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Buckwheat (*Fagopyrum esculentum* Moench.) as an emerging companion crop in annual cropping systems: a systematic review

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Highlights

- Intercropping is one of the most studied practices to promote sustainable intensification.
- Buckwheat is a minor crop with documented weed suppressing abilities and attractive flower resources.
- Intercropping with buckwheat has received little attention, although the existing literature reports positive findings.

Abstract

Sustainable intensification is considered an efficient alternative to conventional agriculture to feed a growing population while maintaining and benefitting the environment. Intercropping is one of the most studied practices to obtain production gains and other ecosystem services. Most intercrops involve legumes and cereals, but other species combinations should be explored to further increase the diversity of intercropping systems. Buckwheat (*Fagopyrum esculentum* Moench.; *Polygonaceae*) is an emerging minor crop which is gaining attention in alternative intercropping systems. This review provides a comprehensive view of the state of the art on the role of buckwheat as a companion crop in arable cropping systems. Despite buckwheat being well-known for its weed-suppressive ability, intercropping using buckwheat for weed control has received little attention. Few crops have so far been considered in relation to the introduction of buckwheat in annual cropping systems. This review uncovers a largely untapped research field involving buckwheat. The research perspectives are multiple as buckwheat consumption is increasing and its attractive flower resources and rapid growth offer the provision of several agro-ecosystem services that directly and indirectly benefit crop yield stability.

Introduction

Sustainable intensification has been proposed as an achievable solution to meet the nutritional needs of a growing population with fewer inputs while enhancing or sustaining natural ecosystems services (Martin-Guay *et al.*, 2018; Tilman, 2020; Khanal *et al.*, 2021). In a forecasted scenario of erratic climatic events, changing precipitation patterns (Koskey *et al.*, 2022) and limited agricultural land (Yang *et al.*, 2020), increasing the adoption of sustainable agronomic practices is crucial to improve the resilience of agroecosystems worldwide (Rebouh *et al.*, 2023).

Intercropping (the simultaneous growth of at least two crops at the same time) has been repeatedly demonstrated to provide benefits both in terms of production gains and other ecosystem services (Martin-Guay *et al.*, 2018). Some of these benefits include: 1) reducing reliance on chemical inputs such as herbicides and fertilizers (Koskey *et al.*, 2022; Leoni *et al.*, 2022) 2) decreasing greenhouse gas emissions and leaching (Crews and Peoples, 2004; Allende-Montalban *et al.*, 2022) 3) sustaining local biodiversity which can result in increased conservation biological control (Letourneau *et al.*, 2011). From a production standpoint, a meta-analysis performed by Martin-Guay *et al.* (2018) reported that intercropping used 23% less land to achieve the same yields as sole cropping while improving farmer incomes by 33%.

The same meta-analysis concluded that legume-cereal intercrops represent 68% out of the total 939 results related to intercropping. Legumes are widely used as companion crops for cereals due to their N-fixing capacity (Hauggaard-Nielsen *et al.*, 2008). This type of intercropping has been shown to be highly advantageous for cereals, while legumes usually remain unaffected (Ren *et al.*, 2014; Yu *et al.*, 2016).

Regardless of the popularity of legume-cereal intercrops, other species combinations should be explored to further increase the diversity of intercropping systems (Cheriere *et al.*, 2020). There is a growing interest in minor and pseudo cereals (e.g., oat, millet, quinoa, buckwheat) for their nutritional potential and their use in gluten free products (Ghiselli *et al.*, 2016; Mir *et al.*, 2018; Niro *et al.*, 2019). Including minor and pseudo cereals in cropping systems enriches biodiversity and lowers the environmental impact of arable crops as they are often adapted to grow in nutrient-poor soils (Izydorczyk *et al.*, 2014; Manners *et al.*, 2020).

