that it was lower.

attract more pollinators. In fact, a review published on the pollination services offered by weeds supports this view (Bretagnolle & Gaba, 2015). The review, however, only demonstrated the potential of weeds in offering floral resources to pollinators but did not give quantitative data on the consequences for crop pollination or for pollinator abundance and diversity.

Although the pest control service provided by weeds has been described abundantly, the articles did not provide much insight into the mechanisms responsible for the beneficial effects, or for the lack of increased crop yield despite the presence of ecosystem service providers (ESP). More fundamental research aimed at elucidating the complex trophic interactions between crops, weeds, beneficials and pests would help to provide more precise management guidelines for farmers and would possibly also reduce uncertainty in the response of agroecosystems to manipulation of weed communities.

Research needs at crop yield level

It is difficult to draw a conclusion about the effect of weeds on yield because only 30 papers quantified crop yield in relation to weed abundances. Articles including a measure of the variability in crop yield are even fewer (seven articles, Fig. 2). Therefore, studies that quantify the effect of weeds on crop yield with a measure of the variability are required. Despite the common view that weeds have a negative effect on crop yield, over half the articles that measured yield did not report a significant decrease due to the presence of weeds. However, this is only true for articles from the systematic map where weeds were supposed to provide a regulating ecosystem service. The vast majority of studies on weeds, not included in this systematic map, focus on weed competition with the crop and on their negative effect on crop production. Furthermore, it is possible that some studies focussing on regulating ecosystem services provided by weeds did not publish the negative effects weeds had on crop yield. Looking at the effect sizes (Fig. 2), we see that they tend to be centred around zero. There were two cases where the effect sizes were larger than 1 or −1. In Frank and Barone (1999), there was one unusually large effect size due to total crop failure in the plots without weeds. In Afun *et al*. (1999), the service provided by weeds in hosting natural enemies of pests was completely negated by the strong competition of weeds with the crop. In this case, the yield loss due to competition was greater than the benefit obtained from service provisioning. A possible explanation for the small effect size found on crop yield could be that the studies were performed under optimal external input conditions, leaving no margin for measuring a yield increase. For example, if the aim was to measure the contribution of weeds to soil fertility, in a system characterised by high soil fertility levels, the weed contribution would not be detected.

From an agroecological perspective, the role of weeds would be to partly compensate for reduced external inputs such as fertilisers, pesticides or tillage, with the ecosystem services they can provide while maintaining competition with the crop at a minimum through optimisation of resource use efficiency. This means that the yield measured is the result of a series of parameters as formulated in (Eqn 1):

$$\text{Yield} = Y_{\max} - Y_{\text{loss.comp}} - Y_{\text{ext.inp}} + Y_{\text{gain.ES}}, \qquad (1)$$

where $Y_{\max}$ is the maximum yield that can be obtained for the crop in the optimal growth condition, $Y_{\text{loss.comp}}$ is the yield loss due to competition with the crop, $Y_{\text{ext.inp}}$ is the yield loss due to reduced use of the external input that the weed is hypothesised to provide, and $Y_{\text{gain.ES}}$ is the yield increase due to ecosystem service provisioning by the weed(s). In order to calculate $Y_{\text{gain.ES}}$, a series of four experiments needs to be set up as indicated in Table 4. This system allows to estimate $Y_{\max}$, $Y_{\text{loss.comp}}$ and $Y_{\text{ext.inp}}$. The yield (Y) in the system with weeds providing ecosystem services is measured and from Eqn (1) $Y_{\text{gain.ES}}$ is calculated.

In such a system, the research objective is to select for weed communities that minimise competition with the crop while providing an ecosystem service that can help to reduce the use of external inputs. Therefore, two more treatments could be added where the spontaneous weed community could be replaced by a weed community managed with the aim to increase service provisioning while decreasing competition by, for example, accepting legume weeds while suppressing grass species. In that case, $Y_{\text{loss.comp}}$ in the system with selected weeds is hypothesised to be lower while $Y_{\text{gain.ES}}$ is hypothesised to be higher than that in the system with the spontaneous weed community. Ideally, $Y_{\text{gain.ES}}$ would equal the yield loss if all external inputs were avoided. As we are dealing with weeds, this is rather improbable and this situation can probably only be created using functional living mulches or intercropping.

