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# How agricultural techniques mediating bottom-up and top-down regulation foster crop protection against pests.

## A review.

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### Abstract

The heavy use of synthetic pesticides in agriculture has been responsible for detrimental effects on human and environmental health, making it necessary to develop more sustainable pest management strategies. A promising approach consists in the integration within cropping systems of agricultural techniques producing bottom-up effects or supporting top-down regulation of crop pests. However, there is still a lack of information on the extent to which this approach is currently being developed. In this paper we review the last ten years of published literature on the use in annual cash crops of three agricultural techniques: (i) crop spatial diversification, (ii) crop temporal diversification, and (iii) soil management influencing crop pests either through bottom-up effects or by supporting the top-down regulation of four categories of bioprotection agents: (i) macro- and (ii) micro-organisms, (iii) semiochemicals, and (iv) natural substances. We found that each agricultural technique is adopted to support a specific bioprotection category and to control a specific pest taxon. Crop spatial diversification was generally found to target herbivorous insects and to support macro-organism bioprotection agents. Crop temporal diversification and soil management mainly targeted pathogenic fungi and supported microorganism bioprotection agents. Despite the widespread idea that semiochemicals and natural substances are promising agents for pest regulation, their adoption remains largely unexplored. We also found that agricultural techniques are mostly adopted to support bioprotection in a conservation biological control approach while ignoring augmented bioprotection. In addition, the top-down regulation by means of bioprotection supported by agricultural techniques is just as effective against crop pests as the bottom-up effect produced by the agricultural techniques alone. We argue that a concerted effort to integrate bioprotection with agricultural techniques would open new research opportunities to reduce synthetic pesticide inputs fostering the transition from a conventional agriculture towards sustainable agroecosystems.

### Keywords

Agroecology, biocontrol, crop protection, conservation biological control, Integrated pest management, spatiotemporal crop diversification

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# 1 Introduction

In the last century, the biggest contribution by farming to food production was through massive natural landscape simplification into highly productive monoculture fields (Meehan et al. 2011). However, major concerns have been raised on the unsustainability of this management, and particularly on the high volumes of synthetic pesticide inputs used to reduce pest damage and to guarantee high yields (Kremen and Miles 2012). These concerns are linked to undesired environmental consequences (Lewis et al. 1997), such as negative effects on biodiversity and on its associated ecosystem services (Desneux et al. 2007) such as pollination (Whitehorn et al. 2012) and biological pest control (Geiger et al. 2010). Research evidence has also shown that a pest control strategy based on synthetic pesticides provides only short-term crop protection (Hawkins et al. 2019) followed by secondary pest outbreaks later in the growing season (Dutcher 2007). Considering these negative consequences, stakeholders such as governances, policy-makers and the scientific community, have strongly recommended the integration of more sustainable and long-term pest management strategies (Wezel et al. 2014; Lamichhane et al. 2016; Alyokhin et al. 2020; MacLaren et al. 2020). Potential benefits can be evaluated not only in the reduction of synthetic pesticide inputs but also in the reinforcement of several ecosystem services fostering crop health (Lewis et al. 1997; Wezel et al. 2014; Nicolopoulou-Stamati et al. 2016).

Support for the integration of sustainable pest management strategies has been provided by the European Parliament and the EU Council, as set out in the Directive 2009/128/EC (European Parliament 2009). The Directive provides a framework for integrated pest management (IPM), providing outlines for preventive and curative methods to keep pest populations below economically damaging thresholds (Barzman et al. 2015; Stenberg 2017). IPM methods are designed to discourage synthetic pesticides, giving priority, wherever possible, to alternative and sustainable approaches. Potential levers in IPM include living organisms and nonliving natural substances, grouped under the umbrella term bioprotection agents (Stenberg et al. 2021, Table 1), which have proved to be efficient in controlling exotic and endemic crop pest populations (Lenteren et al. 2006; Van Driesche et al. 2010; Lenteren 2012). Bioprotection agents can be mobilized through different approaches, depending on whether they are released for permanent or temporary purposes (classical or augmentation biological control, respectively) or whether they are already resident in cropping fields and supported through human intervention (conservation biological control) (Stenberg et al. 2021). Despite their availability, the full integration of bioprotection agents in the agroecosystem (Table 1) is far from being a concrete and established pest management strategy (Lamichhane et al. 2017).