Buckwheat (*Fagopyrum esculentum* Moench.; *Polygonaceae*) has been traditionally cultivated in temperate climates (Farooq *et al.*, 2016; Fijen *et al.*, 2022), but is also widely grown globally, adapting well also to Mediterranean conditions (Ponti *et al.*, 2007; Ghiselli *et al.*, 2016; Arduini and Mariotti, 2018; Salehi *et al.*, 2018a). The optimal germination temperature of buckwheat is around 10 °C (Kalinova and Moudrý, 2003), while maximum yields are obtained when flowering occurs between 18 and 23 °C (Farooq *et al.*, 2016). During the past century buckwheat cultivation has declined due to erratic yields (Farooq *et al.*, 2016) and cultivar selection has received little attention (Brunori, 2006; Arduini and Mariotti, 2018). Nonetheless, this minor crop is making a comeback and recent studies have investigated buckwheat in alternative intercropping combinations (Salehi *et al.*, 2018; Cheriere *et al.*, 2020; Biszczak *et al.*, 2020)(Figure 1). Buckwheat is an interesting species choice for intercropping as its life cycle is compatible with many spring/summer crops and it can also be harvested as a cash crop (Sobhani *et al.*, 2014; Ghiselli *et al.*, 2016; Kolarić *et al.*, 2021). Moreover, buckwheat has a long flowering period (Cawoy *et al.*, 2009) which makes it an effective species for beneficial insects due to its nectar-rich flowers (Fiedler *et al.*, 2008; Pandey and Gurr, 2019). Even though buckwheat has been reported as an effective species to enhance pollination services, recent research (Miyashita *et al.*, 2023) mentioned that the type and number of pollinators that benefit from this service might also be related to local weather conditions and surrounding landscape composition.

Buckwheat has been historically employed as a cover crop due to its ability to suppress weeds both during its rapid growth cycle and after termination (Falquet *et al.*, 2015). However, the biocontrol or weed suppression services of buckwheat used as a cover crop have mostly been investigated in vegetable cropping systems (Candelaria-Morales *et al.*, 2022). Little is known about ecosystem services related to intercropping with buckwheat, particularly in arable cropping systems.

The objective of this work is to provide a comprehensive view of the state of the art on the role of buckwheat as a companion crop in arable cropping systems. We aim to highlight the major knowledge gaps that need to be addressed in this field of research. For this purpose, the review focusses on buckwheat intercropping and considers the effects related to introducing buckwheat in arable cropping systems on yield gains, input reduction and increased agro-biodiversity.

Research Methodology

In the Scopus database we searched for titles, abstracts and keywords which included at least one of the following terms: "buckwheat", "intercropping", "relay cropping", "strip cropping". The formulation used for the search was: "Buckwheat" AND ("intercrop*" OR "relay crop*" OR "strip crop*"). Research papers/publications were selected according to the PRISMA ("preferred reporting items for systematic reviews and meta-analysis") flowchart (Figure 2) designed by Page *et al.* (2021). No date range was set, thus indicating inclusion of all available publications on the topic. The search included book chapters and conference proceedings but was limited to findings written in English. The publications were considered appropriate to be included in this review if they satisfied the following criteria: 1) buckwheat had to be a companion crop 2) there had to be a temporal overlap with the main crop 3) the cropping systems had to be annual 4) there had to be a clear and definable agroecosystem service provided by buckwheat 5) the research focus had to be at field scale. These criteria excluded cover crops, perennial systems and papers which studied buckwheat as main or sole crop.

Each paper was screened for selection following the aforementioned rule set. The full-text analysis of the publications included the type of annual crop associated with buckwheat (e.g., cereals, legumes, vegetables), the type and number of ecosystem services provided by buckwheat, the impact of buckwheat on crop yield and the spatial and temporal patterns of intercropping. In some cases, papers which used the word "cover crop" referred to living mulches (especially in vegetable cropping systems), so were kept in the final selection.

Results and Discussion

Our research query yielded 42 results which ranged from 1990 to 2023. During the screening phase ten reports were excluded because the authors could not obtain access to the full text. Out of the remaining 32 results eligible for analysis, 15 results were discarded due to at least one of the following reasons: 1) referred to perennial cropping systems (n=6); 2) were carried out at pot or petri-dish scale (n= 5); 3) mentioned buckwheat but not in an intercropping system (n=2); 4) the benefit from buckwheat intercropping was unclear (n=2; e.g., interaction with inputs or field management).

