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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 is 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 regarded 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 amount of studies presented data on crop yield. Experimental approaches are proposed that can: 1) disentangle the benefits obtained from ecosystem services provisioning from the costs due to weed competition, and 2) 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 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 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 are hardly 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 attracting or arresting 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 increases 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 1) giving a bibliometric overview of the articles that provided scientific evidence of regulating services (directly and indirectly) provided by weeds, and 2) identifying the weeds providing ecosystem services and quantifying the effect on crop yield.

Materials and Methods

Literature search

The systematic map approach consists 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 to the traditional narrative review (Collins and 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 16th of 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, and 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 was 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 if they met the set criteria. Whenever it was unclear if 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 (Supplementary 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 thirty 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, 4,449 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 sixty 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. 1(A)). 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 7 articles (5%), weeds were shown to improve soil physical properties. Finally, benefits of weeds in enhancing crop pollination were only found in 5 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 of greenhouse gas emissions).

Fig. 1 near here

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 of 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 greenhouse 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 broadleaf annual weeds (*Acalypha ostryaefolia* Riddell, *Acalypha virginica* L., *Amaranthus hybridus* L., *Chenopodium album* L., *Galinsoga ciliata* Ruiz & Pav., *Sida spinosa* L., *Solanum ptychanthum* Dunal, *Xanthium strumarium* L.). In a couple of cases, the presence of weeds was shown to decrease the number of damaged crop plants (Franck & 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. 1(B)). By far the most common means was by attracting or arresting 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 attracting or arresting 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 & 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 near here

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. 1(C)) 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 immobilization 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 out 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 and colleagues (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 runoff (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 if 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 & 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 attraction or arrestment 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 to rice (Holzapfel-Pschorn *et al.*, 1986). Yagioka *et al.* (2015) reported that weed cover mulching had a reduced net global warming potential compared to 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 only 23 studies, the focus was on one individual weed species. In small assemblages of less than 5 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 to the grass weed *Setaria faberi* Herrm. (Lindsey *et al.*, 2013).

Table 2 near here

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.

Table 3 near here

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 not be analysed because all the studies contained different species (Supplementary Information). The log response ratios (lnR) representing an estimation of the effect size of the presence of weeds on crop yield is 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.

Fig. 2 near here

Gaps in knowledge and future perspectives

The number of articles retained in the systematic map was low considering that the original search yielded 4,449 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 and colleagues (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. Since agricultural land often offers low amounts of nectar compared to other habitats (Baude *et al.*, 2016), it stands to reason that the presence of weeds would diversify and augment nectar availability, which could 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. 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 were the effect sizes were larger than 1 or -1. In Frank & 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.

In 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):

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

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.

Since we are dealing with weeds this is rather improbable and this situation can probably only be created by using functional living mulches or inter cropping.

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 & 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 the moment, there are functional trait databases that 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 to extract information on functional traits for a list of species from nine publically 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 a low weed diversity is illustrated in Figure 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.

Fig. 3 near here

Since 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 in order determine the most effective weed management strategies. 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 few species with the desired traits is recommended in order to obtain maximum result 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 arbuscular mycchorhizal fungi, 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 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 case 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 ecosystem service providers (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 Liebmann & Gallant (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 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 tend to lower 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 of 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 being little competitive. 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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Figure captions

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.

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.

Fig. 3. Theoretical relationship between increase of 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 of 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.

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.

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
Sinapsis 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.

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.

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	Y1	Y2*
	$Y1=Y_{max}$	$Y_{loss.comp}=Y1-Y2$
Reduced input	Y3	Y4
	$Y_{ext.inp}=Y_{max}-Y3$	$Y_{gain.ES}=Y4-Y_{max}+Y_{loss.com}+Y_{ext.inp}$

*Y2 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.

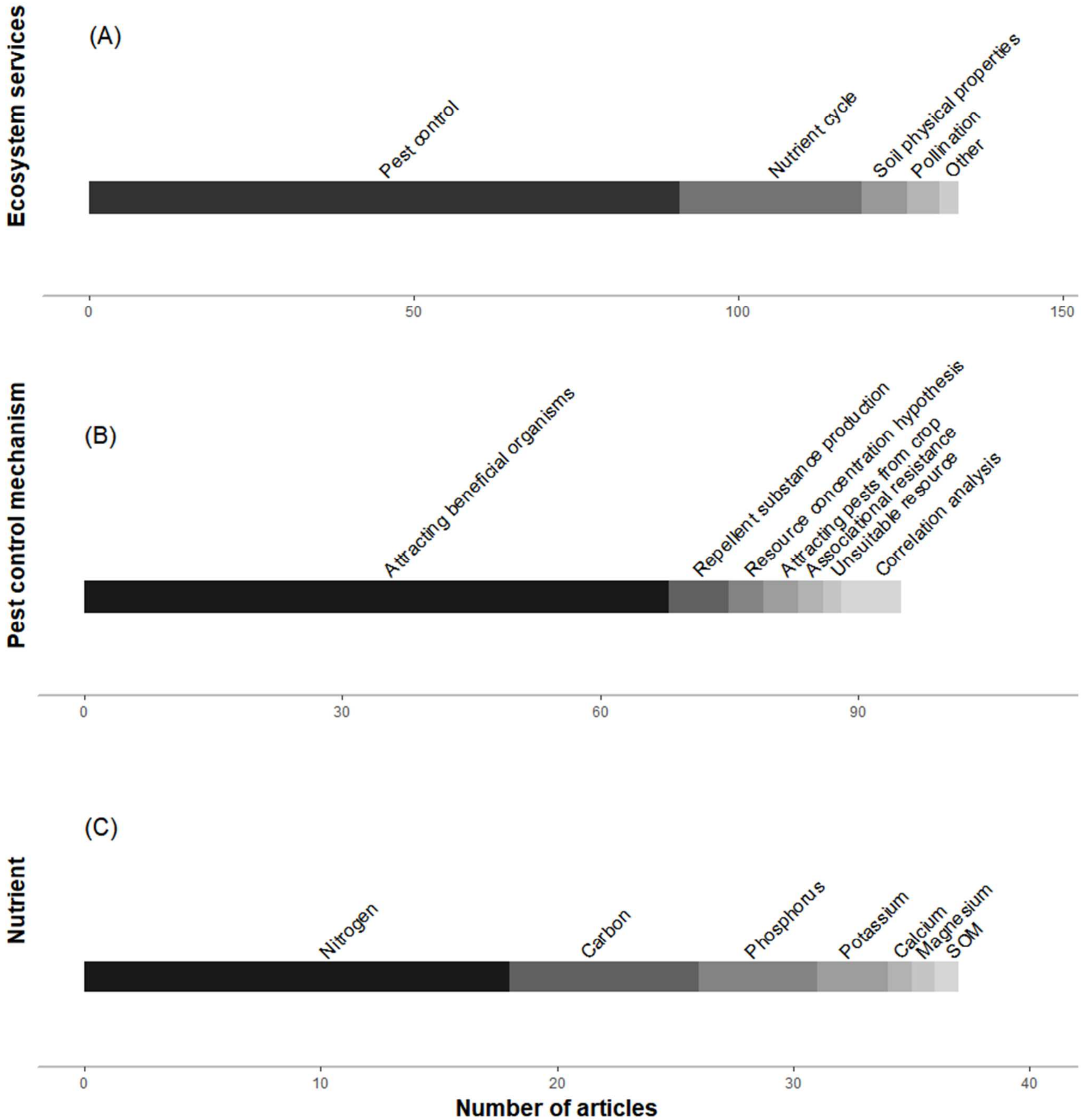
Ecosystem services
(A)
Pest control
Nutrient cycle
Soil physical properties
Pollination
Other
0
50
100
150
Pest control mechanism
(B)
Attracting beneficial organisms
Repellent substance production
Resource concentration hypothesis
Attracting pests from crop
Associational resistance
Unsuitable resource
Correlation analysis
0
30
60
90
Nutrient
(C)
Nitrogen
Carbon
Phosphorus
Potassium
Calcium
Magnesium
SOM
0
10
20
30
40
Number of articles

Fig. 1

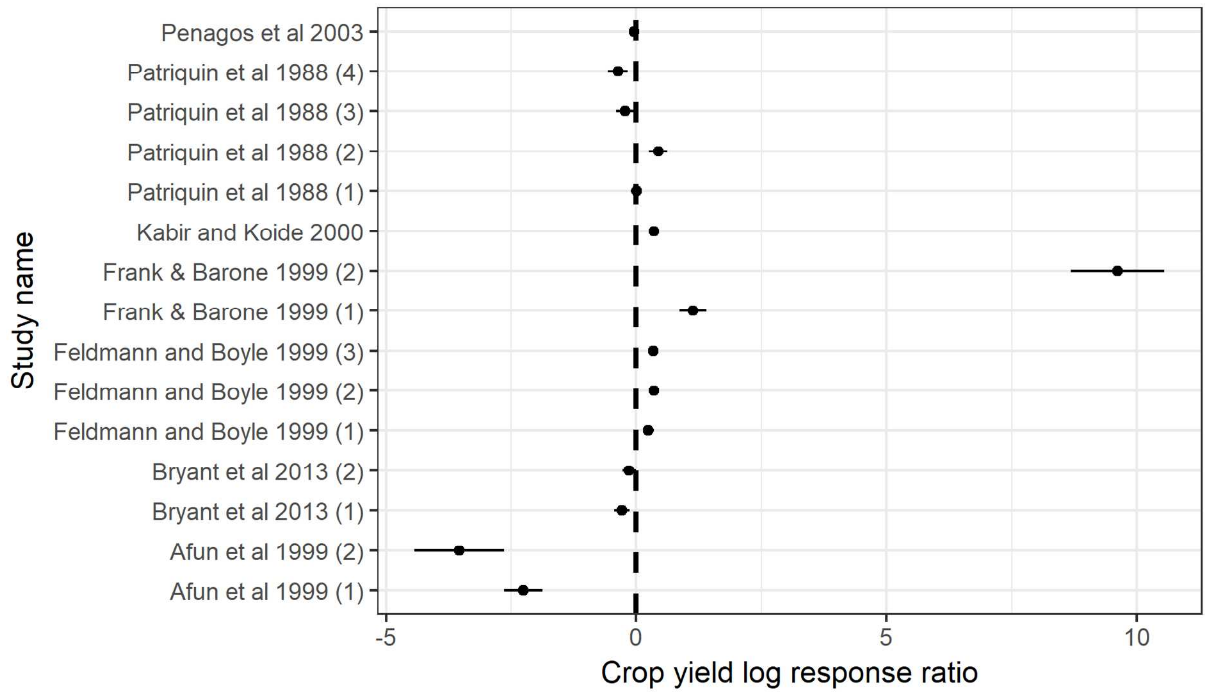
Penagos et al 2003
Patriquin et al 1988 (4)
Patriquin et al 1988 (3)
Patriquin et al 1988 (2)
Patriquin et al 1988 (1)
Kabir and Koide 2000
Frank & Barone 1999 (2)
Frank & Barone 1999 (1)
Feldmann and Boyle 1999 (3)
Feldmann and Boyle 1999 (2)
Feldmann and Boyle 1999 (1)
Bryant et al 2013 (2)
Bryant et al 2013 (1)
Afun et al 1999 (2)
Afun et al 1999 (1)
Study name
-5
0
5
10
Crop yield log response ratio

Fig. 2

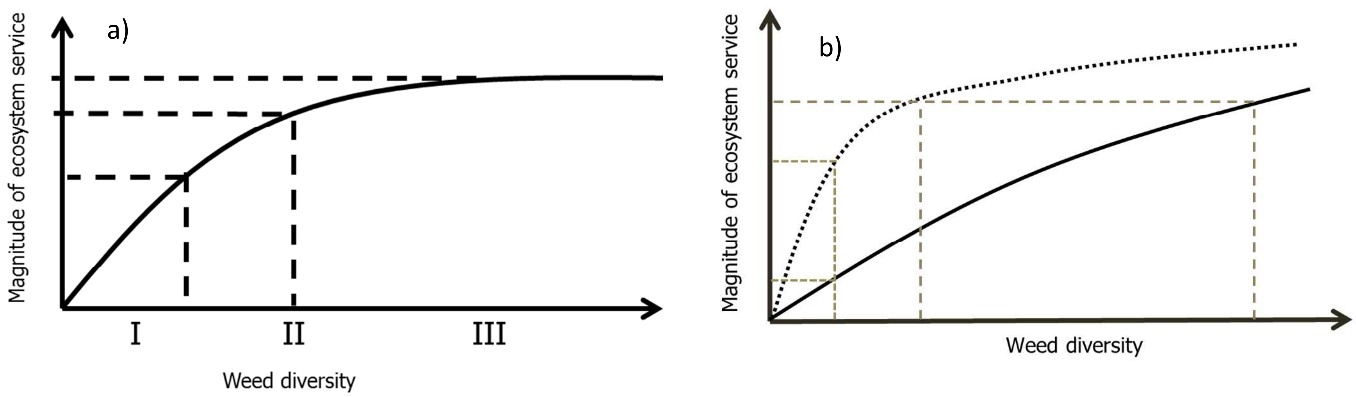
a)
Magnitude of ecosystem service
I
II
III
Weed diversity
b)
Magnitude of ecosystem service
Weed diversity