One reason behind the scarce integration of bioprotection is the higher environmental variability characterizing open habitats such the agroecosystem, where abiotic and biotic stressors can affect the performance of bioprotection agents negatively (Peng et al. 2011). These stressors can include unpredictable weather (Norris et al. 2002) and competitive interactions with living organisms already present in the agroecosystem (Snyder and Ives 2001). Bioprotection agents, especially in an augmentation biological control approach, have found more adoption in controlled environments, i.e., greenhouses, where they are favored by the reduced biological diversity, the lower agent dispersal, the favorable climatic conditions, the absence of competitions or alternative food resources and the reduced developmental costs (Lenteren 2012; Michaud 2018). A second reason behind the scarce adoption of bioprotection agents is the widespread belief that they can be used as “silver bullets” replacing synthetic pesticides, in the hope of a fast and magical solution against pest problems (Hokkanen 2015). Bioprotection should instead be considered in a long-term systemic approach supported, wherever possible, with agricultural techniques commonly used to design sustainable cropping systems through habitat modifications (Fig.1) within crop fields and their surroundings (González-Chang et al. 2019). Yet previous evidence has shown that the adoption of agricultural techniques *per se* can have a bottom-up effect (Table 1) on pest regulation by reducing crop accessibility or interrupting their life cycle (Hokkanen 1991). In addition, agricultural techniques can reduce the environmental variability that characterizes cropping fields, thus supporting a

top-down regulation (Table 1) of crop pests by bioprotection agents which can benefit from a more stable environment (Médiène et al. 2011; Hatt et al. 2018).

Table 1. Terminology of the keywords used in our systematic review

<b>Term</b>	<b>Definition</b>
Agroecosystem	Agroecosystems are complex systems in which many species interact, with ecological processes that take place at different spatial scales, and with strong interactions between ecological and management processes (Loeuille et al. 2013).
Pest	Any living species, whether plant, fungus or animal, whose activities cause economic losses to human possessions, directly threaten human health, or are an annoyance (Uneke 2007). In this review, we focused on non-plant pests (i.e. excluding weeds).
Agricultural techniques	A part of the crop management, in the production process, defined by actions to be performed on the cultivated field. In this review, we focused on crop spatial diversification, crop temporal diversification, and soil management.
Bottom-up effect	A direct effect caused by an agricultural technique on crop pest populations without the mediation of bioprotection solutions.
Top-down regulation	The indirect effect of an agricultural technique on crop pest populations acting through the support of bioprotection.
Bioprotection	Crop protection, as part of integrated pest management, based on biological control agents (macro- and micro-organisms) and/or non-living substances (semiochemical and natural substances) originating from nature or synthesized (Stenberg et al. 2021).
Biological control	The use of living organisms to reduce the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be (Eilenberg, Hajek and Lomer 2001).
Crop spatial diversification	A vegetational association arranged within or adjacent to a field involving a crop of interest (cash crop) and one or more secondary service crops or non-crop plants (Malezieux et al. 2009).
Crop temporal diversification	In comparison with an initial state, addition of cash or service crops (different species or different varieties) in the cash crop cycle (Bullock 1992).
Soil management	Planning of all inputs into and outputs from the soil ecosystem so that there is a favorable balance of essential components that constitute the basis of the soil's life-support system <ul style="list-style-type: none"> <li>- Organic amendment supplement such as manure, green manure, mulches, mineral substances (Cesarano et al. 2017).</li> <li>- Change in tillage intensity (Roger-Estrade et al. 2010).</li> </ul>
Experimental treatment	A modification of the habitat within the field or on its margins to test the pest control efficacy of an agricultural technique by comparison with a control treatment.
Control treatment	A conventional way of managing an agricultural field as opposed to the alternative agricultural techniques tested in the experimental treatments. The control treatment for the three techniques are: <ul style="list-style-type: none"> <li>- Crop spatial diversification: monoculture or untreated plots</li> <li>- Crop spatial diversification with bioprotection: monoculture or untreated plots</li> <li>- Crop temporal diversification: same crop over a rotation period on the same plot</li> <li>- Crop temporal diversification with bioprotection: same crop over a rotation period or untreated plots</li> <li>- Soil management: no soil treatment or conventional tillage plot</li> <li>- Soil management with bioprotection: no soil treatment or conventional tillage plot</li> </ul>
-	A score given to each treatment in each research article, based on the statistical difference of the effect on pests or pest damage of the treatment in comparison with the appropriate control treatment.
Overall pest control score	The overall pest control score given by the sum of the scores of all the treatments included in the article.



Fig. 1. Habitat modification occurring at field level, in particular the modification of crop field margins with the presence of flower strips created to facilitate the top-down regulation and to enhance the persistence of bioprotection agents such as macro-organisms (photo credit: Paola Salazar).