Research needs at weed species level

The list of weeds providing ecosystem services (Table 2) must be interpreted with caution. The fact that a species is more often cited than others does not necessarily mean that it is the most beneficial species. Many species listed in Table 2 are very common weeds, and their high frequency in literature might simply be related to the higher likelihood of being studied. In the majority of articles, weeds were studied as an assemblage rather than investigating the ecosystem services provided by individual species. Norris and Kogan (2000) warned about this generalisation of weeds and claimed that to describe and elucidate the complex mechanisms regulating pest control, the weed species identity and their relevant functional traits must be known. Furthermore, this information is crucial for the development of agroecological weed management aimed at reducing competition with the crop while optimising service provisioning. This means that more effort should be spent on the identification of weed species with effective functional traits for ecosystem service provisioning. It would be desirable to select these traits from species that have a low competitive ability with the crop, a limited seed production capacity and limited seed longevity, in order to avoid uncontrollable weed problems in the cropped field. At present, there are functional trait databases that

Table 4 Experimental plots needed to calculate the yield gain provided by a predefined ecosystem service provided by weeds ($Y_{gain.ES}$) in cropping systems, where the reduced input level refers to a reduction in those external inputs that are supposed to be replaced by the ecosystem service provided by the weeds. Y is the yield measured in the four experimental treatments needed to determine the parameters in Eqn 1

	No weeds	Weeds
Optimal input	Y_1	Y_2*
	$Y_1 = Y_{max}$	$Y_{loss.comp} = Y_1 - Y_2$
Reduced input	Y_3	Y_4
	$Y_{ext.inp} = Y_{max} - Y_3$	$Y_{gain.ES} = Y_4 - Y_{max} + Y_{loss.com} + Y_{ext.inp}$

*Y_2 is the result of weed competition with the crop where, due to the optimal input level, the ecosystem service provided cannot result in a yield increase and the only measurable effect is the yield reduction due to competition.

contain information on spontaneous vegetation, including many plant species that are considered weeds in the main cropping systems. An R package has been developed that enables the extraction of information on functional traits for a list of species from nine publicly available databases (Bocci, 2015). However, many of the available traits are response traits (*sensu* Lavorel & Garnier, 2002), while the effect traits available are mostly limited to provisioning of floral resources to arthropods. Furthermore, it must also be taken into consideration that traits measured from the spontaneous vegetation may be slightly different from the traits observed in the same species grown in cropped systems (Storkey *et al.*, 2015), and therefore, fundamental research on weed species traits in relation to ecosystem service provisioning potential would be recommended.

Research needs at weed community diversity level

The hypothesis that an increase in weed diversity may increase ecosystem service provisioning and that this effect is stronger in systems with low weed diversity is illustrated in Fig. 3A. At high levels of weed diversity, with higher levels of redundant functional traits among the weed species, there will be a higher resilience of the service provisioning, especially under changing environmental or cropping system conditions (Hooper *et al.*, 2005; Tscharntke *et al.*, 2005). Although weed community diversity was often mentioned as a positive aspect, none of the studies included weed diversity as a factor for determining its effect on service provisioning, nor did they quantify or explain how diversity reduced competition with the crop. Smith *et al.* (2010) formulated the resource pool diversity hypothesis, which predicts that, in diversified cropping systems, having a diverse weed community increases resource use efficiency and, therefore, competition between weeds and crops is expected to decrease. As far as we know, only Cierjacks *et al.* (2016) and Ferrero *et al.* (2017) provided results from research aimed at testing this relationship. However, they did not manipulate weed densities and simple correlation analyses were the only means with which weed diversity–crop yield relationships were tested.

As the objectives for increased weed species diversity should be to minimise competition with the main crop while maximising profitability in terms of ecosystem service provisioning, a multi-criteria assessment of weed communities should be performed based on weed species traits. From a research point of view, stimulating species diversity may provide satisfactory solutions, but from a management point of view, diversification may result in an exponential increase in complexity. Therefore, guided diversification by stimulating a few species with the desired traits is recommended, to obtain maximum results with a minimum increase in vegetation complexity in the cropped fields. In theory (comparison of the light grey and dashed lines in Fig. 3B), a higher increase in diversity is needed to reach the maximum functionality if species diversity increases randomly instead of managing it based on the functional traits of weed species. Equation 1 and the experimental layout proposed in Table 4 may be used to compare the efficacy of these diversified systems, while the layout of the Jena Experiment, aimed at establishing plant diversity in relation to ecosystem functioning (Weisser *et al.*, 2017), is a stimulating example to design experiments testing the effect of weed diversity on ecosystem services provisioning.