Fig. 3

Literature map

First Author	Title	Year	Reference	Ref Type	Text read	Linked studies
Yagioka	Effect of no-til	2015	Yagioka, A., K	Journal	Full text	10
de Rouw	Stable carbon	2015	De Rouw, A.,	Journal	Full text	
Araj	Comparing ex	2015	Araj, S.-E., Wi	Journal	Full text	
Morgado	Pollen resourc	2014	Morgado, L.N	Journal	Full text	
Das	Effects of tillag	2014	Das, A., Lal, F	Journal	Full text	
Kagawa	Ground beetle	2014	Kagawa, Y., M	Journal	Full text	
Kaasik	The relative a	2014	Kaasik, R., Kovács, G.,	Journal	Full text	
Yagioka	The effect of r	2014	Yagioka, Atsushi,	Journal	Full text	3
Premrov	Effects of ove	2014	Premrov, A., Coxon, C.E.,	Journal	Full text	
Arai	Changes in w	2014	Arai, M., Minamiya,	Journal	Full text	
Manfrino	Potential plan	2013	Manfrino, R.G	Journal	Full text	
Dahlin	Aphid perform	2013	Dahlin, I., Ninl	Journal	Full text	39, 92, 94, 96
Pettis	Crop Pollinatic	2013	Pettis, J.S., Lichtenberg,	Journal	Full text	
Han	Effects of tillag	2013	Han, H., Ning, T., Li,	Journal	Full text	
Bryant	Cover crop mı	2013	Bryant, A., Brainard,	Journal	Full text	
Amaral	Non-crop veg	2013	Amaral, D.S.S.L.,	Journal	Full text	
Belz	Olfactory attra	2013	Belz, E., Kölliker, M.,	Journal	Full text	
Gholamhoseir	Weeds - Frien	2013	Gholamhosei ni, M.,	Journal	Full text	22
Pisani Gareau	Relative densi	2013	Pisani Gareau, T.L.,	Journal	Full text	
Gholamhoseir	Interactions o	2013	Gholamhosei ni, M.,	Journal	Full text	20
Lindsey	Nitrogen relea	2013	Lindsey, L.E.,	Journal	Full text	
Calumpang	Behavioral res	2013	Calumpang, Susan May	Journal	Full text	
Ghosh	Effects of gras	2012	Ghosh, B.N., Dogra, P.,	Journal	Full text	
Gupta	An entomopha	2012	Gupta, R.K., Srivastava,	Journal	Full text	
Sarfraz	Influence of th	2012	Sarfraz, R.M.,	Journal	Full text	
Szendrei	The impact of	2012	Szendrei, Z., 2012. The	Journal	Full text	

Literature map

Caballero-Lóp	Weeds, aphid	2012	Caballero-López, B.,	Journal	Full text	
Arun	Plant growth p	2012	Arun, B., Gopinath, B.,	Journal	Full text	
Ojeniyi	Soil productivi	2012	Ojeniyi, S.O., Odedina,	Journal	Full text	
Mazzoncini	Long-term effe	2011	Mazzoncini, M., Sapkota,	Journal	Full text	
Carvalheiro	Natural and w	2011	Carvalheiro, L.G.,	Journal	Full text	
Sæthre	Aphids and th	2011	Sæthre, M.-G.,	Journal	Full text	
Gupta	Effects of app	2010	Gupta, S., Narayan, R.,	Journal	Full text	
Atakan	Influence of w	2010	Atakan E., 20	Journal	Full text	
Gill	*Mulch as a Pc*	2010	Gill, H.K., McS	Journal	Full text	
Wang	Labile organic	2009	Wang, L., Wen, L., Cai,	Conference pa	Full text	
Ninkovic	Weed-barley i	2009	Ninkovic, V., Glinwood,	Journal	Full text	14, 92, 94, 96
Lundgren	Population res	2009	Lundgren, J.G.,	Journal	Full text	
Gemmill-Herr	Role of native	2008	Gemmill-Herren, B.,	Journal	Full text	
Holzschuh	Agricultural la	2008	Holzschuh, A., Steffan-	Journal	Full text	
Lykouressis	Assessing the	2008	Lykouressis, D., A.	Journal	Full text	
Banik	A mathematic	2007	Banik, P., Pramanik,	Journal	Full text	
Grosch	Analysis of an	2007	Grosch, R., Lottmann, J.,	Journal	Full text	
Lian	Influence of ol	2006	Lian, J.Y., Ye, W.H.,	Journal	Full text	
Gianoli	Benefits of a r	2006	Gianoli, E., Ramos, I.,	Journal	Full text	
Promsakha	Weeds - Frien	2006	Promsakha Na	Journal	Full text	
Stephens	Parasitic wasp	2006	Stephens, C.J.,	Journal	Full text	
Vatovec	Responsivene	2005	Vatovec, C., N. Jordan,	Journal	Full text	
Cetintas	Distribution ar	2005	Cetintas, R., Dickson,	Journal	Full text	
Macdonald	The use of co	2005	Macdonald, A.J., Poulton,	Journal	Full text	
Holland	The spatial dy	2004	Holland, J.M., L.	Journal	Full text	
Ariosa	Epiphytic cyar	2004	Ariosa, Y., Quesada, A.,	Journal	Full text	
Banks	Aphid respons	2004	Banks, J.., Sta	Journal	Full text	
Chen	The occurrenc	2003	Chen, X., Lan	Journal	Full text	

Literature map

Penagos	Effect of weec	2003	Penagos, D.I.	Journal	Full text	
Dosdall	Weed control	2003	Dosdall, L.M.,	Journal	Full text	
Andersen	Long-term exp	2003	Andersen, A. Long-Term	Journal	Full text	63
Sengonca	Attractiveness	2002	Sengonca, C., Kranz, J.,	Journal	Full text	
Siddiqui	Evaluation of /	2002	Siddiqui, I.A., Shaukat,	Journal	Full text	
Alexander	Suppression c	2002	Alexander, S.A.,	Journal	Full text	
Andersen	Plant protectic	1999	Andersen, A.,	Journal	Full text	59
Afun	Weeds and na	1999	Afun, J.V.K., .	Journal	Full text	68
Frank	Short-term fiel	1999	Frank, T., Barone, M.,	Journal	Full text	66.67
Frank	Density of adu	1999	Frank, T., 1999.	Journal	Full text	65.67
Frank	Laboratory foc	1999	Frank, T., Friedli, J.,	Journal	Full text	65.66
Afun	The effects of	1999	Afun, J.V.K., .	Journal	Full text	64
Krooss	The effect of c	1998	Krooss, S., Schaefer, M.,	Journal	Full text	
Salveter	The influence	1998	Salveter, R., 1998. The	Journal	Full text	
George, T	Recycling in s	1998	Geoge, T; Bur	Journal	Full text	
Miller	Survey of vesi	1998	Miller, R.L., Jackson,	Journal	Full text	
Merbach	Uptake of wee	1997	Merbach, I. "Uptake of	Journal	Full text	
Pannkuk	Fallow manag	1997	Pannkuk, C, F	Journal	Full text	
Ohno	Species comp	1997	Ohno, K., & T	Journal	Full text	
Webster	Effect of one y	1995	Webster, C.P.,	Journal	Full text	
Tonhasca Jr.	Effects of agrc	1993	Tonhasca, A.,	Journal	Full text	
Kiss	Importance of	1993	Kiss, J., Kádá	Journal	Full text	
Alston	Relationship c	1991	Alston, D.G., I	Journal	Full text	
Brust, G	Augmentation	1991	Brust, G (199	Journal	Full text	
Bottenberg	Presence of tu	1990	Bottenberg, H., Litsinger,	Journal	Full text	
Swamy	Nutrient budgı	1988	Swamy, P.S.,	Journal	Full text	
Patriquin	Aphid infestati	1988	Patriquin, D.G., Baines,	Journal	Full text	
Holzapfel-Psc	Effects of veg	1986	Holzapfel-Pschorn, A.,	Journal	Full text	

Literature map

Collins	Reproductive	1985	Collins, F.L., Johnson,	Journal	Full text	
Heinrichs	Leersia hexan	1984	Heinrichs, E.A	Journal	Full text	
Mishra	Nitrogen budg	1984	Mishra, B.K., Ramakrishna	Journal	Full text	
Gliessman	Nitrogen distri	1982	Gliessman, S.R., 1982.	Journal	Full text	
McMurty	Establishment	1978			Full text	
Ghosh	Effects of diffe	1977	Ghosh, S.P., Babu, R.,	Journal	Full text	
Albajes	Responsivene	2009	Albajes, R., Lumbierres,	Journal	Full text	
Glinwood	Barley expose	2004	Glinwood, R., Ninkovic,	Journal	Full text	14, 39, 94, 96
Hong	Paddy weed c	2004	Hong, N.H., Xuan, T.D.,	Journal	Full text	
Glinwood	Change in acc	2003	Glinwood, R.,	Journal	Full text	14, 39, 92, 96
Hawes	Responses of	2003	Hawes C., Ha	Journal	Full text	
Ninkovic	Searching beh	2003	Ninkovic, V., &	Journal	Full text	14, 39, 92, 94
Griffin	Factors poten	2002	Griffin, M.L., Yeargan,	Journal	Full text	98
Griffin	Oviposition sit	2002	Griffin, M.L., Y	Journal	Full text	97
Buckelew	Effects of wee	2000	Buckelew, L.D	Journal	Full text	
Kabir	The effect of c	2000	Kabir, Z., and R. T.	Journal	Full text	
Feldmann	Weed-mediate	1999	Feldmann, F., Boyle, C.,	Journal	Full text	
Cottrell	Factors influe	1999	Cottrell, T.E.	Journal	Full text	103
Cottrell	Influence of a	1998	Cottrell, T.E.,	Journal	Full text	102
Wang	Influence of ra	1998	Wang, W., Zh	Journal	Full text	
Honek	The effect of p	1997	Honek, A. 199	Journal	Full text	
Schellhorn	The impact of	1997	Schellhorn, N.	Journal	Full text	
Stansly	Apparent para	1997	Stansly, P.A.,	Journal	Full text	
Hausammann	The effects of	1996	Hausammann	Journal	Full text	
Zangger	Increasing the	1994	Zangger, A., L	Journal	Full text	110.114
Lys	Improvement	1994	Lys, J.A., Nen	Journal	Full text	109.114
Lagerlöf	The abundanc	1993	Lagerlöf, J., Wallin, H.,	Journal	Full text	
Coop	Pearl millet inj	1993	Coop, L.B., Cr	Journal	Full text	

Literature map

Andow	Population de	1992	Andow, D.A.,	Journal	Full text	
Lys, JA	Augmentation	1992	Lys, JA & Ner	Journal	Full text	109;110
Chiverton	The effects of	1991	Chiverton, P.A.,	Journal	Full text	
Andow	Population dy	1990	Andow, D.A.,	Journal	Full text	
Ofuya	Effect of weec	1989	Ofuya, T.I., 1989. Effect	Journal	Full text	
House	Soil arthropod	1989	House, G.J., 1	Journal	Full text	
Altieri	The effects of	1985	Altieri, M.A., V	Journal	Full text	122.123
Powell	The influence	1985	Powell, W., D	Journal	Full text	
Ali	Vegetation ma	1985	Ali, A.D., Rea	Journal	Full text	
Altieri	Effects of plar	1983	Altieri, Miguel A.,	Journal	Full text	88,119, 123
Altieri	Weed manipu	1980	Altieri, M. A., and W. H.	Journal	Full text	
Tingle	Parasites of S	1978	Tingle, F. C., T. R. Ashley,	Journal	Full text	
Speight	The influence	1976	Speight, M. R., and J. H.	Journal	Full text	
Smith	Influence of cr	1976	Smith, J.G., 1	Journal	Full text	127;130
Smith	Influence of cr	1976	Smith, J.G., 1	Journal	Full text	126;130
Perrin	The role of the	1975	Perrin, R. M. "The Role of	Journal	Full text	
Dempster	Some effects	1969	Dempster, J. P. "Some	Journal	Full text	
Smith	Some effects	1969	Smith, J.G., 1969. Some	Journal	Full text	126.127
Green	Food selectio	1980	Green, R.E., 1980. Food	Journal	Full text	

Literature map

Objectives	Intervention	English	Countrie(s)	Length of study in years	Study type	Control
To examine th	Tillage system	Y	Japan	3	Experimental	Y
To 1) investigate	Vegetation typ	Y	Laos	3	Observational	N
To investigate	Plant species	Y	Jordan	1	Experimental	Y
To determine	Pollen grains	Y	Portugal	1	Experimental	N
To assess the	Tillage system	Y	India	4	Experimental	Y
To clarify the	Weed manage	Y	Japan	2	Experimental	N
To assess the	Pest host spe	Y	Estonia	3	Experimental	Y
To assess the	Tillage system	Y	Japan	2	Experimental	Y
To investigate	Tillage system	Y	Ireland	3	Experimental	Y
To investigate	Tillage system	Y	Japan	17	Observational	Y
To identify potential	Weed species	Y	Argentina	3	Observational	N
To investigate	Plant species	Y	Sweden	3	Experimental	Y
To investigate	Crop grown	Y	USA	1	Observational	N
To investigate	Weeding/ tillag	Y	China	2	Experimental	Y
To determine	Herbicide	Y	USA	2	Experimental	Y
To evaluate (a	Weed species	Y	Brazil	1	Observational	Y for experime
To investigate	Flowering plan	Y	Netherlands	Unknown	Experimental	Y
To evaluate th	Nitrogen/pigw	Y	Iran	2	Experimental	Y
To assess the	Hedgerow	Y	USA	2	Observational	Y (for hedgerc
To determine	Nitrogen/pigw	Y	Iran	2	Experimental	Y
To determine	Field manage	Y	United States	1	Experimental	Y
To determine	Plant species	Y	Philippines	5	Experimental	Y
To see if vege	Field manage	Y	India	4	Experimental	Y
preference of	cropping syste	Y	India	3	observational	N
To test the hy	Weed species	Y	Canada	Unknown	Manipulative	N
To investigate	Herbicide app	Y	USA	1	Experimental	Y