There is, however, still a large gap in the information on the integration between bioprotection and agricultural techniques and their potential synergistic effects on pest control (Deguine et al. 2021). To fill this gap, we provide information here about the conditions under which agricultural techniques and bioprotection are combined in a holistic IPM approach to control pests in annual cash crops. To gather this information, we reviewed the published peer-reviewed literature of the last ten years, that is, since the European Parliament and EU incentives to foster integrated pest management were introduced. We focused on the integration of three agricultural techniques at crop field level and in its surroundings: (i) crop spatial diversification (Table 1), i.e., intercropping or field margin modification; (ii) crop temporal diversification (Table 1), i.e., crop rotation or cover crops; and (iii) soil management (Table 1), i.e., reduction of tillage and addition of organic amendments (Alyokhin et al. 2020; De Corato 2020). These three techniques have been shown to affect pest populations through ecological mechanisms that include bottom-up effects and top-down regulation by bioprotection which exploit the principles of a conservation-oriented biological control approach (González-Chang et al. 2019; Alyokhin et al. 2020; Iuliano and Gratton 2020). In the aforementioned agricultural techniques, we distinguished four categories of bioprotection agents, based on Stenberg et al. 2021 (Table 1): (a) macro-organisms, mostly arthropod predators or parasitoids and nematodes; (b) microorganisms including viruses, bacteria and fungi; (c) semiochemicals, including allelochemicals and pheromones; and (d) natural substances, including mineral oils and plant and animal molecules. This classification avoids the confusion between biocontrol or biological control (Table 1), which relies exclusively on living organisms to eliminate pest populations (Stenberg et al. 2021).

The objectives of our review were: 1) to reveal knowledge gaps and indicate directions for further research to promote the integration, in annual cash crops, of agricultural techniques employed for their bottom-up effect and their support of the top-down regulation of crop pests by means of bioprotection; 2) to compare the probability of success in pest control between agricultural techniques producing a bottom-up effect, and support for top-down regulation through bioprotection. Analyzing the last ten years of published literature provides useful information required to design future field trials on the integration of bioprotection and

agricultural techniques in line with Directive 2009/128/EC (European Parliament 2009). Assessing the probability of obtaining positive results in pest control will enable us to determine whether agricultural techniques that support top-down regulation by bioprotection would be an efficient strategy in comparison with agricultural techniques that have a bottom-up effect on crop pests. The main findings of the review are discussed to provide suggestions for better integration of agricultural techniques and bioprotection into cropping systems with a view to more sustainable management of crop health.

## 2 Methodology

### 2.1 Search term strategy in peer-reviewed literature

In a comprehensive literature review in February 2021 on the Scopus database ([www.scopus.com](http://www.scopus.com)), we performed three separate searches respectively for: (a) crop spatial diversification, (b) crop temporal diversification and (c) soil management. We followed the PRISMA guidelines (Liberati et al. 2009) and used an explicit and systematic method to identify the studies that were relevant to pest control. We limited our searches to articles published in English from January 2011 to February 2021, and which reported trials performed in agricultural fields, specifically on annual cash crops, thus excluding laboratories, greenhouses, glasshouses or pots, as well as non-arable crop habitats such as orchards, vineyards or forests. We selected only annual cash crops since synthetic pesticides are still the main pest control tool and there is a real need for alternative pest management strategies. In addition, the ephemeral nature of annual cash crops might affect bioprotection efficacy differently in comparison with orchards, vineyards or forest ecosystems that can be considered as long-term and more stable environments. We furthermore excluded duplicate articles and those that were not accessible (either for the language or for lack of full-text access), and we focused on original research articles, excluding monographs, book chapters, reviews and syntheses. Lastly, the study did not focus on weed control. We instead focused on animal, fungus, bacterial and viral pests which cause damage that incurs economic losses to agriculture (Uneke 2007). The search terms and their combinations (Table 2) were applied to the article “Title”, “Abstract” and “Keywords”.

Article abstracts resulting from each of the three separate searches were read to verify the following criteria:

- A. Does the article focus on pest control?
- B. Does the article provide results about experimental trials performed in agricultural fields?
- C. Does the article include at least one experimental trial (Table 1) involving one agricultural technique, either producing a bottom-up effect or in support of top-down regulation by bioprotection, assessed against an appropriate control treatment (Table 1)?

Based on the abstracts, articles were excluded from our review if the answer to question A was “No”. If the answer to question A was “Yes”, then articles were excluded if one of the two answers to the questions “B” or “C” was “No”. Articles fulfilling these criteria were kept for further examination. The number of articles resulting from each initial search and from the following steps are shown in the supplementary material (Supplementary material Fig. S1, S2, S3).