The remaining 17 results are summarized in the table below (Table 1), based on the main agroecosystem service(s) investigated in the studies. Only one study was carried out in the Southern hemisphere (Australia), three in China and three in Iran. Five studies were carried out in the USA ranging from New Jersey (n=1) to Hawaii (n=2). Six field trials were set in Europe (Slovenia n=1, France n=1, Germany n=2, Poland n=2) (Figure 3).

The role of buckwheat in directly improving production of annual crops has been scarcely explored. Only three papers reviewed in the literature addressed the provisioning service of buckwheat. Three studies by Salehi *et al.* (2018a; 2018b; 2019) focussed on fenugreek as the main crop, in which a 2:1 row intercropping arrangement with buckwheat resulted in the highest Land Equivalent Ratio (LER: 1.56), total seed yield and bioactive compounds in fenugreek seeds. Porte *et al.* (2022) found that a 1:1 row intercropping arrangement of soybean and buckwheat in a replacement design resulted in increased soybean yield compared to sole soybean. Biszczak *et al.* (2020) reported that 1:1 soybean-buckwheat relay strip intercropping produced the highest soybean yields (5 dT ha^{-1} compared to 3 dT ha^{-1} of sole soybean) and the lowest weed infestation. This was also partly confirmed by Cheriere *et al.* (2020) who proposed 1:1 alternate row intercropping with buckwheat to be the best spatial arrangement to obtain both acceptable soybean yields and weed control.

Another study on sunflower alternate row intercropping found that buckwheat was the best companion species at suppressing weed biomass when intercropped with a competitive sunflower variety (cv. Azargol), with no significant impact on crop grain yield (Latify *et al.*, 2017). Similarly, a 1:1 ratio of lentil and buckwheat produced the best lentil production/weed suppression combination with the highest LER (1.29) compared to other sowing ratios (Wang *et al.*, 2012).

Strip or row intercropping with maximum equal ratios of crop-buckwheat seemed to give the best results both in terms of yield of the main crop and weed suppression. As concluded by Cheriere *et al.* (2023), buckwheat has a rapid biomass accumulation which makes it efficient in suppressing weeds but can also hinder crop growth. Thus, spatial separation of crops can give the main crop a competitive advantage while providing weed control. Moreover, strip cropping may be worth investigating compared to other intercropping patterns, as it allows the use of small combine harvesters without negatively affecting LER (Yu *et al.*, 2016; Martin-Guay *et al.*, 2018).

Within the literature, there seems to be a stronger focus on the use of buckwheat in Integrated Pest Management (IPM) strategies. Most of the papers studied field vegetable crops in which buckwheat was used to increase predation/parasitism rate by supporting beneficial arthropods (i.e., Conservation Biological Control) or by acting like a sink for the crop pest (i.e., Biological Pest Control). It is unclear why this service has not been addressed in other arable crops, which are also prone to pressure from insects and pathogens (Bailey *et al.*, 2009; Lechenet *et al.*, 2017).

In general, all papers on the topic concluded that buckwheat was a suitable species to support parasitoids or predators of crop pests (Al-Doghairi and Cranshaw, 2004; Bickerton and Hamilton, 2012; Pandey and Gurr, 2019; Li *et al.*, 2019), to act as a sink species for crop viruses/pests (Trdan and Žnidar, 2006; Manandhar and Hooks, 2011; Li *et al.*, 2019) and to support pollinators (Pandey and Gurr, 2019).

Out of the nine papers found on the topic, four analysed the trade-off between the IPM service provided by buckwheat and the effect of the companion species on crop yield, while five reported results on just the IPM service. Introducing buckwheat in broccoli and zucchini squash in a strip cropping arrangement did not result in a reduction of crop yield (Ponti *et al.*, 2007; Manandhar *et al.*, 2009; Razze *et al.*, 2016) while increasing parasitization of crop pests (Ponti *et al.*, 2007) or supporting natural enemies by increasing their abundance (Razze *et al.*, 2016). Only Trdan and Žnidar (2006) concluded that although buckwheat worked efficiently as a sink for a common pest in onion (*Thrips tabaci* Lindeman), crop yield was compromised due to high inter-specific competition.