Literature map

To examine (1	Field managei	Y	Spain	1	Experimental	N
To screen free	Bacteria isolat	Y	India	Unknown	Experimental	N
To investigate	Weed fallow	Y	Nigeria	Unknown	Experimental	Y
To examine th	Field managei	Y	Italty	16	Experimental	Y
To characteriz	Ruderal plants	Y	South Africa	1	Observational	N
increase the k	species comp	Y	Benin	3	observational	N
(i) To investiga	Weed leaves	Y	India	Unknown	Experimental	Y
To investigate	Tillage systen	Y	Turkey	2	Experimental	Y
To evaluate th	Mulch type, i.e	Y	USA, Florida	1	Experimental	Y
To elucidate tl	Vegetation typ	Y	China	Unknown	Experimental	N
To investigate	Plant species	Y	Sweden	3	Experimental	Y
To test the hy	Weeding	Y	USA	1	Experimental	Y
To investigate	Pollination typ	Y	Kenya	2	Observational	Y
To examine w	Field managei	Y	Germany	1	Observational	Y
Suitability of S	Plant species	Y	Greece	1	Experimental	No
To observe th	Weeding	Y	India	2	Experimental	Y
To select fung	Fungal strains	Y	Brazil	Unknown	Experimental	Y
parasitoids	species comp	Y	China	2	Experimental	Y
To evaluate th	Crop managei	Y	Peru	1	Experimental	Y
To assess the	Weeding, ferti	Y	Thailand	2	Experimental	Y
To understanc	Plant species	Y	Australia	1	Observational	N
To determine	Weed manage	Y	USA	2	Experimental	Y
To determine	Plant species	Y	USA	4	Experimental	N
To evaluate th	Cover crop	Y	Britain	3	Experimental	Y
The spatial dis	Weed cover	Y	Britain	1	Observational	N
To investigate	Nitrogen fixati	Y	Spain	2	Observational	N
To measure th	Field managei	Y	USA	1	Experimental	Y
determine spe	parasitism of l	Y	China	3	observational	N

Literature map

To investigate	Field manage	Y	Mexico	1		Experimental	N
To determine	Field manage	Y	Canada	3		Experimental	N
To investigate	Tillage sistem	Y	Norway	3 (all experiment		Experimental	Y
To determine	Weed species	Y	Switzerland	1		Experimental	Y
(i) to study the	Concentration	Y	Pakistan	1		Experimental	Y
To determine	Field manage	Y	USA	3		Experimental	Y
To observe th	Tillage system	Y	Norway	4		Experimental	Y
To assess the	Weed manage	Y	Ivory coast	2		Experimental	Y
To answer the	Weed species	Y	Switzerland	1		Experimental	Y
To clarify whe	Weed strip	Y	Switzerland	2		Observational	Y
To test seedli	Weed species	Y	Switzerland	2		Experimental	Y
weed residue	weed residue	Y	Ghana, Africa	2		observational	Y
To investigate	Field manage	Y	Germany	5		Experimental	Y
To investigate	Field manage	Y	Switzerland	3		Experimental	N
Analyse the s	Field manage	Y	Philippines	2		Experimental	Y
(i) to assess tl	Field manage	Y	USA	1		Observational	N
weed-N uptak	weed competi	Y	Germany	3		Experimental	Y
To determine	Tillage sytem	Y	USA Northwe	5		Experimental	Y
To investigate	Habitat type	Y	Japan	3		Observational	N
To examine fa	Set-aside mar	Y	Britain	3		Experimental	N
Effect of tillag	Tillage system	Y	USA, Ohio	3		Experimental	Y
To investigate	Field margin	Y	Hungary	1		Observational	N
canopy develo	Weed cover	Y	United States	3		Experimental	Y
Effect of cultu	Field manage	Y	USA	3		Experimental	Y
To determine	Field/habitat t	Y	Malaysia	2		Experimental	N
nitrogen and p	nutrient retent	Y	India	1		Experimental	N
To investigate	Weeding	Y	Canada	2		Experimental	Y
To study meth	Plant species	Y	Italty	1		Experimental	Y

Literature map

fecundity of P:	weed density/	Y	United States	1	laboratory	Y
To determinat	Plant species	Y	Philippines	1	Experimental	Y
To investigate	Field manage	Y	India	1	Observational	N
To examine th	Cropping syst	Y	Mexico	1	Observational	N
reporting the e	Plant species	Y	USA	7	Experimental	N
Investigating t	Weeding	Y	India	2	Experimental	Y
To detect the	Herbicide	Y	Spain	2	Experimental	Y
To investigate	Cirsium speci	Y	Sweden	1	Experimental	Y
To estimate th	Weeding	Y	Vietnam	1	Experimental	Y
To test the hy	Exposure to v	Y	Sweden	1	Experimental	Y
To determine	Use of genetic	Y	UK	2	Experimental	Y
To investigate	Weed manage	Y	Sweden	1	Experimental	Y
To examine fa	Weeding	Y	USA South Ea	2	Experimental	Y
To determine	weed species	Y	USA, Kentuck	2	experimental	N: see notes
To examine th	Weeding	Y	USA	2	experimental	Y
effects of dan	plant species	Y	USA, Pennsyl	2	experimental	Y
weed flora infl	selective rem	Y	Germany	2	experimental	Y
To examine th	plant species	Y	USA	1	Experimental	Yes in field ex
To examine th	Weed manage	Y	United States	3	Experimental	Y
to determin if	Plant species	Y	China	2	Observational	Y
To examine th	Field manage	Y	Czech Repub	3	Experimental	Y
effect of prese	adding weed s	Y	USA, Missour	1	Experimental	Y
To obtain info	Plant species	Y	USA Florida	5	Observational	N
To find out if v	Field and wee	Y	Switzerland	2	Experimental	N
To compare th	Field manage	Y	Switzerland (a	1	Experimental	Y
To compare th	Field manage	Y	Switzerland	1	Experimental	Y
To see if a co	Field margin	Y	Sweden	1	Experimental	Y
To determine	Field manage	Y	Mali	1	Experimental	Y

Literature map

To determine	Weeding	Y	USA	1	Experimental	Y
Measure activ	Field manage	Yes	Switzerland	2	Experimental	Yes
To quantify th	Weeding	Y	United Kingdo	1	Experimental	Y
To examine th	Plant species,	Y	USA, NY	1	Experimental	Y
To compare w	Weeding	Y	Nigeria	2	Experimental	Y
(1) to quantif	Herbicide and	Y	USA	2	Experimental	Y
To investigate	Field manage	Y	USA Californi	1	Experimental	Y
To investigate	Herbicide	Y	UK	3	Experimental	Y
To illustrate th	Weeding	Y	USA	2	Experimental	Y
To investigate	Weeding	Y	USA	1	Experimental	Y
Potential of cc	Plant species	Yes	USA	2	Experimental	Yes
To investigate	-	Y	USA	2	Observational	N
assessment o	differing weed	Y	United Kingdo	1	observational	N
To determine	Plant species	Y	UK	3	Experimental	Y
To investigate	Weeding	Y	United Kingdo	3	Experimental	Y
To observe th	-	Y	United Kingdo	2	Observational	N
To study the e	Weeding	Y	United Kingdo	1	Experimental	Y
To assess the	Weeding	Y	United Kingdo	3 (but most result	Experimental	Y
To describe th	Food selectio	Y	Britain	2	Observational	N

Literature map

Randomised	Spatial replicate	Temporal replicate	Study Location	Study Scale	Location of weeds
Y	Y	Y	Experimental farm	Field	Field
N	Y	N	Real farm	Multi field	Field
Y	Y	N	Lab	-	-
Y	N	Y	Greenhouse	-	-
Y	Y	Y	Experimental farm	Field	Field
N	Y	N	Experimental farm	Study site incl	Field and field
Y	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Field	Field
N	Y	Y	Real farm	Field	Field
Y	Y	Y	Real farm	Multi-field	Field margin
Y	Y	Y	Experimental farm anc	Multi-field	Field
N	Y	N	Real farms	Multi-field	Field margin
Y	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Multi-field	Field
Y (field)	Y (field and la	Y (field)	Real farm	Multi-field and	Field and field
Y	Unknown	Y	Lab	-	-
Y	Y	Y	Experimental farm	Field	Field
N	Y	Y	Real farms	Multi-field	Field margin
Y	Y	Y	Experimental farm	Field	Field
Y	Y	N	Experimental farm anc	Field and lab	Field
Y	N	N	Lab	-	-
Y	Y	Y	Experimental farm	Field	Field
Yes	N	Y	Experimental farm	multi field	field
Y	Y	N	Lab experiment	-	-
Y	Y	N	Experimental farm	Field	Field

Literature map

Y	Y	N	Real farm	Multi-field	Field
N	Y	N	Lab experiment	Lab	-
Y	Y	N	Lab and probably expe	Lab experime	Field
Y	Y	Y	Experimental farm	Field	Field
N	Y	N	Real farm	Multi-field	Field
Y	Y	Y	Real farm	Field	Field
N	Y	N	Lab	Lab experime	-
Y	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farms	Multi field	Field
N	N	N	Lab	Lab experime	-
Y	Y	Y	Lab and experimental	Plots	Field
Y	Y	N	Experimental farm anc	Field	Field
Y	Y	N	Real Farm	Field	Field and field
N	Y	Y	Real Farm	Multi-field	Field margin
Y	Y	No	Lab	Lab	-
Y	Y	Y	Experimental farm	Field	Field
N	Y	N	Lab	Lab experime	-
Y	Y	N	Real farm	Field	Field
Y	Y	N	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Field	Field
N	Y	Y	Real Farm	Multi-field	Field margin
Y	N (soil is used	Y	Glasshouse	Glasshouse	
Y	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Field	Field
N	Y	Y (but within 4	Real farm	Field	Field
N	Y	Y	Experimental farm	Field	Field
Not specified	Y	N	Experimental farm	Multi-field	Field margin
Y	Y	Y	Real farm	Field	Field

Literature map

Y	Y	N	Experimental farm	Multi field	Field
Y	Y	Y	Experimental farm	Plots	Field
Y	Y	Y	Experimental farm	Plots in field tr	Field
N	Y	N	Experimental farm	Field	Field margin
Y	Y	N	Greenhouse	-	-
N	Y	Y	Experimental farm	Multi field	Field
Y	Y	Y	Experimental farm	Multi field	Field
Y	N	Y	Farmers field	Plots within fie	Field
Y	Y	N	Experimental farm	Field	Field
N	Y	Y	Experimental farm	Multi-field	Herb strips
N	Y	Y	Lab	Lab experimei	-
Y	Y	Y	Experimental farm	field	Field
N	Y	Y	Experimental farm	Multi-field	Field
N	Y	Y	Experimental farm	Multi-field	Herb strips
Y	N	Y	Experimental farm	Field	Field
N	Y	N	Real Farm	Multi-field	Field
Y	Y	N	Experimental Field	Field	Field
Y	N	Y	Experimental field	Plots	Fallow
Y	Y	Y	Experimental farm	Multi-field	Field margin
N	Y	Y	Experimental farm	Field	Field
Y	N	Y	Experimental farm	Plot, within fie	Field
N	N	N	Real Farm	Field	Field margin
Y	Y	Y	experimental farm	field	Field
Y	Y	Y	Experimental farm	Field	Field
N	Y	N	Real farm	Multi-field	Field
Y	Y	N	Real farm	Field	Field
N/Y	N/Y	N	Experimental farm	Field	Field
N	Y	N	Experimental farm, lab	Multi field	Field

Literature map

Y	Y	Y	laboratory	lab	
N	Y	N	Greenhouse	multi plots	-
N	Y	N	Real Farm	Multi-field	Field
N	Y	N	Experimental farm	Multi-field	Field
N	Y	N	Real Farm	Multi-field	Field
N	N	Y	Experimental farm	Plots	Field
Y	Y	Y	Experimental farm	Field	Field
Y	Y	N	Greenhouse	-	-
Y	Y	Y	Experimental farm	Plots	Field
N	Y	N	Lab	-	-
Y	Y	Y	Real farm	Multi-field	Fields
Yes for lab co	Y	N	Experimental or real fa	Field and lab	Field
Y	Y	Y	Experimental farm	Multi field	Field
Y	N	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental Farm	Field	Field
Y	Y	N	Experimental Farm	Field	within field
Y	Y	Y	Experimental farm	Field and gree	in field
Yes in field ex	Yes in field ex	Yes in field ex	Lab + Greenhouse + E	Lab, greenhou	Petri dishes (i
Y	Y	Y	Experimental farm	Field	Field
?	N	N	Experimental farm	Plots	Field
Y	N	Y	Experimental field	Plots	Fallow
Y	Y	N	experimental farm	6 m2 plots	Field
N	Y	Y	Experimental farm	Multi field	Field edges
N	Y	Y	Experimental farm	Fields, strips a	Field edges
N	N	N	Experimental farm and	Field and lab	Field
N	Y	N	Experimental farm	Field	Field strips
Y	N	N	Experimental farm	Plots	Field margin
Not specified	Y	N	Experimental farm	Field	Field

Literature map

Y	Y	N	Experimental farm	Plots	Field
No	No	Yes	Real farm	Field	In strips
N	Y	N	Experimental farm	Field	Field margin
Y	N	N	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Plots	Field
Y	Y	Y	Experimental farm	Plots	Field
Y	Y	N	Experimental farm	Field	Field
N	Y	Y	Experimental farm	Field	Field
Y	Y	Y	Experimental farm	Plots	Field
N	Y	N	Experimental farm	Plots	Field
Yes	Yes	Yes	Experimental farm	Field	Field strips
N	N	Y	Info not given	Field	Field
N	Y	N	experimental station	field	field center
Y	Y	Y	Farm	Plots in fields	Field
Y for experime	Y	N	Experimental farm	Plots	Field
N	Y	Y	Experimental farm		Info not given
N	N	N	Experimental farm	Plots	Field
N	N	Y	Experimental farm	Info not given	Field
N	Y	Y	Real Farm	Multi-field	Field