Tab. 2 Search terms for each of the three agricultural techniques included in our review: (i) crop spatial diversification, (ii) crop temporal diversification, and (iii) soil management. We selected keywords included in the topic (title, abstract and keywords) of resulting literature that refer to biocontrol, the agroecosystem, and the techniques adopted in each practice. The subsequent steps to select and review the resulting literature are included in the Supplementary Material (Supplementary Material Fig. S1, S2, and S3).

<u>Agricultural technique</u>	<u>Search sequence</u>
<u>(i) Crop spatial diversification</u>	(( "biocontrol" OR "bio-control" OR "biological control" OR "control" ) AND ( "pest*" OR "pathogen*" OR "herbivor*" OR "plant damage*" ) AND ( "crop*" OR "agroecosystem*" OR "agro-ecosystem*" ) AND ( "diversification*" OR "spatial crop diversit*" OR "intercrop*" OR "habitat manipulation" OR "push-pull" OR "hedgerow*" OR "service crop*" OR "living mulch*" OR "companion plant*" OR "trap crop*" OR "field margin*" ) AND NOT ( "orchard*" OR "forest*" OR "weed*" OR "greenhouse*" OR "lab*" ) )
<u>(ii) Crop temporal diversification</u>	(( "biocontrol" OR "bio-control" OR "biological control" OR "control" ) AND ( "pest*" OR "pathogen*" OR "herbivor*" OR "plant damage*" ) AND ( "crop*" OR "agroecosystem*" OR "agro-ecosystem*" ) AND ( "diversification*" OR "temporal crop diversit*" OR "habitat manipulation*" OR "cover crop*" OR "rotation*" OR "crop rotation*" OR "crop cycle*" ) AND NOT ( "orchard*" OR "forest*" OR "weed*" OR "greenhouse*" OR "lab*" ) )
<u>(iii) Soil management</u>	(( "biocontrol" OR "bio-control" OR "biological control" OR "control" ) AND ( "pest*" OR "pathogen*" OR "herbivor*" OR "plant damage*" ) AND ( "crop*" OR "agroecosystem*" OR "agro-ecosystem*" ) AND ( "soil management*" OR "habitat manipulation*" OR "tillage*" OR "no-tillage*" OR "manure*" OR "PGPR*" OR "amendment*" OR "mulch*" ) AND NOT ( "orchard*" OR "forest*" OR "weed*" OR "greenhouse*" OR "lab*" ) )

## 2.2 Analyzed information of the selected peer-reviewed literature

After the initial screening, the selected articles were examined in depth. In the first step, they were divided into two categories according to whether the agricultural technique investigated had a bottom-up effect or supported a top-down regulation of crop pests by means of bioprotection. An agricultural technique was considered to have a bottom-up effect whenever this effect was not mediated by bioprotection agents. For instance, crop spatial diversification implies the use of companion plants in intercropping or on the field margins as deterrent /repellent barriers (chemical or physical) against crop pests, or with the capacity to attract pests away from cash crops (trap crops). Temporal diversification implies a sequence of host/nonhost crops and cover crops that interrupts the pest's life cycle. Soil management implies modifications to the physical and chemical characteristics of the soil, which affect crop pest viability.

An agricultural technique was considered to promote a top-down regulation of crop pests if it supported bioprotection via a classical, augmentation or conservation biological control approach. For instance, when considering crop spatial diversification, it would imply the use of companion plants in intercropping or at the field margin to provide bioprotection agents with food resources and shelter, or to host natural substances or semiochemicals involved in the recruitment of macro-organisms. Crop temporal diversification implies sequences of different cash crops alternated or not with cover crops favoring the presence and the persistence of bioprotection agents enhancing pest control. Soil management implies modifications to the physical and chemical characteristics of soil that influence the performance of bioprotection agents and, in turn, the effectiveness of pest control. Articles focusing on semiochemicals and natural substances were taken into consideration only if they supported a top-down regulation of crop pests, i.e., attracting natural enemies or repelling pests. We excluded articles where semiochemicals and natural substances were used to stimulate plant defense.



Within the selected articles, we then looked for replicated trials testing one or more experimental treatment (Table 1) against an appropriate control treatment, which differed for the three agricultural techniques (Table 1). To be included in the review, the experimental treatments needed to perform a biological survey measuring the effect (a) on pest population dynamics (i.e., effect on abundance, mortality, predation, parasitism, density, severity), or (b) on crop damage (i.e., leaf or fruit damage, mortality), in comparison to the control treatment. If an article reported several trials, we reported only those that met the requirements of our review and excluded the others. In case we found a lack of statistical evidence about the pest control regulation of bioprotection with the agricultural techniques, the article was included as if only the agricultural techniques were applied. Articles that fulfilled these requirements were examined with a view to extracting the information for our review.