Buckwheat can also indirectly benefit cropping systems by influencing soil health. Yang *et al.* (2016) found that intercropping peanut with buckwheat significantly increased the bacterial diversity of the rhizosphere compared to that of the sole crop. Similar studies have been carried out in legume-cereal intercropping (Duchene *et al.*, 2017). For example, Koskey *et al.* (2023), found that intercropping of lentil and wheat increased mycorrhizal activity in the rhizosphere. Generally, intercropping can favour diverse microbial communities, which are important to maintain a healthy rhizosphere and can positively contribute to plant productivity (Duchene *et al.*, 2017; Tamburini *et al.*, 2020).

Finally, Yan *et al.* (2020) concluded that strip intercropping of genetically modified (gm) cotton with buckwheat could reduce the gene flow from the gm crop to surrounding fields. Although this is a unique agroecosystem service, the increasing cultivation of gm crops could lead to major ecological consequences due to pollen-mediated gene flow (Raybould and Wilkinson, 2005; Randall *et al.*, 2016). Gene flow is favoured by pollinator activity, but intercrops can effectively divert pollinators to alternative flower resources limiting the potential damage from gm crops (Yan *et al.*, 2020).

Generally, few crops have been considered so far to test the potential of buckwheat as a companion species in annual cropping systems. If considering weed control in legumes, we find multiple examples of intercropping with different types of cereals (Verret *et al.*, 2020; Koskey *et al.*, 2022; Tosti *et al.*, 2023). Despite buckwheat being well-known for its weed-suppressive ability (Falquet *et al.*, 2015), buckwheat intercropping for weed control has received little attention. Introducing buckwheat in legume-based systems seems to be promising, as most legumes are considered poor competitors (Corre-Hellou *et al.*, 2011). Soybean-based intercropping has started to receive attention (Cheriere *et al.*, 2020; Biszczak *et al.*, 2020; Porte *et al.*, 2022) and some studies have investigated intercropping buckwheat with alfalfa, a perennial legume used for fodder (Pecetti *et al.*, 2009; Tabacco *et al.*, 2018). Although buckwheat does not seem to improve alfalfa yield (Basaran *et al.*, 2020), buckwheat intercropping is worth considering in fodder crops as it is capable of reseeding (Candelaria-Morales *et al.*, 2022), it has a high ecological value (Amelchanka *et al.*, 2010; Small, 2017) and can add nutritional quality to animal feed as it is rich in secondary metabolites (Amelchanka *et al.*, 2010). There is some evidence on the use of buckwheat as an alternative feed for poultry and horses (Jacob and Carter, 2008; Radics and Mikóházi, 2010; Leiber, 2016). Valido et al. (2022) showed no negative impact in introducing buckwheat in the diet of cows (see also Amelchanka *et al.*, 2010). The tolerated quantities still remain unclear as buckwheat hull contains fagopyrin, which can cause photosensitization (Radics and Mikóházi, 2010).

From the literature review, only one study has considered buckwheat intercropping with a cereal (maize) at field scale. The publication mentions buckwheat in a maize-potato relay-strip cropping system as a subsequent crop after potato (Zhongmin and Guang, 1990). In this case buckwheat was used to diversify production/income and fill the gap left by harvesting one of the previous crops.

It is unclear why there is little focus on intercropping buckwheat with cereals (i.e., oat, barley, wheat), since their life cycles are almost entirely compatible. Even though cereals are strong competitors (Andrew *et al.*, 2015), short rotations dominated by spring-summer cereals have selected for competitive weed communities and cultural methods have proven to be increasingly effective in lowering weed pressure by promoting more diverse weed communities (Fried *et al.*, 2012; Bàrberi *et al.*, 2018; Adeux *et al.*, 2019). One paper mentions a negative allelopathic effect of buckwheat on root border cells of maize (Yang *et al.*, 2023), but few pot experiments involving buckwheat and wheat (Zhu *et al.*, 2002; Castillo *et al.*, 2022) or maize (Lopes *et al.*, 2022) found that buckwheat can mobilize phosphorus in the rhizosphere, by decreasing soil pH (Hallama *et al.*, 2019).