Literature map

Time of year of measurements	Weeds considered as a factor	CROP POLLINATION	Mechanistic explanation provided	Effect on pollinator diversity
All year	N	Not measured	-	-
Autumn	N	Not measured	-	-
-	Y	Not measured	-	-
Winter	Y	Not measured	-	-
Summer, autumn	N	Not measured	-	-
March-Jan.	Y	Not measured	-	-
Summer	Y	Not measured	-	-
All year	N	Not measured	-	-
Winter	Y	Not measured	-	-
Summer	N	Not measured	-	-
Summer, autumn	Y	Not measured	-	-
Information not giv	Y	Not measured	-	-
Unknown	N	Positive	Attracted bees	Not measured
“growing season”	Y	Not measured	-	-
Summer, “growing	Y (indirectly)	Not measured	-	-
Autumn, Winter	Y	Not measured	-	-
-	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer, autumn	Y (but not main facto	Not measured	-	-
Summer	Y	Not measured	-	-
June	Y	Not measured	-	-
-	Y	Not measured	-	-
Summer, autumn	N	Not measured	-	-
Autumn (March -M	N	Not measured	-	-
-	Y	Not measured	-	-
Summer	Y	Not measured	-	-

Literature map

Summer	Y	Not measured	-	-
-	N	Not measured	-	-
-	Y	Not measured	-	-
Spring, summer, au	N	Not measured	-	-
Autumn	N	Positive	Increased flower visitor s	Increase
All year	Y	Not measured	-	-
Spring, summer	Y	Not measured	-	-
Winter, Spring, Sur	N	Not measured	-	-
Summer and autun	Y	Not measured	-	-
-	Y	Not measured	-	-
Spring – Summer (	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer, autumn	N	Positive	Increased pollination nea	Not measured
Summer	N	Positive	Increased pollinator dive	Not measured
Any time: controlec	Y	Not measured	-	-
Winter	Y	Not measured	-	-
-	N	Not measured	-	-
All year	Y	Not measured	-	-
“growing season”	Y	Not measured	-	-
After dry season	Y	Not measured	-	-
Summer, autumn	Y	Not measured	-	-
Experiment 1: May	Y	Not measured	-	-
Unknown	N	Not measured	-	-
Autumn, Winter, Sp	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
All year	N	Not measured	-	-

Literature map

August-September	Y	Not measured	-	-
Fall-Summer	Y	Not measured	-	-
Summer, Autumn	Y	Not measured	-	-
Summer	Y	Not measured	-	-
-	Y	Not measured	-	-
Autumn	Y	Not measured	-	-
Summer	N	Not measured	-	-
Summer	Y (weed control)	Not measured	-	-
Autumn	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Autumn	Y	Not measured	-	-
Summer (July -Oct	Y	Not measured	-	-
Spring, summer	N	Not measured	-	-
Spring, summer, au	N	Not measured	-	-
During the rice grov	Native weeds were (	Not measured	-	-
Summer	Y	Not measured	-	-
Spring, Summer, A	Y	Not measured	-	-
Year	Y	Not measured	-	-
June-October	Y	Not measured	-	-
Winter, Spring	Y	Not measured	-	-
Summer	N	Not measured	-	-
Spring – summer	N	Not measured	-	-
Summer (August)	Y	Not measured	-	-
During the corn grc	Yes, together with til	Not measured	-	-
Dec.-May	N	Not measured	-	-
All year	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-

Literature map

Autumn	Y	Not measured	-	-
-	Y	Not measured	-	-
Spring, Winter	N	Not measured	-	-
All year	Y	Not measured	-	-
Spring, summer ("S	N	Not measured	-	-
Rainy season (sum	Y (but not main facto	Not measured	-	-
Summer	Indirectly	Not measured	-	-
-	Y	Not measured	-	-
Spring and summer	Y	Not measured	-	-
Information not give	N	Not measured	-	-
Summer	Y	Y	Significant covariate effe	Increase in beet and r
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Information not give	N	Not measured	-	-
Summer	Y	Not measured	-	-
Spring and summe	Y	Not measured	-	-
Lab: no date (envir	Yes, in the field expe	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
November-August	N	Not measured	-	-
Spring summer	Y	Not measured	-	-
June-July and Janu	Y	Not measured	-	-
Summer	Y	Not measured	-	-
April-July	Y	Not measured	-	-
Winter	Y	Not measured	-	-
Summer and autun	N	Not measured	-	-
Summer	Y	Not measured	-	-

Literature map

Summer	Y	Not measured	-	-
Spring and summe	Yes	Not measured	-	-
Spring – summer	N	Not measured	-	-
May-August	Y	Not measured	-	-
Spring – summer a	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Spring-summer	Y	Not measured	-	-
Spring, summer	Indirectly	Not measured	-	-
Summer, autumn	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Spring - summer (A	Yes	Not measured	-	-
Summer	Y	Not measured	-	-
Summer	Y	Not measured	-	-
Summer, Autumn	N	Not measured	-	-
Summer, autumn	Y	Not measured	-	-
Spring, summer, au	Y	Not measured	-	-
Information not give	N (indirectly yes)	Not measured	-	-
Summer, autumn	N	Not measured	-	-
Spring	Y	Not measured	-	-

Literature map

Range of values for increase in pollinator abundance (in %)	Range of values for increase in pollinator visits (in %)	Range of values for increase in pollen deposition (in %)
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
-	-	-
Not measured	Not measured	Not measured
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Literature map

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Not measured	Not measured	Not measured
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Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
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Literature map

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Literature map

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Genetically modified herbicide-tolei	Not mesured	Not mesured
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Literature map

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Literature map

PEST CONTROL	Mechanistic explanation provided	Range of values for pest abundance reduction (in %)
Not measured	-	-
Not measured	-	-
Positive	By providing nectar to paris	Not measured
Positive	By providing a food source	Not measured
Not measured	-	-
Positive	Ground beetles are considered to be beneficial arthropods	
Positive	Attracting parisitoids of the	Not measured
Not measured	-	-
Not measured	-	-
Not measured	-	-
Positive	Source of entomopathoger	Not measured
Positive	Associational resistance; a	Intrinsic rate of increase of pest
Not measured	-	-
Not measured	-	-
Positive	Attracting natural enemies	Cabbage looper: -350(NS)-17.2
Positive	Attracting natural enemies	Not measured
Positive	Attracting parisitoids	Not measured
Not measured	-	-
Positive	Attracting natural enemies	Not measured
Not measured	-	-
Not measured	-	-
Positive	By providing toxic food to t	Increase in mortality (314-329 %
Not measured	-	-
Positive	flowering weeds provide food source for adults	
Positive	Attracting parisitoids and n	Not measured
Positive	Attracting pests away from	~65-68.75

Literature map

Positive	Attracting natural enemies	Not measured
Not measured	-	-
Not measured	-	-
Not measured	-	-
Not measured	-	-
positive and n	habitat	Not measured
Not measured	-	-
Positive	By providing alternative foo	The number of adults thrips pea
Positive	Resource concentration hy	Not measured
Not measured	-	-
Positive	By emitting volatiles that re	After exposure to Chenopodium
Positive	Hosting predator	Not measured
Not measured	-	-
Not measured	-	-
Positive	Providing food and breedir	Not measured
Not measured	-	-
Positive	Hosted fungi that suppress	Reduced the germination of *R.*
Positive	habitat	10 to 70
Positive	Reduced maximum density	Maximum abundance: 21,86
Not measured	-	-
Positive	Source of parisitoids	Not measured
Not measured	-	-
Positive	Increased # of beneficial n	Not measured
Not measured	-	-
Positive	By hosting beneficials; by I	Not measured
Not measured	-	-
Positive	Increased vegetative diver	55-84% reduction in pest abunc
Positive	parasitism	Not measured

Literature map

Positive	By benefiting predatory cal	Reduction of pest densities by 6
Positive	By disrupting the ovipositic	Reduction in egg deposition by
Positive	By providing a food source	Not measured
Positive	Attracting natural enemies	17.65 – 57.14
Positive	Weed species powder and	0 – 69
Positive	Reduced number of nemat	0 – 81
Positive	Weeds attracted beneficial	Not measured
Positive	Speculative; habitat, food	approx. -500% - +500%; see cc
Positive	Provided alternative food s	Not measured
Positive	Attracting natural enemies	Not measured
Positive	Provided alternative food s	Not measured
Positive and n	incresed activity/abundanc	Not stated
Positive	Attracting staphylinid beetl	Not measured
Positive	Offered oviposition sites fo	Not measured
Not measured	-	-
Not measured	-	-
Not measured	-	-
Not measured	-	-
Positive	Weeds (and other plants) a	Not measured
Not measured	-	-
Positive and n	Speculative; food and / or I	Not measured
Positive	providing habitat	Not measured
Positive	weeds provide habitat for r	15 - 30%
Positive	Presence of weeds increas	Not measured
Postive and N	Many ricefield weeds play	% decrease in tungro vectors (c
Not measured	-	-
Positive	Reduced number of aphids	0-78.95
Not measured	-	-

Literature map

Positive	poor nutritional value of ne	163 - 2.125 % decrease in egg
Positive	By attracting natural enemi	Not measured
Not measured	-	-
Not measured	-	-
Positive	providing habitat	Not measured
Not measured	-	-
Positive	Increased # of predators; r	Cicadellidae= 7.29 – 77.12; Apl
Positive	Reduced number of aphids	% of aphids settling: 14 – 19
Positive	By producing allelochemic	51.1-84.9 in weed density ; 71.7
Positive	By producing allelochemic	14.29
Positive	providing habitat	13-40% more consumers (herbi
Positive	Odour cues from plant vola	Not measured
Positive	By providing refugia from p	Not measured
Positive	Y; protection of ladybird be	see notes
Positive	Not explained	Not measured
Not measured	-	-
Not measured	-	-
Positive	*C. maculata* prefers to ovi	Not measured
Positive	Presence of *A. ostryaefolia*	Not measured
Positive	not measured	total: 44, range: 22-76
Positive	By providing shade and co	Not measured
Positive	Interference with host plan	-75% till 60%
Positive	By providing refugia for pa	Not measured
Positive	Weed strip (field A, B) prov	Predator-prey relationship: A:94
Positive	Weed strip vegetation in a	Not measured
Positive	Increase of beneficial orga	Not measured
Positive	By hosting beneficials	Not measured
No effect	Ground cover (weeds) may	Not measured

Literature map

Positive	No explanation provided- tl	21.32 – 86.71
Positive	Providing resource for ben	Not measured
Positive	Provided diverse food sour	Not measured
Positive	Resource concentration hy	larvea, 66-91%; adults 35-86%
Positive	Root theory or resistance t	*E. dolichi*: 0 – 41.49 ; *O. mutab*
Positive	Provided resources for pre	Not measured
Positive	By benefiting ground preda	On tomato, reduction of Epitrix l
Positive	By providing resources to l	No effect
Positive	By providing food	0 – 45.93 (NS)
Positive	Attracted pests away from	80.59
Positive	By providing shelter to ben	Expressed as reduction of dama
Positive	By providing a food source	Not measured
Positive	pupae removal higher due to higher ground beetle abundar	
Positive	By being less attractive an	Alate aphids: -36.36 – 95.82; *A*
Positive	By hosting beneficials	Not measured
Positive	By hosting beneficials	Not measured
Positive	By hosting beneficials	19.05 – 84.34
Positive	By making plots less attrac	27.92 – 96.71
Positive	Damaged seedlings tende	Not measured

Literature map

ECOSYSTEM SERVICES		
Range of values for increase in predation/parasitism (in %)	Range of values for increase in beneficial abundance/diversity (in %)	SOIL PHYSICAL PROPERTIES
-	-	Not measured
-	-	Not measured
250-255	35-37 (egg abundance)	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
as they are usually generalist predatc	Top 5 weed species, % increase in numb	Not measured
-12-8	Not measured	Not measured
-	-	Positive
-	-	Not measured
-	-	Positive
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
-	-	Not measured
Not measured	Spined soldier bug : -23.08(NS)-196.59, (	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
Not measured	No control for weed species to compare v	Not measured
-	-	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
-	-	Positive
200 - 600% depending on the specie	0 - 400% more parasitoids and predators	Not measured
86.93 – 90.54% of pest parasitised o	Not measured	Not measured
Not measured	Not measured	Not measured

Literature map

Not measured	No control to compare with	Not measured
-	-	Not measured
-	-	Positive
-	-	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
more predator than prey on faba with	Not mesured	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
15.02 (NS)	~70 of adults and ~40 of nymphs	Not measured
-	-	Not measured
-	-	Not measured
Not measured	The presence of *S. nigrum* contributes to	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
Not measured	0 to 250	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
Not measured	No control for weed species to compare v	Not measured
-	-	Not measured
0 – 67	Not measured	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured

Literature map

Negative - Decrease in parasitism (9(	Increase in predatory carabids captured ir	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Predator abundance: -25 – 450	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	0-275%	Not measured
Not measured	Not measured	Not measured
Not measured	Abundance in margins: 80-300	Not measured
Defoliation reduction: 5.88 – 38.23	Not measured	Not measured
Not measured	200 - 310 % (spider activity and abundanc	Not measured
Not measured	Species richness of staphylinids: 31; # of	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
-	-	Not measured
-	-	Not measured
-	-	Positive
Not measured	Cannot calculate because there is no con	Not measured
-	-	Not measured
Not measured	-58% - 212% (abundance)	Not measured
Not measured	FM vs. 250m: Arachnids 35.26, carabids !	Not measured
Not measured	abundance: 50 - 300% increase early (Jul	Not measured
Not measured	Between 32 and 44% of increase	Not measured
:ontrol = mean of unweedy habitats): I	% increase in pest predator abundance (c	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
-	-	Not measured