Several tables were used to store the information extracted (Supplementary Material: Table S1 crop spatial diversification; Table S2 crop spatial diversification and bioprotection; Table S3 crop temporal diversification; Table S4 crop temporal diversification and bioprotection; Table S5 soil management; Table S6 soil management and bioprotection). When an article provided a trial with different experimental treatments that involved both bottom-up effects and top-down regulation on crop pests, the different experimental treatments were split according to the presence or not of bioprotection and the article was reported in both tables. When an article provided a trial that involved experimental treatments focusing on more than one technique (i.e., both spatial and temporal crop diversification) and if, according to the author of the articles, the effect on crop pests was produced by both techniques, the article was reported in both the tables for each technique. For all experimental treatments, we recorded the following information: (i) the habitat modification within each agricultural technique; (ii) the type of crop pest; (iii) the target cash crop; and (iv) the continent on which the article originated. We also recorded (v) the companion plant and (vi) the rotation period for the experimental treatments in crop spatial and temporal diversification articles respectively. In addition, for the experimental articles focusing on agricultural techniques supporting top-down regulation by bioprotection, we also included in our database (i) the category of bioprotection agents: macro-organisms, microorganisms, semiochemicals, and natural substances, and (ii) the type of biological control approach: classical, augmentation or conservation biological control.

We attributed a pest control score to each experimental treatment (Table 1) based on the statistical significance of its effect on crop pests, measured against the appropriate control treatment. If the experimental treatment had a significant positive pest control effect such as a reduction in pest population or pest damage in comparison with the control treatment, we assigned a score of +1. If the treatment showed no significant difference with the control treatment, we assigned a value of 0. If the treatment had a significant negative pest control effect such as an increase in pest population or pest damage in comparison with the control treatment, we assigned a score of -1. If a treatment was repeated for multiple periods (years, seasons), the score of each treatment was obtained by the sum of the score of each period. If treatments were repeated on both pest population and crop damage, in different locations or different pest life stages, they were recorded as independent measures (Johnson et al. 2021). For each article, we calculated the overall pest control score given by the sum of the scores of all the treatments within each article (Supplementary Material: Table S1 crop spatial diversification; Table S2 crop spatial diversification and bioprotection; Table S3 crop temporal diversification; Table S4 crop temporal diversification and bioprotection; Table S5 soil management; Table S6 soil management and bioprotection). Wherever the overall pest control score was positive, the whole article was considered to have a positive effect on pest control, whereas if the overall score was 0 or negative, we considered that the article reported a null or negative effect on pest control, respectively.

In order to have a quantitative measure of the pest control efficacy and its variability across case studies, we calculated an effect size of the trials within each article based on the estimates of the control and the experimental treatments (in total 99 number of papers and 188 experimental trials). Effect sizes were computed for each individual experimental treatment within each trial depending on the extracted result as follows:

A. When a trial focused on pest populations or plant damage, the effect size was obtained by the averaged ratio between the estimates of the control over each treatment within the experimental trial.

B. Conversely, when a trial focused on bioprotection actions like predation, parasitism rate, the size effect was obtained by the averaged ratio between the estimates of the each experimental treatment over the control treatment within the trial.

The difference in the calculation between (A) and (B) was necessary to assign bioprotection efficiency an effect sizes superior to 1 in order to homogenize the threshold for an efficient pest control between the different biological surveys. In both (A) and (B) if a treatment was repeated for multiple times (i.e., years, seasons), its effect size was obtained by averaging the measured period. Estimates for both control and experimental treatment were obtained from each article from the published tables or extracted from the figures using Engauge digitizer software (<https://markummitchell.github.io/engauge-digitizer/>). We did not perform any statistical analysis on the effect size due to the large heterogeneity in the ways of which the biological surveys are done. The effect size extracted for all trials and their distribution for each agricultural techniques and bioprotection strategy are available in the Supplementary material: Table S1 to S6 and Supplementary Material: Fig. S4, respectively.