The types of ecosystem services that are most suitable for investigation are services directly provided by the weeds, such as nitrogen accumulation, amelioration of the physical soil structure, stimulation of soil AMF and production of pest-repellent chemicals. Both the weed traits and the service provided can be measured and quantified, and this can be directly related to crop yield. The indirect services provided by weeds, such as pest control through supporting pest predators or crop pollination through supply of nectar and pollen resources to pollinators, occur in successive steps where the potential benefits derived from the weeds on

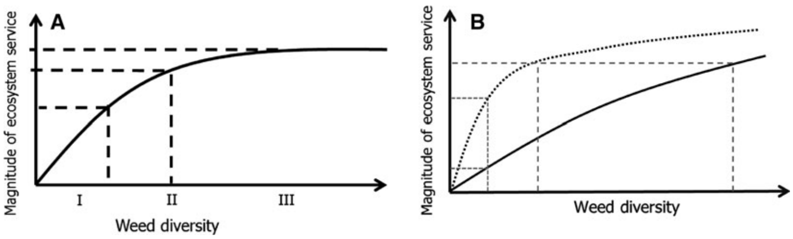

Fig. 3 Theoretical relationship between increase in weed diversity and the increase in magnitude of ecosystem service provisioning (e.g. increase in beneficial abundance). (A) At low levels of diversity (I), there is a high potential for affecting ecosystem processes. At medium levels of diversity (II), the magnitude of increase in ecosystem processes is reduced. In diverse weed communities (III), the increase in diversity increases the resilience of the ecosystem service under changing environmental or farming system conditions, but it will not affect the magnitude of the service provisioning. (B) The continuous function shows the increase in magnitude of the service when weed diversity is randomly increased. The dashed function shows the increase when management is aimed at conserving those weed species that are most effective for the desired service while at the same time being little competitive with the crop.

yield increase can easily be disrupted by external factors at each step. For example, weeds attract beneficial insects, but if there are many predators of these beneficial insects, there will be no increase in pest control. In cases where pest control increases due to the presence of beneficial insects, yield increases may not be verified due to, for example, adverse weather conditions or diseases. The lack of actual service provisioning in terms of pest control and crop yield has also been identified in studies focussing on promotion and conservation of semi-natural habitats around cropped field with the aim of increasing pest control and, subsequently, crop yield (Tscharntke *et al*., 2016). Studies investigating how weeds sustain ESP should, therefore, focus on the interactions between the weeds and the ESP by comparing diversity and abundance of ESP communities in crops with and without weed communities. In the case of weed support to pest predators, the review by Norris and Kogan (2000) could be a helpful start to plan a weed management strategy, and care should be taken to evaluate the potential pest species response to the weed community.

The magnitude of the impact that can be expected from single management tactics for agroecosystem service provisioning is limited and the ‘many little hammers’ approach for Integrated Weed Management proposed by Liebman and Gallandt (1997) should be applied. This means that, in order to increase agroecosystem service provisioning by vegetation, weed management strategies should be used in conjunction with other vegetation management strategies, such as intercropping or the establishment of semi-natural habitats, to maximise the provision of the desired services. By having a low but homogeneous distribution of weeds in a cropped field, we should obtain a homogenous distribution of a service provided by the weeds. This would complement the services provided by the vegetation present in field margins and adjacent semi-natural habitats, because their influence tends to decline as the distance from the field edge increases (e.g. Pisani Gareau *et al*., 2013).

Conclusion

In conclusion, this review highlights how few studies have specifically investigated and quantified the ecosystem services provided by weeds. We proposed an experimental design able to disentangle the benefits obtained from ecosystem service provisioning from the costs due to weed competition. The proposed approach can be useful in other studies aiming at the quantification of the role of weed community diversity in the reduction in competition with the crop and in determining the magnitude of ecosystem services provisioning by weed communities with different levels of diversity. Existing vegetation databases can be used to select weed species with functional traits facilitating ecosystem service provisioning while having a low competitive ability. However, for services such as pest control there are hardly any specific plant traits that have been identified, and more fundamental research is needed.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Data S1 An Excel spreadsheet file. The ‘Literature map’ tab contains data that were extracted from all the relevant articles found in the literature search. The ‘Category key’ tab contains explanations for the different headings in the ‘Literature map’ tab.