Literature map

Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
-	-	Not measured
-	-	Not measured
Not measured	Not measured	Not measured
-	-	Positive
Not measured	Nabis: 1300; Orius: -20.83 – 25; Araneae	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	In field experiment: 90-120% increase in	Not measured
Not measured	700-2780 (egg cluster survival)	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
-	-	Positive
-	-	Not measured
Not measured	Presence of this weed in margins of swee	Not measured
% increase in predation of *H. zea* (pe	% increase of *C. maculata* eggs in weedy	Not measured
Not measured	Not measured	Not measured
Not measured	Higher than 10-20%	Not measured
Not measured	133% till 2360%	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	Increase in *Poecilus cupreus* (pest predat	Not measured
Not measured	Increase of 4.4 times (341%) in Carabida	Not measured
Not measured	No control for weed species to compare w	Not measured
Reduction in defoliation by 33.5-37.9	Not measured	Not measured

Literature map

Not measured	Not measured	Not measured
Up to 400% (5 to 10 times higher in tl	Not measured	Not measured
Not measured	Highly ranked polyphagous predators: 10(	Not measured
Not measured	Not measured	Not measured
Not measured	Not measured	Not measured
Not measured	-54.9 - 386.15	Not measured
In cauliflower, increase in parasitism	In tomato plots, increase in pitfall catches	Not measured
Not measured	Amara spp.: 418.6 – 1311.76; Loricera pil	Not measured
Not measured	Diversity :Foliage associated predators 67	Not measured
45.04 (leaf damage)	Not measured	Not measured
Not measured	Increase of 20% in the number of predato	Not measured
Not measured	Not measured	Not measured
40 - 100%	0 - 1000% (depending very much on the s	Not measured
Not measured	Not measured	Not measured
Not measured	*Syrphus* spp. : 0 – 87.5 ; *S . ribesii* : 0 – !	Not measured
Not measured	No control	Not measured
Not measured	Not measured	Not measured
Not measured	500 (*Anthocoris nemorum* eggs); 206.65	Not measured
Not measured	Not measured	Not measured

Literature map

Mechanistic explanation provided	Range of values for enhancement of soil physical properties (in %)	NUTRIENT CYCLE	Mechanistic explanation provided
-	-	Positive	Reduced nitrate leachir
-	-	Positive	Increased soil organic r
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Increased nitrogen, phc
-	-	Not measured	-
-	-	Not measured	-
Due to added C and weed r	Can't be measured due to tilling	Positive	weed residues provide
-	-	Positive	Reduced nitrate leachir
Reduced bulk density, improved soil aggregation		Positive	Increased soil carbon
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Reduced nitrate leachir
-	-	Not measured	-
-	-	Positive	Reduced nitrate leachir
-	-	Positive	Nitrogen release from w
-	-	Not measured	-
Reduced run-off and soil lo:	45.33 less run-off; 36-63.24 less soi	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-

Literature map

-	-	Not measured	-
-	-	Positive	Positively affects growtl
Reduced bulk density, incre	Bulk density reduction: 7-29; soil mc	Positive	Increased N, P, K in soi
-	-	Positive	Increased soil organic c
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Increased soil carbon
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Increased soil carbon c
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Increased soil N
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Reduced nitrate leachir
-	-	Not measured	-
-	-	Positive	Host to AMF symbiosis.
-	-	Not measured	-
-	-	Positive	Reduced nitrate leachir
-	-	Not measured	-
-	-	Positive	Increased N fixation rat
-	-	Not measured	-
-	-	Not measured	-

Literature map

-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	When legume, which wi
-	-	Positive	Increase in vesicular-ar
-	-	Positive	When cut, weed releas
Water storage, reduced soil	Water storage efficiency:14%; Incre	Not measured	-
-	-	Not measured	-
-	-	Positive	Reduced nitrate leachir
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Helped retain more nutı
-	-	Not measured	-
-	-	Not measured	-

Literature map

-	-	Not measured	-
-	-	Not measured	-
-	-	Positive	Recycled N
-	-	Positive	Reduced N loss
-	-	Not measured	-
Reduced soil loss and runo	Soil loss reduction: 65.81 – 98.32	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
proportion of water stable a	10 - 19%	Positive	Phosphorous content ir
-	-	Positive	AMF weed hosts increa
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-

Literature map

-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-
-	-	Not measured	-

Literature map

Range of values for increase in nutrients (in %)	OTHER(S)	Mechanistic explanation provided
C: 300-1900, N: 171-1462; ΔS	Positive	Reduced global warmin
Not measured	Not measured	-
-	Not measured	-
-	Not measured	-
N: 1.2-1.8, P: 1.5-2.7, K: 3.3-5	Not measured	-
-	Not measured	-
-	Not measured	-
56 - 76	Not measured	-
Weed and cereal volunteers re	Not measured	-
Not measured	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Y	Increased relative humi
-	Not measured	-
-	Not measured	-
-	Not measured	-
nitrate leaching reduced by: 4	Not measured	-
-	Not measured	-
Reduced by : ~44.43-~49.19	Not measured	-
Based on rate of N application	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-

Literature map

-	Not measured	-
Not measured	Not measured	-
N: 39-206, P: 3- 41, K: -30-57	Not measured	-
Not measured	Not measured	-
-	Not measured	-
-	Not measured	-
: -95.72-105.1	Not measured	-
-	Not measured	-
-	Not measured	-
Total organic carbon was 13.8	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
For *M. denticulata* only: N: 3.0	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
Reduced by 8.5	Not measured	-
-	Not measured	-
Mean % root colonization: *Abu*	Not measured	-
-	Not measured	-
Nitrate leaching reduction: -34	Not measured	-
-	Not measured	-
No control	Not measured	-
-	Not measured	-
-	Not measured	-

Literature map

-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
ill become green manure, are	Not measured	-
Not measured	Not measured	-
6.9-32.4 = residual uptake of v	Not measured	-
-	Not measured	-
-	Not measured	-
N leaching reduction: 58.82-62	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
Soil pool: N: 4.98 - 7.48; P: 37	Not measured	-
-	Not measured	-
-	Positive	Reduced CH4 emission

Literature map

-	Not measured	-
-	Not measured	-
No control	Not measured	-
No control	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
compared to control: 3.5 - 6.5	Not measured	-
100% more spore types (6 cor	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-

Literature map

-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-

Literature map

Range of values for increase of the other ecosystem service(s) (in %)	Effect on yield quantity	Range of values for the increase in yield quantity (in %)
Reduced GWP by 104%	Negative	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Negative	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Negative	-
-	Not measured	-
1.17-1.87	No effect (in no til	-
-	Negative	-
-	Not measured	-
-	Not measured	-
-	Positive	32.71
-	Not measured	-
-	Negative	-
-	Not measured	-
-	Not measured	-
-	Positive	Wheat= 80-120; maize= 8.5-60.56
-	Not measured	-
-	Not measured	-
-	Unknown – there	-

Literature map

-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Negative	-
-	Not measured	-
-	Not measured	-
-	Negative (NS)	-
-	Positive	Seed dry weight: 38.08 – 60.61 (broa
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-

Literature map

-	Not significant	-
-	Increase but also	Increase between 2-7%
-	Positive	Grain yield(1000 kg/ha): 4.06-5.64 (au
-	Not measured	-
-	Not measured	-
-	Positive	5.4 – 76.7
-	Not measured (bu	-
-	Positive or negati	-900%; see comments
-	Positive	131.58 – 210.53 more plants per m2
-	Not measured	-
-	Not measured	-
-	No effect	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Negative	-
-	Not measured	-
-	Not significant	-
-	Not measured	-
-	Negative	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Positive	Between 0 and 11.4%.
-	Not measured	-
-	Not measured	-
-	Positive	-30.70 - 55.43
Reduction of CH4 emission by 30%	Not measured	-

Literature map

-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Increase	4.7-23.3
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Positively (shoot (	30% (25 days after emergence)
-	Positive	0 - 35% depending on the AMF spore
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured	-
-	-29%, but non-sig	-
-	Not measured	-
-	Not measured	N
-	Not measured	
-	Not measured	-
-	Not measured	-
-	Postive (indirect)	-

Literature map

-	Not measured	-
-	Not measured	-
-	Not measured	-
-	Not measured, bı	-6.4%
-	Negative	-
-	Not measured	-
-	Negative	-
-	Negative	-
-	Negative	-22.05 (S) - 17.66 (NS)
-	No effect	-
-	Negative	-
-	Not Measured	-
-	Not Measured	-
-	Not measured	-
-	Not Measured	-
-	Not Measured	-
-	Negative	-
-	Not Measured	-
-	Not measured	-

Literature map

Effect on yield quality	Range of values for the increase in yield quality (in %)	Heterogeneity of results	Statistically tested	Extracting data
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Difficult
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Negative	-	No het	Y	Medium
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Easy
positive	Reduced nitrate concentration by	No het	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	No het	N	Medium
Not measured	-	No het	Y	Easy
Not measured	-	No het	N	Medium
Not measured	-	No het	Y (NS)	Medium
Not measured	-	Spatial	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Positive	Crude protein content increased b	No het	Y	Medium
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Medium

Literature map

Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Hard
Not measured	-	No het	Y	Easy
Not measured	-	No het	N	Medium
Not measured	-	No het	Y	Medium
Not measured	-	No het	N	No data?
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
not measured	-	spatial and temp	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	Temporal	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	No het	N	Medium
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Hard
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Positive	Seed N: 34.59 – 54.29 (legume/br	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	Temporal	Y	Moderate
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Moderate
Not measured	-	No het	N	Easy

Literature map

Not measured	-	Temporal	Y	Easy
Not measured	-	Spatial and temp	Y	Medium
Positive	-	No het	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	medium
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	temporal (somet	Y	Easy
Positive	-	No het	N	Medium
Not measured	-	No het	N	Medium
Not measured	-	No het		Difficult
Not measured	-	No het	Y	Easy
Not measured	-	No het	N	easy
Not measured	-	Temporal	Y	Easy
Not measured	-	No het	N	Moderate
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	easy
Not measured	-	No het	Y	Easy
Not measured	-	temporal (for artl	Y	Easy
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	difficult
Not measured	-	In yield due to fe	Y	Easy
Not measured	-	No het	Y	Easy

Literature map

Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	No het	N	Medium
Not measured	-	No het	N	Medium
Not measured	-	No het	N	Easy
Not measured	-	No het	N	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Difficult
Not measured	-	No het	Y	Moderate
Not measured	-	No het	Y	Medium
Not measured	-	het not explaine	Y	no data extrac
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	spatial (AMF spc	Y	Easy
Not measured	-	No het	Y	Easy
Not measured		No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	N	Easy
Not measured	-	Non-normal distr	Y	Moderate
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy

Literature map

Not measured	-	No het	Y	Easy
Not measured	-	No het	Yes	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Easy
Not measured	-	Temporal	Y	Easy
Negative	-	Temporal	Y	Moderate
Not measured	-	No het	Y	Easy
Positive	-3.16 (NS) - 5.52 **(S)**	Temporal	Y	Medium
Not measured	-	No het	Y	Easy
Not measured	-	Yes in crop yield	Yes	Moderated
Not measured	-	No het	N	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	Y	Medium
Not measured	-	Temporal	N	Medium
Not measured	-	No het	N	Easy
Not measured	-	No het	Y	Easy
Not measured	-	No het	N	Easy
Not measured	-	No het	Y	Easy

Literature map

Organism investigated - Crop	Organism investigated - Weed		Organism investigated - Pest	
	Positive effect	Neutral or negative effect	Negatively affected	No effect/Positively affected
Pumpkin, okra	Not named	-	-	-
Rice, maize, J	C4 perennials	-	-	-
-	*Capsella burs*	-	*Brevicoryne b.*	-
Pumpkin, tom	*Amaranthus b*	-	-	-
Rice	-	-	-	-
Rice paddy fie	Several, top 5 = *Amara macronota, Carabus yaconinus, Harpalus cha*			
Oilseed rape	*Brassica junc*	*Brassica rapa, Sin*	*Meligethes ae*	-
daikon	all weed	-	-	-
Spring barley	-	-	-	-
Zea mays, Capsicum	*Veronica didy.*	-	-	-
Wheat	*Brassica rapa*	-	Aphids	-
Barley	*Sinapis arven.*	Chenopodium albu	Aphids	-
Cucumber, wa	Only named a	-	-	-
Wheat	Not named	-	-	-
Cabbage	Not named	-	Cabbage loop	Diamondback moth, *F*
Chili pepper	*Ageratum con*	*Baccharis* sp., *Em*	Aphids	-
-	*Iberis amara,*	-	*Mamestra bra*	-
Maize and pig	*Amaranthus r*	-	-	-
Vegetables	*Achillea millef*	-	-	-
Maize	*Amaranthus r*	-	-	-
Zea mays L.	*Chenopodium*	-	-	-
Corn	Ageratum con	-	Ostrinia furna	-
Maize, wheat	Not named (w	-	-	-
vegetable, cer	Bidens pilosa;	neutral: Avena fatu	Helicoverpa a	-
-	*Sinapis arven.*	-	*Plutella xylost*	-
Carrots	Corn chamom	-	*Macrosteles q*	-