### **2.3 Statistical analysis of pest control probability**

All statistical analyses were conducted with R (R Core team 2020). To test the effects of agricultural techniques on bottom-up and top-down pest control, we performed exact binomial tests (function ‘binom.test’) with the success probability set to 0.5. We thus tested the hypothesis that overall pest control scores computed for each research article deviate from a random probability of having positive effects on pest control (i.e., 50% of success). In the second analysis, we used a Fisher’s exact test (function ‘fisher.test’) to verify the null hypothesis that the probability of having a positive pest control effect did not differ between agricultural techniques producing a bottom-up effect and agricultural techniques supporting bioprotection top-down regulation on crop pests. We also controlled for publication bias in the overall pest control score, for each article, that could have influenced the probability of obtaining a positive effect in pest control. Thus, the same statistical tests and null hypotheses were used to verify the probability of having a positive effect on pest control using the pest control score assigned to each experimental treatment on its own, without adding it up with the other scores of the same article (Supplementary material Fig. S5a,b,c).

## **3 Literature review of agricultural techniques and their integration with bioprotection**

### **3.1 Agricultural technique and bioprotection used**

Intercropping was the most widely adopted spatial crop diversification technique producing a bottom-up effect on crop pests, reported in 17 out of 29 articles, followed by a field margin modification, in 12 articles, and a push-pull strategy, in 3 articles (Fig. 2a). When addressing crop spatial diversification in support of a bioprotection top-down regulation of crop pests, the most adopted techniques were intercropping, reported in 14 out of 26 findings, and field margin modification, in 10 articles. Both intercropping and field margin modification were mostly adopted to support the top-down regulation of macro-organisms such as arthropod predators and parasitoids (Fig. 2b). Bioprotection agents were mostly used with a conservation biological control approach, reported in 25 articles, and an augmentation biological control approach, in 5 articles.

In articles where crop temporal diversification produced a bottom-up effect on crop pests, the rotation between different cash crops was the most widely adopted technique, reported in 6 out of 10 articles, followed by the rotation between a cash crop and a cover crop, in three articles (Fig. 2c). Crop temporal

diversification techniques facilitating top-down regulation of crop pests by bioprotection agents mostly focused on the consequences of cash crop rotation with micro-organisms, especially fungi and bacteria, as reported in 6 out of 10 articles (Fig. 2d). Bioprotection agents were mobilized with a conservation biological control approach in 8 out of 10 articles, and an augmentation biological control approach in 2 articles.

When considering soil management producing a bottom-up effect on crop pests, the addition of an amendment, reported in 18 out of 25 articles, was the most widely adopted technique, followed by the variation in soil tillage intensity, in 6 articles, and soil solarization, in two articles (Fig. 2e). In articles studying soil management that favor top-down regulation of crop pests by bioprotection, the adding of an amendment was the most widely used technique but without the predominance of any bioprotection category (Fig. 2f). Bioprotection agents were mobilized with a conservation biological control approach in 4 out of 6 articles, and an augmentation biological control approach in two articles.

### 3.2 Cash crop targeted in the reviewed literature

The *Poaceae* family, in 7 out of 29 articles, was the most studied cash crop with regard to the bottom-up effect produced by crop spatial diversification techniques, followed by the *Brassicaceae* family, in 6 articles (Fig. 3a). Similarly, in crop spatial diversification techniques supporting the top-down regulation of crop pests by means of bioprotection, the most studied cash crop belonged to the *Brassicaceae* and *Poaceae* families, each in 7 out of 26 articles (Fig. 3b).

When investigating crop temporal diversification techniques producing a bottom-up effect on crop pests, the most widely investigated cash crops belonged to the *Solanaceae* family, in 4 out of 10 articles, followed by the *Fabaceae* family, in 3 articles (Fig. 3c). When investigating crop temporal diversification techniques supporting the top-down regulation of crop pests by means of bioprotection, *Solanaceae*, in 4 out of 10 articles, was the most widely investigated cash crop families, followed by the *Fabaceae* and *Malvaceae* families in 2 articles, (Fig. 3d).

In articles focusing on soil management techniques and bottom-up pest control, the most widely investigated cash crop belonged to the *Solanaceae* family, reported in 11 out of 25 articles (Fig. 3e). In articles on soil management techniques supporting the top-down regulation of crop pests by means of bioprotection, the most widely investigated cash crop belonged to the *Solanaceae* family, followed by the *Brassicaceae* family, in 3 and 2 out of 6 articles, respectively (Fig. 3f).

### 3.3 Targeted pests in the reviewed literature

The most targeted pest in research focusing on crop spatial diversification techniques, producing both a bottom-up effect and in support of top-down regulation by means of bioprotection, were lepidopterans, with respectively 9 out of 29 articles and 13 out of 26 articles, respectively (Fig. 4a-b). The second most targeted pests in cases of crop spatial diversification techniques producing a bottom-up effect were coleopterans, reported in 7 articles (Fig. 4a), and in cases of crop spatial diversification techniques supporting bioprotection top-down regulation, they were hemipterans, in 11 articles (Fig. 4b).