Generally, no major drawbacks were highlighted with respect to buckwheat intercropping. In a few cases buckwheat competed with the main crop, but this pertained to specific sowing ratios and spatial sowing patterns out of several considered in the trials (Wang *et al.*, 2012; Cheriere *et al.*, 2020). Reseeding was mentioned as a possible concern, although this trait is not specific to buckwheat and concerns cover crops in general (Taranenko *et al.*, 2016; Liebert *et al.*, 2023). Meyers and Meinke

(1994) pointed out that buckwheat reseeding is easily controlled by tillage; thus, reseeding may be an issue only in conservation agriculture. It is an aspect worth considering since none of the analysed studies mentioned whether buckwheat harvested after flowering was found in field in the following year.

Cultivar selection is also a major issue to address (Farooq *et al.*, 2016; Arduini and Mariotti, 2018). Out of 17 analysed records, only six - which were carried out in temperate/continental climates - mentioned the buckwheat cultivar used in the trial. The buckwheat cultivars were adapted to the climatic region of the trial and was generally sown in mid to late spring (May-June) (Wang *et al.*, 2012; Cheriere *et al.*, 2020; Biszczak *et al.*, 2020). Historical evidence of buckwheat cultivation is present in Southern Europe, particularly in Italy (Ghiselli *et al.*, 2016; Arduini and Mariotti, 2018). This could be deceiving as this region is mainly associated with a Mediterranean climate. In Italy buckwheat has mainly established been in the northern and central mountainous regions, which experience cooler summers and higher precipitations compared to the coastal areas. Although buckwheat can adapt to Mediterranean conditions, high temperatures (>30 °C) can cause lodging due to a reduction of stem diameter (Michiyama and Sakaurai, 1999) and can increase flower sterility (Farooq *et al.*, 2016). Exploring the best agronomical practices along with cultivar selection would increase adoption of this species outside of its traditional growing areas (Mariotti *et al.*, 2016).

Conclusions

We investigated the body of literature on the use of buckwheat as a companion species in arable cropping systems. We focussed on the effect of buckwheat on crop yield, input use and agro-biodiversity. In the three decades of scientific literature which included "buckwheat" and "intercropping", only 17 papers met the criteria of our query. Most of the literature has focussed on intercropping buckwheat in vegetable cropping systems to deliver services linked to IPM. The low number of retrievable full text publications posed a major limitation to conduct an in-depth analysis of the data. Moreover, data in the results were not always reported in a table (mean ± standard deviation) format, but presented in a figure with no references to means in the text. This inaccuracy prevented the authors from extrapolating important information, limiting the review descriptive considerations in some points. Systematic reviews would greatly benefit from an improved standardization and transparency of data reporting (e.g., by showing tables or referring to open access databases), especially in novel fields of research.

Further research is needed to consolidate data regarding potential yield gains for the main crop and to explore the potential trade-offs related to providing multiple AES. Moreover, little is known about cultivar choice and selection. We found that there is a largely untapped research field involving buckwheat, an emerging minor crop, which is gaining increasing importance due to both its use in modern diets and to its attractive traits for the provision of several agro-ecosystems services which can directly and indirectly benefit crop yield stability.

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Figure 1. Lentil- buckwheat row intercropping at a 2:1 ratio. Photo taken 54 days after sowing (intercropping trial in Udine, Northeast Italy).