Literature map

Wheat	*Avena sativa,*	-	Cereal aphids	-
Vigna radiata	*Cassia occide*	-	-	-
Maize	*Imperata cylin*	-	-	-
Maize, wheat,	Not named	-	-	-
Sunflower	*Flaveria biden*	-	-	-
African eggpla	Catharanthus	Amaranthus spino	-	Aphis gossypii, Ahpis
Wheat, pea	*Parthenium hy*	-	-	-
winter faba be	*Calendula arv*	-		*Frankliniella occidenta*
Bush bean	Oenothera lac	same	Elasmopalpus	-
Maize	Not named	-	-	-
Barley	Chenopodium	Sinapis arvensis ir	Rhopalosiphu	-
Soybean	*Chenopodium*	-	*Aphis glycines*	-
Eggplant	*Leucas massa*	-	-	-
Wheat	Not named	-	-	-
-	Solanum nigru	Neutral: *Ditrichia v*	-	-
Barley, wheat	*Medicago den*	-	-	-
Potato, lettuce	Not named	-	*Rhizoctonia* d	-
-	Cuscuta camp	-	Mikania micra	-
Maize, bean	*Brassica camp*	-	*Carpophilus* s	*Pagiocerus frontalis*, *L*
Maize	*Amaranthus v*	-	-	-
Vegetables ar	*Diplotaxis tenu*	-	-	-
-	*Abutilon theop*	*Amaranthus retrof*	-	-
Peanut, bahia	Not named	-	*Meloidogyne a*	-
Barley	Not named	-	-	-
Wheat	Not named	-	Aphids	-
Rice	*Chara vulgaris*	-	-	-
Broccoli (*Bras* Brassica chinensis, B.	*Amaranthus p* Veronica undu	- -	Aphids, mainly Chromatomy ia horticola,	- -

Literature map

Maize	Cyperus rotun	-		Spodoptera fr	Leafhoppers, thrips, p
Canola (rapes	Dominant wee	-		Delia radicum	-
spring cereals	different weed	depend on the we		*Chromatomyia*	-
Lettuce	*Artemisia vulg*	-		Aphids	-
Tomato	Argemone me	-		*Macrophomina*	-
Potato, tomato	Not named	-		*Pratylenchus*	-
Wheat, barley	Not named	-		Not named	-
Rice	Digitaria horiz	Digitaria horizonta		Cofana spp., I	Nephotettix spp., Hete
Oilseed rape	*Stellaria medi*	*Taraxacum officina*		*Deroceras reti*	-
Rape, maize,	Not named	-		Not named	-
Oilseed rape	*Capsella burs*	*Taraxacum officina*		*Deroceras reti*	-
upland rice	weed residue	neutral to negative		Delphacidae;	No effect: Diopsis, Co
Rape, wheat,	Not named	-		Not named	-
Wheat	*Cirsium arven*	-		Aphids	-
Rice	Dominant wee	-		-	-
Lettuce	Not named	-		-	-
maize	Chenopodium	-		-	-
Spring and wi	Not named	-		-	-
Eggplant	White clover a	-		*Thrips palmi*	-
Wheat	Not named	-		-	-
Maize Soyabe	Not specified	Not specified		Herbivores, no	Herbivores, not specif
Wheat	Not named	-		Not measured	-
Soybean	Digitaria sang	-		Heliothis zea	-
Corn	Not reported.	-		Diabroticha ur	-
Rice, *Oryza S*	*Fimbristylis m*	*Fimbristylis miliace*		Tungro vector	-
Not named	Not named	-		-	-
Faba bean	Not named	-		*Aphis fabae*	-
Rice	*Echinogloa crus-galli,*	-		-	-

Literature map

soybean	Sesbania exal	-	Pseudoplusia	-
Rice	*Leersia hexar*	-	*Nilaparvata lu*	-
Solanum tube	Not named	-	-	-
Corn, bean, ri	Not named	-	-	-
Strawberry	Malva sp., Co	-	Tetranychus	-
Strawberry, pi	Not named	-	-	-
Cereals, alfafa	*Amaranthus s*	-	Cicadellidae, a	-
Barley, wheat	*Cirsium arven*	-	*Rhopalosiphu*	-
Rice	*Bidens pilosa, Tephrosia candida*		*Other weed sp*	-
Barley	*Elytrigia reper*	-	*Rhopalosiphu*	-
Beet, maize, s	170 weed spe	-	-	-
Barley (Horde	*Cirsium arvense* (L.) and *Elytrigia repens* (L.)			-
Corn	Abutilon theop	Amaranthus hybric	-	-
sweet corn	Abutilon theop	-	various, incluc	-
Soy bean	*Chenopodium*	-	*Empoasca fab*	*Cerotoma trifurcata, H*
Maize	Taraxacum of	-	-	-
maize	Anagallis arve	-	-	-
Sweet corn	*Acalypha ostr*	-	-	-
Sweet corn (Z	*Acalypha ostr*	-	*Helicoverpa Z*	-
Soy bean	Ambrosia arte	Ambrosia artemisi	Aphelenchoid	Pratylenchus, Tylench
-	-	-	-	-
Collard	Trifolium prate	Barbarea vulgaris,	Phyllotreta sp	Trichoplusia ni, Philae
Tomato, collar	Bidens spp., A	-	Bemisia tabac	-
Winter wheat	25 weed spec	-	*Sitobion aven*	-
Winter rye	-	-	-	-
Cereal	Variety of herl	-	-	-
Wheat, barley	Couch-grass	-	-	-
Pearl millet –	*Digitaria cilian*	-	-	Grasshopper – *Krauss*

Literature map

Beans	>25 listed in tl	-	*Empoasca fab*	-
Winter barley	-	-	-	-
Wheat	> 10 listed in t	-	-	Aphids
Dry bean, Pha	Brassica kabe	-	Epilachna varivestis	
Cowpea	Eleusine indic	Amaranthus hybric	*Empoasca do*	-
Wheat, maize	*Eupatorium ca*	-	Not named	-
Tomato, corn,	In tomato and	In tomato plots, Sc	Epitrix hirtiper	Nysius spp., Dactinotu
Wheat	16 species	-	-	*Sitobion avenae*
Sugarcane	54 species	-	*Diatraea sacc*	-
Collard	*Brassica camp*	-	*Phyllotreta cru*	-
Maize	Naturally occu	-	*Spodoptera fr*	-
Maize	*Amaranthus h*	-	*Spodoptera fr*	-
Winter wheat	Poa Annua	-	pupae of Dros	-
Brussels spro	All, which occ	-	*Brevicoryne brassicae*	*Myzus persic*
Brussels spro	*Chenopodium*	-	-	-
Not named (m	*Urtica dioica*	-	Aphids	-
Brussels spro	*Avena fatua, I*	-	*Pieris rapae*	-
Brussels spro	Not named	-	*Brevicoryne b*	-
Sugar beet	Many weeds i	-	Skylarks	-

Literature map

Organism investigated – Weed associated beneficial organism	Opinion on reliability of the paper	Reasons for the unreliability of the paper	Notes
-	1	-	Best nitrogen
-	1	-	Carbon isotop
Diaeretiella rapae	1	-	Weeds increas
Chrysoperla agilis	1	-	Gut content of
-	1	-	For results in t
Pest predator: *Coleoptera Carabida*	1	-	A significant p
Tersilochus heterocerus, Diospilus (	2	I am not sure that the identifie	The weeds ca
-	1	-	a bit chaotic. V
-	1	-	Although weed
-	1	-	Positive effect
Entomophthoralean fungi	2	No control	No control so
-	1	-	-
Bees	2	Effect of weeds was not the f	Bees visited s
-	1	-	Increase in rel
Propylea quatuordecimpunctata, Cc	1	-	-
Coccinellidae (including *Cycloneda*	2	No control for field observatic	Some weeds p
Microplitis mediator	1	-	Olfactory expe
-	2	Pigweed considered as a cro	The yield refe
Orius spp., Geocoris spp., Nabis sp	1	-	*A. millefolium*
-	1	-	The presence
-	2	No temporal replicate. Uncle	There are mar
-	1	-	Weeds decrea
-	1	-	Weed mulch (
Several groups: Coccinellids, syrphi	2	No real "control" for comparis	in the categor
Diadegma insulare	2	Actual pest control on a crop	*Percentage of*
-	1	-	The presence

Literature map

Grass aphids, Forb aphids, Parisitoi	2	No control. Measurements of	Weeds hostec
-	1	-	-
-	1	-	Weed fallow ir
-	1	-	Weed biomas:
Coleoptera, Diptera, Lepidoptera,He	2	They used some modelling	Weeds indirec
Cheilomenes propinqua, Lysiphlebu	2	A basic survey on organisms	A large but sin
-	1	-	Powdered leat
Orius sp.	1	-	Controlling we
-	1	-	-
-	1	-	Total organic (
-	1	-	Volatiles emitt
Orius insidiosus	1	-	Increased nun
Xylocopa caffra, Macronomia rufipe	1	-	Weeds hostec
Bees, solitary bees, bumble bees (A	1	-	The authors th
Macrolophus pygmaeus	1	-	Authors comp
-	2	Some strange results for the	Although the p
Trichoderma viride	1	-	*Trichoderma* s
-	1	-	-
Paratriphleps, Coccinellidae, Arane	1	-	Mixed croppin
-	1	-	Presence of b
Parasitic wasps	1	-	Weeds suppoı
Arbuscular mycorrhizal fungi	1	-	Substantial va
Pasteuria penetrans	1	-	Benefits of we
-	1	-	Weeds only ef
Carabid larvae, Bathyphantes spp. /	1	-	Weed cover w
Cyanobacteria	1	-	*Chara vulgaris*
-	2	No temporal replicate. Many	This study wa:
-	2	A basic survey on organisms	It only observa

Literature map

Calosoma calidum and other predat	1	-	In weedy plots
-	1	Some data are difficult to extr	Removing wee
carabis and staphylinids species	1	-	Several benef
Coccinella septempunctata, Adalia	1	-	Presence of w
-	1	-	Although yield
-	1	-	Weed fallow re
Amara plejeba, Loricera pilicornis, T	1	-	Tillage system
Spiders, ants, Reduviidae	1	-	Weeds have n
-	1	-	Presence of w
Aphidophagous hoverflies	1	-	Significantly m
-	1	-	Most of the tim
-	2	missing values for statements on significant	
Staphylinids	2	Not statistically tested; weeds	Authors believ
Syrphids	2	Not statistically tested; weeds	High densities
-	1	-	The main obje
-	1	-	Correlation be
-	1	-	-
-	1	-	Weeds growin
Predacious natural enemy: *Orius sp*	2	Not statistically tested. There	Without a cont
-	1	-	Yield was only
see comments	1	-	Problems here
Arachnids, carabids, staphylinids, ca	2	No replication. Effect of weeds not directly n	
predators in general (Orius insidiosu	1	-	Weed cover ha
Heterorhabditis heliothidis	1	-	-
Pest predators = Hunting spiders (*L*	2	No temporal replicate.	Weeds in rice
-	2	difficult to find the correct nur	-
Not named	1	-	Effect on yield
-	1	-	Weed plants c

Literature map

-	1	-	Article compris
L. pseudoannulata, C. lividipennis, A	1	-	*Leersia* popula
-	1	-	Comparison b
-	1	-	-
Phytoseiulus persimilis	2	no controll implemented, no i	P. oersimilis w
-	1	-	-
Orius , Carabidae, Araneae, *Nabis* s	1	-	Results varied
-	1	-	Cirsium volatil
-	1	-	Some weed sp
-	1	-	Volatiles extra
different herbivores, predators, para	1	-	This paper sho
Pest predator: *Coccinella septempu*	2	No temporal replicate.	The article pro
Coleomegilla maculata	2	Objectives do not always mee	Coleomegilla m
Coleomegilla maculata	1	-	This paper des
Orius insidiosus	1	-	A negative cor
vesicular-arbuscular mycorrhiza (VA	1	-	results often o
Arbuscular mycorrhizal fungi of the (	1	-	AMF hosting v
Coleomegilla maculata (Coccinelida	1	-	Increased pred
Natural enemy: *Coleomegilla macul*	1	-	This paper sho
none	1	-	nematodes are
Predatory ground arthropods	1	-	Large differen
Coccinellids, Carabids	1	-	-
Encarsia spp., Eretmocerus spp.	1	-	Moderately hir
Poligophagous and aphidophagous	1	-	-
Pest predator: *Poecilus cupreus*	2	No temporal or spatial replica	This paper rec
Carabidae, Staphylinidae, Araneae	1	-	Herbaceous p
Coccinellids, Carabids, Staphylinids	1	-	Staphylinids w
saria angulifera	2	No temporal replicate.	This article dis

Literature map

-	1	-	Pest reduction
carabid beetles *(Poecilus cupreus , (*	1	-	It is also meas
Forficula auricularia (L.), Agonum d	2	Aphid reduction higher in her	Carabid fecun
coccinellids, stinkbugs, phalangids,	1	-	In addition to p
-	1	-	-
predators in general	1	-	-
Formicidae, Carabidae, spiders, Ori	1	-	Weedy plots h
Carabids and Staphylinids	1	-	Pests were no
Solenopsis invicta and others	1	-	Higher numbe
-	1	-	-
Different predatory species not repo	1	-	Predator abun
Spodoptera exigua, Spodoptera eridania, Herpetogramma	2	No data given on parasitism of cash crop pe	
several ground beetle species	2	experimental design questionable (randomisa	
ae and other alate aphids	1	-	-
Syrphus spp., *Melanostoma* spp., *A*	2	Not statistically tested	-
Coccinella septempunctata, Adalia	2	No data given on predation or presence of p	
Granulosis virus, *Harpalus rufipes,*	1	-	-
Melanostoma spp., *Anthocoris nem*	1	-	Increase of be
-	1	-	Correlation be

Literature map

leaching reduction: 48.6%, Decrease in global warming potential in no tilling with cover mulching syste

e was used as proxy for plant contribution to soil organic pools

sed longevity, egg load, and aphid parasitism rate of the parisitoid compared to the control but not as

predator showed more weed pollen than cultivated plant pollen

he map weeding compared with no weeding in similar tillage system. Increase in nutrient input not sta

ositive effect of weed height was noted. It might seem as though the effect of weed height is simply re

n potentially be used as trap crops as well as be used to attract parisitoids

Veed mulch effect mixed with tillage effect

ds and cereal volunteers reduced nitrate leeching, better results were obtained for using mustard as a

on carbon is due to the presence of weeds as well as worms. Positive effect on soil physical structure

it was not possible to measure pest reduction. Plus, pest reduction in crops was not measured.