When focusing on crop temporal diversification techniques with a bottom-up effect on crop pests, pathogenic fungi were the most targeted pest, in 6 out of 12 articles, followed by nematodes, in 3 out 12 articles (Fig.4c). For crop temporal diversification techniques in support of top-down regulation of crop pests by bioprotection, nematodes were the most targeted pest, found in 4 articles (Fig.4d).

Pathogenic fungi were the most targeted pest where soil management techniques were adopted to produce a bottom-up effect, as in 12 out of 25 articles (Fig.4e). When investigating soil management techniques supporting the top-down regulation of crop pests by bioprotection, the targeted pests were spread equally, with 1 article each (Fig.4f).

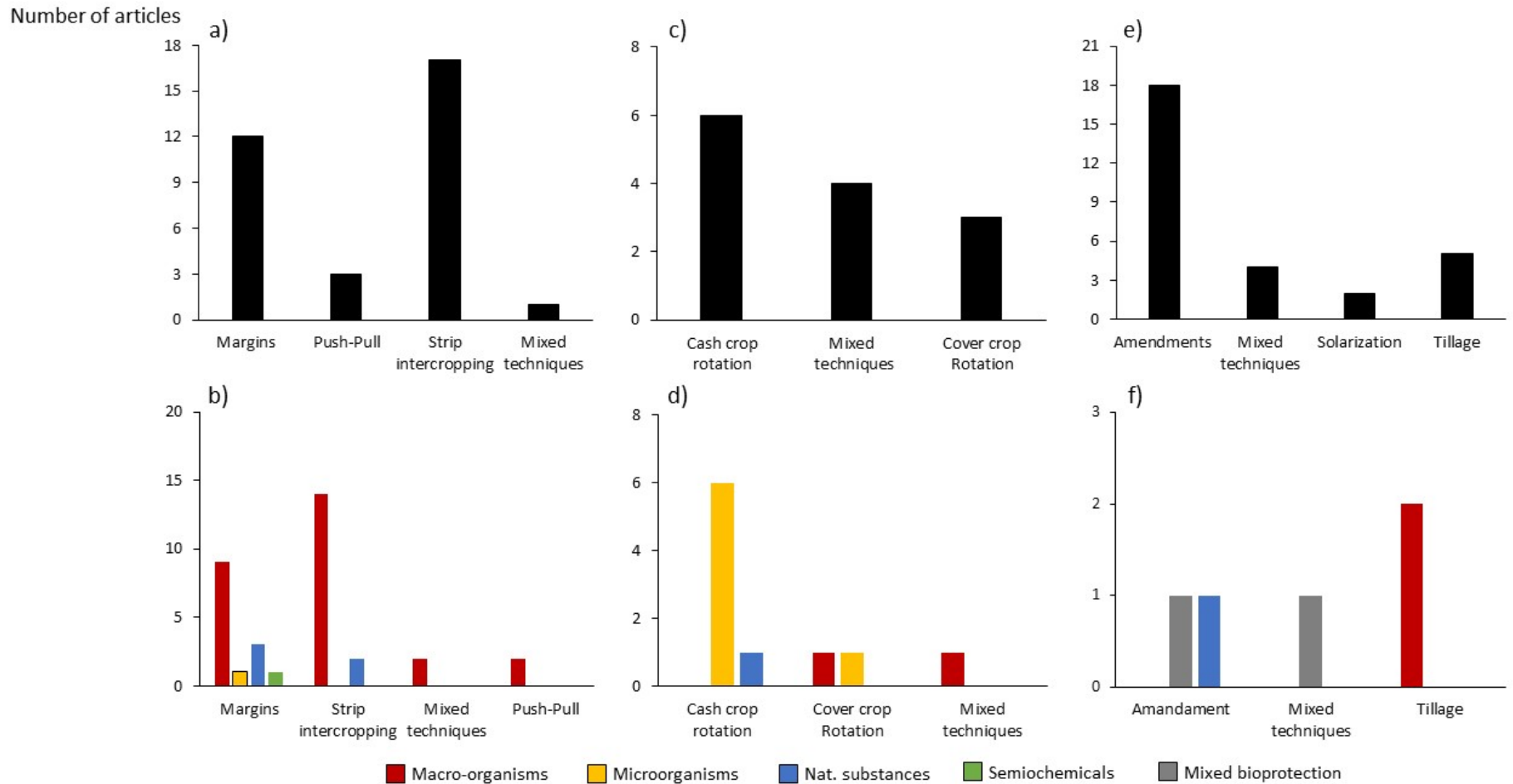


Fig.2. Distribution of the number of research articles with experimental trials investigating, in the first row, on agricultural techniques producing a bottom-up effect on pests through a) spatial diversification, c) temporal diversification, e) soil management and in the second row, on agricultural techniques supporting a top-down regulation by bioprotection agents through b) spatial diversification, d) temporal diversification, f) soil management. Mixed techniques indicate the use of two techniques in combination within the same research articles. Mixed bioprotection indicate the use of two or more bioprotection agents within the same research article.