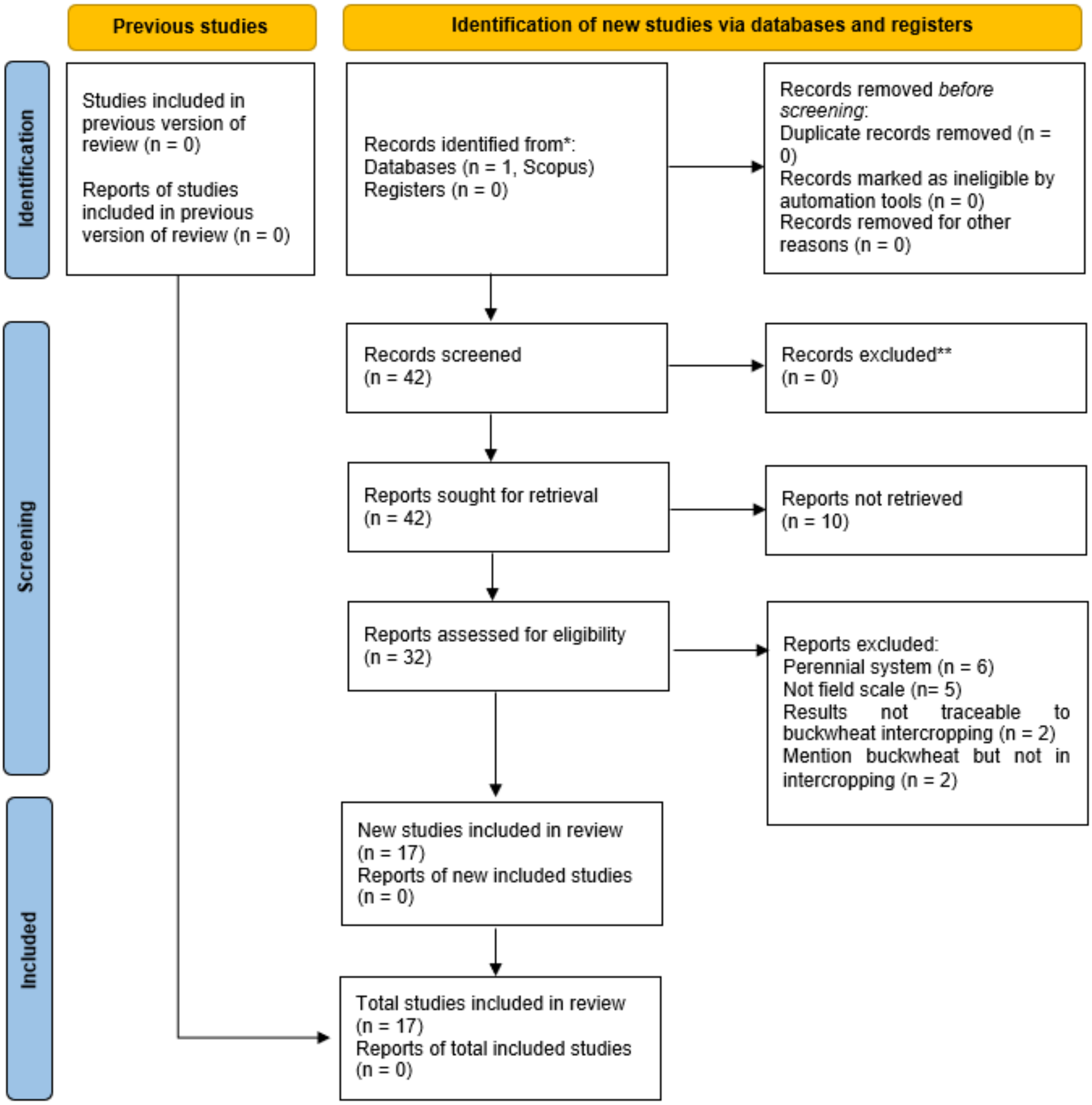

Figure 2. PRISMA flowchart proposed by Page *et al*. (2021) for the selection of the publications included in this systematic review.