urrounding weeds as well as crops.

ative humidity was correlated with an increase in number of spikes.

provided resources such as flowers, extrafloral nectar, prey, refugefor natural enemies. No abundanc

eriments found the paristoid species to be attracted to the weeds

s to the yield of forage (maize + pigweed). Pigweed is considered both as a crop and weed since it is

attracted many different beneficial insects in hedgerows. *A. millefolium* is an indicator species of *Geo*

of pigweed decreased nitrate leeching but also decreased nitrogen use efficiency

ny variables to this study: weed type, rate of N application during growth, weed height at collection anc

ased survival of the pest larvae when feeding on the leaves. Impact on the predator not measured.

dead) part of a treatment and not independently tested.

y "pest control" two different observations are recorded: a rise in parasitation rate by only Trichogramr

parasitised pests was significantly lower on Capsella bursa-pastoris than on the other species.

of broadleaf weeds proved to be beneficial in pest regulation but the presence of grasses did not

Literature map

l non-cereal aphids which could provide shelter or an alternate food source for beneficials

nproved maize plant height, stem girth, and leaf area.

s correlated with tillage system and fertilisation which are in turn correlated to SOC and STN

:tly augmented yield by increasing flower visitor deiversity

nple survey. Weeds only a side effect.

f of weeds were used to detect weed effect in the experimen

eds can create a problem in many cases because destruction of weeds surrounding agricultural crops

carbon in soil with weed was compared with soil containing maize

ed by undamaged weeds can decrease acceptance of barley by aphids. Mechanisms not known. Effe

nbers of *O. insidiosus* in plots with weeds . Decrease in aphids NS

l pollinating insects

nink that bees depending on nesting sites in fallow strips benefited from the more abundant flower reso

ared the performance of *Macrolophus pygmaeus* in both species as an alternative food source and wi

presence of *M. denticulata* reduced the biomass of other weeds, the biomass of all weeds was still hig

strains reduced sclerotia germination on potato, and reduced disease effect on lettuce.

g with weeds reduced the maximum density of some pests

roadleaf weeds led to less microbial immobilization of mineral N which resulted in faster net release of

rt a diversity and abundance of parasitic wasps

riation was found in mycorrhizal responsiveness and hosting behavior among the 14 weed species te

eds not discussed

ffective as cover crops in sandy loam soil

as positively correlated with the density of the named beneficials. It was also found to be negatively c

s host cyanobacteria that improve nitrogen fixation rates

s interested in the interaction between margin type (weedy vs. bare ground) and pesticide spray level.

ational. How many parasits were found on what plant. Not compared, no effect measured. Weeds are

Literature map

;, there were more predatory carabids (mechanistic explanation not provided) and less parasitism on

eds late can decrease the negative impact of root maggot on canola yield but removing weeds early h

icial species were positively correlated with any weed group. More carabids were foud in plots with re

/eeds reduced the number of aphids on lettuce

was not measured, plant height was found to be higher in presence of *A. mexicana*

educed nematode numbers only in the soil of potato plots. Both potato and tomato yields increased af

ı was the main factor. Correlation were made between weed groups and beneficial insects.

ıegative effect on yield by competition, positive effect on yield by pest suppression. Some pests were

/eeds improved yield in crops with low slug densities but not significantly in fields with high slug densit

ıore hoverflies were found in the strips compared to the control but not in the fields.

ıes weeds reduced crop defoliation but results were not signifiacant.

differences of pests

/e that a higher weed cover benefited epigeic arthropods.

of aphids found on weeds

:ctive of the paper was to determine if N coming from green manure made in-field was a better supply

tween weed diversity and spore numbers was significant but not very strong (cor. coef.: 0.41)

ıg during the winter generate ground cover that limits soil erosion.

trol or more data it was difficult to draw much valuable information from this article. The article focuses

/ lower for wheat grown in the year after weed rotation and with no added N. Yield was highest after w

: are 1) that weeds were not quantified (however there is a second paper by Tonhasca & Stinner (199

ıeasured

ad a positive effect on arthropod abundance early in the season, when prey was scrace they migratec

fields can be both positive and negative as they are possible reservoirs for tungro virus and vectors, b

positive only when there is no additional N input. Weeds are thought to reduce aphid numbers due to

:aused a relatively high redox potential in the submerged soil so that 95% of the produced CH_4 was o

Literature map

ses a field experiment, but the results only show fecundity increses of the pest with incresing weed de

ation can serve as a suitable host for some of the predators, parasites and pathogens that attack the r

etween 5, 10 15 year fallow

vas apllicated every year on all sites.

l depending on sampling technique. For values, untreated plots were compared to treated plots.

es were used for this experiment.

pecies applied at a dose of 2 t/ha (dried material) decreased weed number and weed dry weight with a

cted from *E. repens* were used to show allelopathy with barley.

ows the effects of genetically modified herbicide-tolerant (GMHT) and conventional (C) crops manage

ovides interesting insights into the searching behaviour of polyphagous predators and supports the imp

maculata preferentially oviposits on plants with glandular trichomes. They may provide protection to th

scribes the effect of different weed species on egg deposition by a ladybird beetle. Another paper (Co

rrelation was found between weed% and the potato leafhopper.

nly significant 25 or 54 days after emergence and not 8 days after emergence

weeds increased shoot dry weight of maize

dator activity in sweet corn if weed is present. Hight mobility of *C. maculata* first instars in bare soil. M

owed that by providing an alternate oviposition site (presence of A. ostryaefolia), densities of predaced

e reduced by ambrosia. 2 are positively affected

ces among arthropod species and effect of weed cover varies with the weather, season and arthropo

rsute plant species may enhance movement and searching ability of parasitoids of Bemisia argentifolii

Aphidophagous predators seemed to be augmented by sown weed strip

commends weed strips in order to offer a better food supply, refuge, extend the reproductive period an

lants of the strips: clover species, Brassicaceae, *Tanacetum vulgare*, *Arctium minus*, *Achillea millefol*

were more numerous in the soil samples of couch-grass plots.

scusses two related experiments. The first experiment does not involve weeds; thus this entry only refe

Literature map

ı only found by visual count on the beans.

Sampling done by marking and recapturing

dity was higher in plots that were not treated with herbicides due to a more diverse food source (and a

›est abundance, different pest demographic rates were quantified separatedly

ıarboured more or less herbivores depending on the crop and the insect species. Because of the stror

ıt affected by weeds because they were either absent or not numerous in the studied years

ır of *Solenopsis invicta* mounds were found in weedy plots. There was a trend of higher infestations of

ıdance and diversity could be greater in fields surrounded by natural vegetation (indirectly seen). Pre

›st.

ation, short time period of observation)

›redators in cash crop. No information given on crop grown.

›neficials abundance was found on the brussels sprouts

tween weed seed density and damaged seedlings: r:-0 474 P < 0.05)

Literature map

ems

much as buckwheat

atistically significant

elated to that of the distance from woodland edges, however the analysis showed that these effects ar

cover crop

e probably more due to effect of no tillage than direct effect of weed.

e of weed species given and no control to compare with in the field study so no % of natural enemies

cumtivated and is historicaly known as a weed.

coris spp.

d incubation time. For this reason the presentation of results is complicated. There is an additional mo

n or Telenomus and second the number of predators/parasitoids present

Literature map

s could cause rapid dispersal of pestiferous thrips to crops and disturbance of the natural enemies of t

ect observed only with Chenopodium album in the lab and in the field.

ources provided by broadleaved weeds in organic crop fields.

ith and without prey (aphids). That is: *S. nigrum* with aphids/without aphids, and the same for D visco

her in unweeded plots.

f mineral N.

sted. Temporal heterogenity was attributed to lower temperature and light levels in experiment 2.

orrelated with aphid density (no explanation given to as to why. Possible allelopathy mentioned).

Thus – results in response to weed presence are intertwined with pesticide spray level.

said to be a reservoir of parasits of the pest.

Literature map

Spodoptera egg masses by the main parasitoid Chelonus insularis (hypothesis = egg masses were le

as a stonger positive impact.

duced tillage and more weeds, compared to autumn ploughed plots with fewer weeds

ter weed fallow.

positively affected, others negatively.

ies. Molluscicide more effective in these fields.

for rice than an external suply of N. The results confirmed this hypothesis when using *S. rostrata* , *V.*

s on the species composition of the pest pradator (*Orius spp.*) without much emphasis on the weeds

eed rotation when N was added and in both situations (with N, withou N) in the 2 year after rotation. F

1) that might be useful), and 2) they found no effect on herbivores

l to weed free plots

out do have the potential to harbor a variety of natural enemies of tungro vectors. Delaying weed contr

limiting crop N uptake.

xidized and did not reach the atmosphere.

Literature map

nsity, here i only stated the positive effects in the laboratory

rice population, specially during dry season when rice is not available.

as a onsequence an increase in rice yield 30 days after application.

ment on invertebrate trophic groups in association of biomass of weeds

portance of biodiversity in natural botanical communities.

ie egg clusters from cannibalism.

ttrell & Yeargan, 1998; No_119) is apparently describing the effect of more eggs on densities of ladyb

lore eggs laid on the weed than in sweet corn. No egg canibalism if *C. maculata* eggs are laid in the w

ous larvae (C. maculata) were markedly increased on sweet corn and predation of a pest species (H.

d body size.

, but there was parasitism on all weed species.

s, which in particular showed positive effects on syrphids Positive correlation between the syrphids ar

d raise the reproductive potential of ground bettles in general, increasing their chance of survival and

iun, *Chrysantenum leucantenum*, *Echium vulgare* and *Centaurea cianus*.

ers to the second experiment. The presence of *D. ciliaris* did not affect spike injury rates in pearl millet

Literature map

abundant) available there. Author suggests that herbicide application has a negative effect on natural

ng negative impact of the weeds on crop yield, it is not easy to say if the reduction/increase in insect n

Diatraea saccharalis in weed-free plots.

esence of weeds negatively affected yield in spite of the increase in beneficial arthropods

Literature map

e independent of each other.

attracted by each species could be calculated.

deling component to this study.

Literature map

hrips on the weeds.

sa. Predator density increased in *S. nigrum*, being the increase 4 times faster in the presence of prey ss apparent).

radiata and weeds as a source of N. In conclusion, in order to better synchronize the rice N demand

. Nevertheless, the article concludes that surrounding habitats (including weeds) serve as important re

Result was not significant.

rol to allow spiderlings to hatch ma

Literature map

ugs on sweet corn (but not this paper).

veed. First instars find difficult to move along the surface of the weed plant due to the trichomes and fa

Zea) on this crop also increased.

ıd the aphids in the strip-managed fields

predatory pressure on noxious insects.

, but did decrease defoliation. Defoliation causes a decrease in grain weight, therefore the presence o

Literature map

pest control in the long term.

umbers is due to the direct presence of the weeds or to their indirect impact on crop quality.

Literature map

Literature map

' than without prey. Predator density decreased in *D. viscosa* with/without prey.

Literature map

with the N supply, the authors suggest to supply the N with a mixt of legumes and weeds. This is wha

eservoirs that harbour *Orius spp.* populations which migrate into eggplants fields.

Literature map

all to the ground in search of plants with less trichomes, like sweet corn.

of *D. ciliaris* provided an indirect positive affect on yield.

Literature map

Literature map

Literature map

Literature map

t I have understood, so far.

Category Key

First Author
Title
Year
Reference
Ref Type
Text read
Linked studies
Objectives
Intervention
English
Countrie(s)
Length of study in years
Study type
Control
Randomised
Spatial replicate
Temporal replicate
Study Location
Study Scale
Location of weeds
Time of year of measurements

Category Key

Weeds considered as a factor
Pollination/Pest control/Soil stability/Nutrient cycling/Soil carbon
Mechanistic explanation provided
CROP POLLINATION
Effect on pollinator diversity
Range of values for increase in pollinator abundance (in %)
Range of values for increase in pollinator visits (in %)
Range of values for increase in pollen deposition (in %)
PEST CONTROL
Range of values for pest abundance reduction (in %)
Range of values for increase in predation/parasitism (in %)
Range of values for increase in beneficial abundance/diversity (in %)
SOIL PHYSICAL PROPERTIES
Range of values for enhancement of soil physical properties (in %)

Category Key

NUTRIENT CYCLE
Range of values for increase in nutrients (in %)
Other(s)
Range of values for increase of the other ecosystem service(s) (in %)
Effect on yield quantity
Range of values for the increase in yield quantity (in %)
Effect on yield quality
Range of values for the increase in yield quality (in %)
Heterogeneity of results
Statistically tested
Extracting data
Organism investigated – Crop
Organism investigated – Weed
Organism investigated – Pest
Organism investigated – Weed associated beneficial organism

Category Key

Opinion on reliability of the paper
Reasons for the unreliability of the paper
Notes

Category Key

Surname, Initial. of first author
Full Article Title
Four digit year of publication
Full reference of article
Journal / Bulletin / Symposium etc.
What type of source did the entry come from
Full Text How much of the text was read by review author when entering
Row numbers of all other entries in review that are part of the same study or in which the first author of the entry is an author
What were the objectives of the study
What is the independent variable (e.g. Tillage system, Field management, Plant species)
Y/N Is the language of the article English
Which country/countries was the study conducted in
During how many calendar years did the study take place
Experimental/ Observational Was the study experimental or observational
Y/N Was there a control
Y/N Was randomisation incorporated into the study design
Y/N Was there a spatial replicate
Y/N Was there a temporal replicate
Experimental Farm/Real Farm/Lab/Greenhouse Was the study done in an experimental farm, real farm, or was it done in a laboratory or greenhouse.
Field/Multi-field/Lab/Greenhouse Was the study restricted to one field, did it incorporate multiple fields or was it done in a laboratory or greenhouse.
Field/ Field margin If the study was done in a farm, indicate where the investigated weeds were located.
Which season(s) was the study conducted in

Category Key

Y/N Were weeds considered as a factor in the study or was their effect observed indirectly as a result of, for example crop management
Y/N Does the article promote the benefits of weeds towards this ecosystem service
Does the paper explain how weeds provide this ecosystem service e.g. Providing shelter, Providing food, Oviposition site, Camouflage (olfactory, sensory)
Positive/No effect/Not measured What effect did the intervention have on crop pollination
Increase/Decrease/Neutral/Not measured
What effect did the intervention have on pollinator diversity
Indicate in % the range of values obtained for the increase in pollinator abundance
Indicate in % the range of values obtained for the increase in pollinator visits
Indicate in % the range of values obtained for the increase of pollen deposition
Positive/No effect/Not measured What effect did the intervention have on the level of pest control (insects pests, weeds, or diseases)
Indicate in % the range of values obtained for the decrease of pest abundance
Indicate in % the range of values obtained for the increase in predation, parasitism or both.
Indicate in % the range of values obtained for the increase in pest predator or parasite abundance
Positive/No effect/Not measured What effect did the intervention have on the physical properties of soil
Indicate in % the range of values obtained for the enhancement of soil physical properties

Category Key

Positive/No effect/Not measured What effect did the intervention have on the nutrients in the soil
Indicate in % the range of values obtained for the increase in nutrients in the soil
Other Ecosystem service(s) provided by weeds
Indicate in % the range of values obtained for the increase in other ecosystem service(s)
Positive/Negative/No effect/Not measured What effect of the intervention on yield quantity
Indicate in % the range of values obtained for the increase in yield quantity that was found
Positive/Negative/No effect/Not measured What effect of the intervention on yield quality (e.g. seed protein content)
Indicate in % the range of values obtained for the increase in yield quality that was found
No het/ Spatial/ Temporal
Y/Y (NS)/N Was the effect of weeds statistically tested
Easy/Moderate/Difficult What level of difficulty was experienced in extracting data from the publication
Which crop organism(s) where the subject of the study
Positive effect Which species of weeds had a positive effect on an ecosystem service
Negative/neutral effect Which species of weeds did not have a positive effect on an ecosystem service
Negatively affected Which species of pests were negatively affected by weeds
No effect/Positively affected Which species of pests were not affected or positively affected by weeds
Which organism associated with the investigated weed provided ES?

Category Key

1/2/3 1: Reliable 2: Some doubt on the reliability of the paper 3. Not reliable	
If the paper is judge to be unreliable, provide an explanation as to why	
Any additional relevant notes about the entry	

Response to reviewer and subject editor's comment

Dear Subject Editor,

We would like to thank you and the reviewer for your constructive feedback. Below you will find the responses to some of the comments that you have provided.

Reviewer

All typos were corrected, thank you. All suggestions were accepted except for the following:

Line 45: modified based on the subject editor's suggestion

Line 47: Sentence changed: "while having a low competitive ability" instead of "being little competitive".

Line 48: sentence altered to make it clearer. "Pest control" instead of "insect pest control" because diseases can be included as well.

Line 65 which suggested changing "communities" to "plant communities" as we were also referring to non-plant communities in this case.

Line 66: "Clean resources" refers to the way which plant communities contribute to the purification of air and water as described by Daily (1997).

Comment on the introduction:

When it comes to weeds within cropping systems, the fundamental issue is a decrease in production vs. the potential of the benefit outweighing the cost regarding other ecosystem services.
Although, given the existence presently of intensive agriculture one can imagine the importance of this question. On the other hand, is this question relatively trivial compared to, for example, promoting the retention of various successional stages (e.g., weedy/old field habitat, mid and late succession forest habitat, mixed cropping etc..) within agroecosystems? Fundamentally, how do weeds within cropping systems compare to other methods of promoting ecosystems services (as noted above)? It is not the specific focus of this study that I am questioning, but rather, I am suggesting that this be put into a larger context. Without some discussion of the larger context, how does one judge the importance of the findings of this study compared to other means of promoting ecosystem services that enhance pest control in agroecosystems while also maximizing production?
Yes, this is specifically mentioned in the following paragraph - but - there are no references, so even if one were interested in following up to determine the relative benefits - no guidance/sources of information are provided by the authors in this regard.

We modified the paragraph to add the requested references. We modified the discussion to include more information on other methods of providing ecosystem services (e.g. semi-natural habitats). We also concentrate more on the fact that weed management should be integrated with other methods of providing ecosystem services.

Comment on the discussion

One complication not noted is that weeds, being weeds, produce lots of seeds. So, for the sake of argument, suppose weeds did provide, in certain cropping systems, a beneficial effect of some sort. How does one then control the abundance of weeds thereafter? If many weeds are present and producing seeds then at some point there are too many weeds and any positive effect from weeds may disappear simply due to their overabundance i.e., how does a farmer use weeds for their ecosystem benefit within a cropping system such that the farmer does not end up, eventually, with so many weeds that production declines? Also, what might work one year and under one set of environmental conditions may very well in subsequent years lead to too many weeds and reduced output - in a wet year weeds may provide a positive ecosystem function and not reduce crop output whereas in a dry year, the same number of weeds may not. If weeds do provide an ecosystem service; they need to be managed such that the soil weed seed bank does not become too abundant - and environmental variability may make the entire prospect of weeds as providers of ecosystem services as too chancy for a producer. In the end, doesn't it simply make more sense to support ecosystem services outside the crop field via an increase in habitat diversity within an entire cropping system or within the crop field by planting fields such that crop variety itself provides the similar ecosystem services?

We modified the discussion to address the issue of weed seeds. We also expand on the idea of integrating weed management into more global agroecosystem management to provide ecosystem services.

Subject editor

All suggestions were accepted except for:

Line 46: We prefer "can" instead of "should" because there are other ways of selecting weed species having desired functional traits.

Line 134: Regarding the spelling of focussing/focusing and benefitting/benefiting, as both ways of spelling those words are correct, we have decided to use the one that uses a double consonant as it is more often used in British English which is the language of publication of Weed Research.

Line 160 as it was modified according to the reviewer's suggestion.

Line 655: the document is a report. No page numbers need to be inserted.

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

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Running head: Regulating ecosystem services by weeds

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Word count = ~~9,198~~ 9,627(previous version ~~8,625~~9,198)

Summary

Ecosystem services have received increasing attention in life sciences, but only a limited amount of quantitative data ~~are~~is available ~~about~~ 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 regarded 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 amount of studies presented data on crop yield. Experimental approaches are proposed that ~~are able to~~can: 1) disentangle the benefits obtained from ecosystem services provisioning from the costs due to weed competition, and 2) 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 ~~being~~ having a lower~~little~~ competitive capacity. However, for services such as pest control there are hardly any specific plant traits ~~available~~that have been identified, and more fundamental research is needed.

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

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

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 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 human~~man~~kind 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 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 are hardly measured (Holland *et al.*, 2016).

Field Code Changed

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 attracting or arresting 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 increases the crop's resistance to pest infestation (Ninkovic *et al*., 2009).

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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 ~~and maintenance~~ 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 1) giving a bibliometric overview of the articles that provided scientific evidence of regulating services (directly and indirectly) provided by weeds, and 2) identifying the weeds providing ecosystem services and quantifying the effect on crop yield.

Materials and Methods

Literature search

The systematic map approach consists 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 to the traditional narrative review (Collins and 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 16th of January 2015. Preliminary searches were carried out to determine the terms associated with the research question. The search string used ~~aimed to~~ circumscribed the search results to papers focussing on plant species defined as weeds~~. Therefore~~ by including ‘weed*’ as a search term~~was included~~. ~~Then p~~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 ~~and maintenance~~ 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~~s~~ service provided by ~~the~~ 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, and Malinga *et al.*, 2015).

Screening of the search result

In ~~T~~the second phase, ~~consisted in a screening of the~~ abstracts of all retained articles were screened based on four predefined inclusion criteria. Firstly, ~~The first criterion was that~~ the document should provide a quantitative result on at least one regulating ~~and maintenance~~ 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 was 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 if they met the set criteria. Whenever it was unclear if 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 (Supplementary 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 thirty 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, 4,449 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~~. S~~ sixty ~~articles~~ 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. 1(A)). 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 7 articles (5%), weeds were shown to improve soil physical properties. Finally, benefits of weeds in enhancing crop pollination were only found in 5 articles (4%), while three articles were found showing evidence of weeds providing regulating ~~and maintenance~~ services that were not directly targeted by the search (e.g. reduction of greenhouse gas emissions).

Fig. 1 near here

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 ~~displaying~~ documenting pest control, it was possible to acquire values for the reduction of pest abundance. An ~~I~~increase in the predation or parasitism of pests was calculated for 10% of the articles. Most commonly, however, studies calculated ~~the~~ 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 greenhouse 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 broadleaf annual weeds (*Acalypha ostryaefolia* Riddell, *Acalypha virginica* L., *Amaranthus hybridus* L., *Chenopodium album* L., *Galinsoga ciliata* Ruiz & Pav., *Sida spinosa* L., *Solanum ptychanthum* Dunal, *Xanthium strumarium* L.). In a couple of cases, the presence of weeds was shown to decrease the number of damaged crop plants (Franck & 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 ~~with~~ having a dry weight over 1 mg (e.g. *Polygonum* spp.). The mechanisms that explained how pest control was provided differed among studies (Fig. 1(B)). By far the most common ~~way~~ means was by attracting or arresting 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~~7~~ 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 attracting or arresting pests away from crops (i.e. weed acting as a trap crop) (e.g. Green, 1980). In seven ~~articles~~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) ~~where~~ 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% ~~thanks~~ due to weedy margins that hosted beneficial insects. For pest predation, the highest value was obtained in a laboratory experiment by Araj & Wratten (2015) ~~where~~ in which they demonstrated that the predation of cabbage aphids *Brevicoryne brassicae* L. on *Capsella bursa-pastoris* L. increased by 255% ~~on *Capsella bursa-pastoris* L.~~. 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 near here

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. 1(C)) often ~~thanks~~ as a consequence of~~to~~ 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 immobilization 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 out 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 and colleagues (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 runoff (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 if 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 & 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 attraction or arrestment 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).

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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).

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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 to rice (Holzapfel-Pschorn *et al.*, 1986). Yagioka *et al.* (2015) reported that weed cover mulching had a reduced net global warming potential compared to 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 only 23 studies, the focus was on one individual weed species. In small ~~communities~~ assemblages of less than 5 species, the ecosystem service provision was attributed to each of the species. For bigger ~~communities~~assemblages, no single weed species effect was indicated. In 44 articles analysed (34%), the services were provided by a plant ~~community~~ 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 to the grass weed *Setaria faberi* Herrm. (Lindsey *et al.*, 2013).

Table 2 near here

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.

Table 3 near here

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 ~~9~~ nine (30%) no significant change in yield was reported, while ~~8~~ 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 not be analysed because all the studies contained different species (Supplementary Information). The log response ratios (lnR) representing an estimation of the effect size of the presence of weeds on crop yield is shown in Fig. 2 (15 cases provided by ~~7~~ seven articles). No clear pattern of the effect size distribution emerged. However, we found more effect sizes with positive values than with negative values.

Fig. 2 near here

Gaps in knowledge and future perspectives

The number of articles retained in the systematic map was low considering that the original search yielded 4,449 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 and colleagues (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 ~~and maintenance~~ 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;~~ crop pollination and~~ 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. Since agricultural land often offers low amounts of nectar compared to other habitats (Baude *et al.*, 2016), it stands to reason that the presence of weeds would diversify and augment nectar availability, which could 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. 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~~7~~ 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 were the effect sizes were larger than 1 or -1. In Frank & 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.

In 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):

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

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. Since we are dealing with weeds this is rather improbable and this situation can probably only be created by using functional living mulches or inter cropping.

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 ~~community~~ rather than investigating the ecosystem services provided by individual species. Norris & 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~~while having a limited competitive ability with the crop~~. At the moment, there are functional trait databases that 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 to extract information on functional traits for a list of species from nine publically 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

~~Figure 3a illustrates~~ T~~t~~he hypothesis that an increase in weed diversity may increase ecosystem service provisioning and that this effect is stronger in systems with a low weed diversity is illustrated in Figure 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.

Fig. 3 near here

Since 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 in order determine the most effective weed management strategies. 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 few species with the desired traits is recommended in order to obtain maximum result 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 arbuscular mycchorhizal fungi, 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 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 case 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 ecosystem service providers (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 Liebmann & Gallant (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 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 tend to lower 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 of 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 being little competitive. ~~However, for services such as pest control there are hardly any traits available, and more fundamental research is needed.~~ 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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Figure captions

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.

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.

Fig. 3. Theoretical relationship between increase of 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 of 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.

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~~0~~ ± 66.32	61.4~~38~~ ± 29.39
Increase in predation/parasitism	49.9~~88~~ ± 79.32	72.14 ± 74.16
Increase in pest enemies abundance	93.64 ± 211.97	423.3~~2~~ ± 563.38
Increase in pest enemies diversity	15.0~~0~~ ± 21.21	131.5~~0~~ ± 115.26

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

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
Sinapsis 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.

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.

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	Y1	Y2*
	$Y1=Y_{max}$	$Y_{loss.comp}=Y1-Y2$
Reduced input	Y3	Y4
	$Y_{ext.inp}=Y_{max}-Y3$	$Y_{gain.ES}=Y4-Y_{max}+Y_{loss.com}+Y_{ext.inp}$

*Y2 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.

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