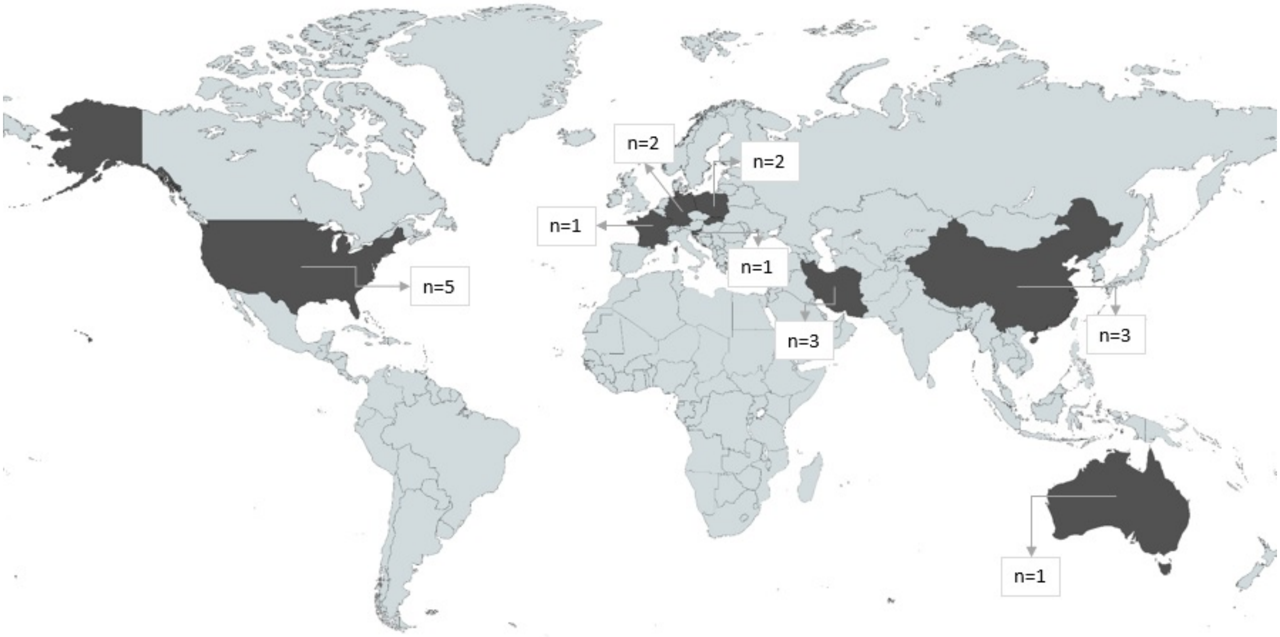

Figure 3. World map indicating the countries in which the trials were carried out for each of the final 17 eligible papers included in the review. The world map was created with mapchart.net.

Table 1. Results of the final selection from the Scopus query (n=17).

	Agroecosystem Service			
	Improve productivity (n=5)	Integrated Pest Management (n=8)	Weed Control (n=4)	Other (n=2; Rhizosphere bacterial diversity, Avoid gene flow from gm crops)
Cropping system	Arable (n=4)	Arable (n=1); Vegetable (n=8)	Arable (n=4)	Arable (n=2)
Main crop associated with buckwheat	Fenugreek (n=3); Soybean (n=2*)	Bell pepper (n=1); Cabbage (n= 2); Cotton (n=1); Onion (n=1); Zucchini (n=3)	Lentil (n=1); Soybean (n=2*); Sunflower (n=1)	Peanut (n=1); Cotton (n=1)
Intercropping spatial pattern	Row (n=4**); Strip (n=1); Mixed (n=1**)	Strip (n=6); Living mulch (n=3)	Row (n=2**); Strip (n=1); Mixed (n=2**)	Row (n=1); Strip (n=1)
Intercropping temporal pattern	Simultaneous (n=4); Relay (n=1)	Simultaneous (n=9)	Simultaneous (n=3); Relay (n=1)	Simultaneous (n=2)
Reference	Salehi et al. (2018a); Salehi et al. (2018b); Salehi et al. (2019); Biszczak *et al.* (2020)*; Cheriere *et al.* (2020)*,**	Trdan and Žnidar (2006); Ponti et al. (2007); Manandhar et al. (2009); Manandhar and Hook (2011); Bickerton and Hamilton (2012); Razze et al. (2016); Li et al. (2019); Pandey and Gurr (2019)	Wang *et al.* *(*2012); Latify *et al.* (2017); Cheriere *et al.* *(*2020) *,**; Biszczak *et al.* *(*2020)*;	Yang et al. (2016); Yan et al., (2020)

*Papers that quantified both yield gains and weed suppression provided by buckwheat; **papers that investigated both row and mixed intercropping spatial patterns.