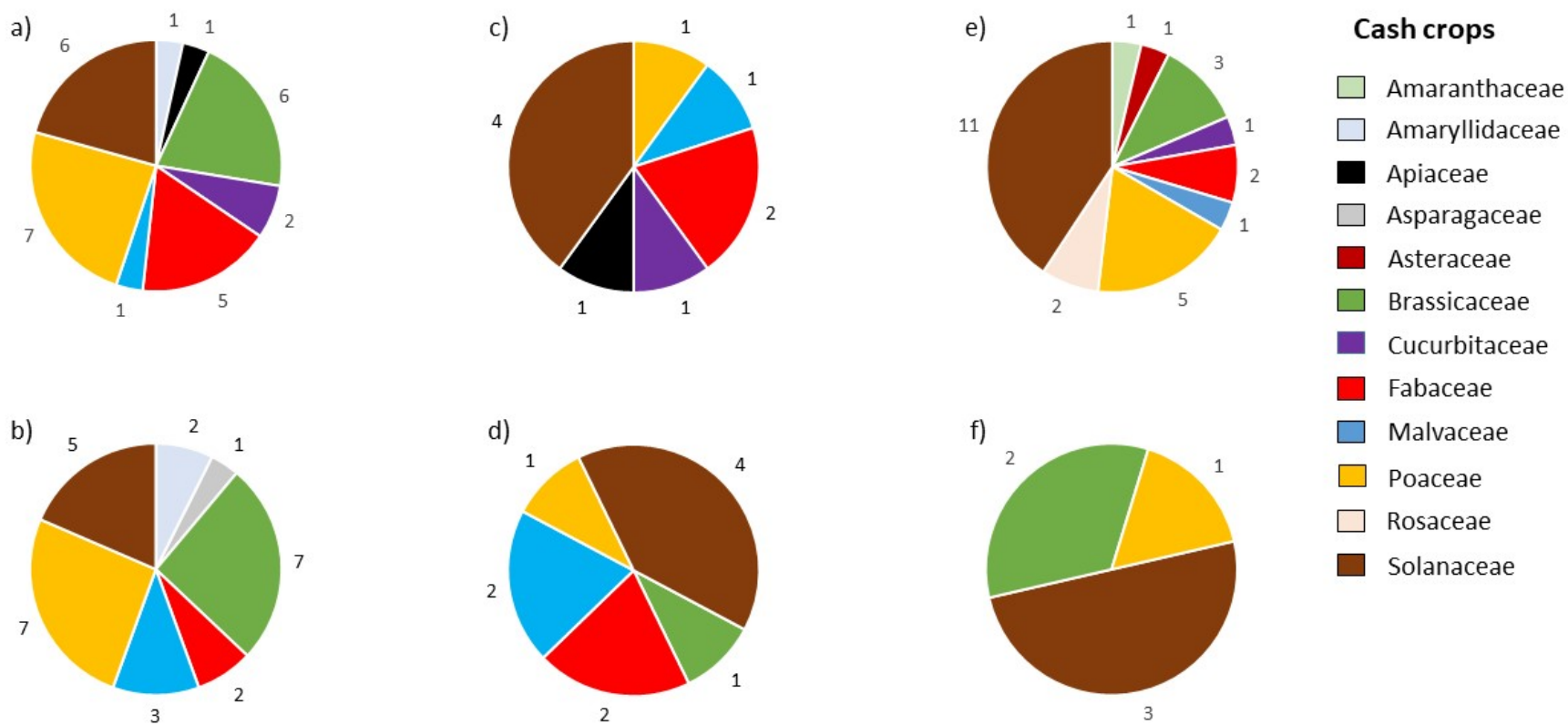


Fig.3. Distribution of the number of research articles by cash crop family for, in the first row, agricultural technique producing a bottom-up effect on crop pests through a) spatial diversification, c) temporal diversification, e) soil management and, in the second row, agricultural techniques supporting a top-down regulation by bioprotection agents on crop pests through b) spatial diversification, d) temporal diversification, and f) soil management. The number next to each slice of the pie chart represents the number of research articles for each cash crop family.

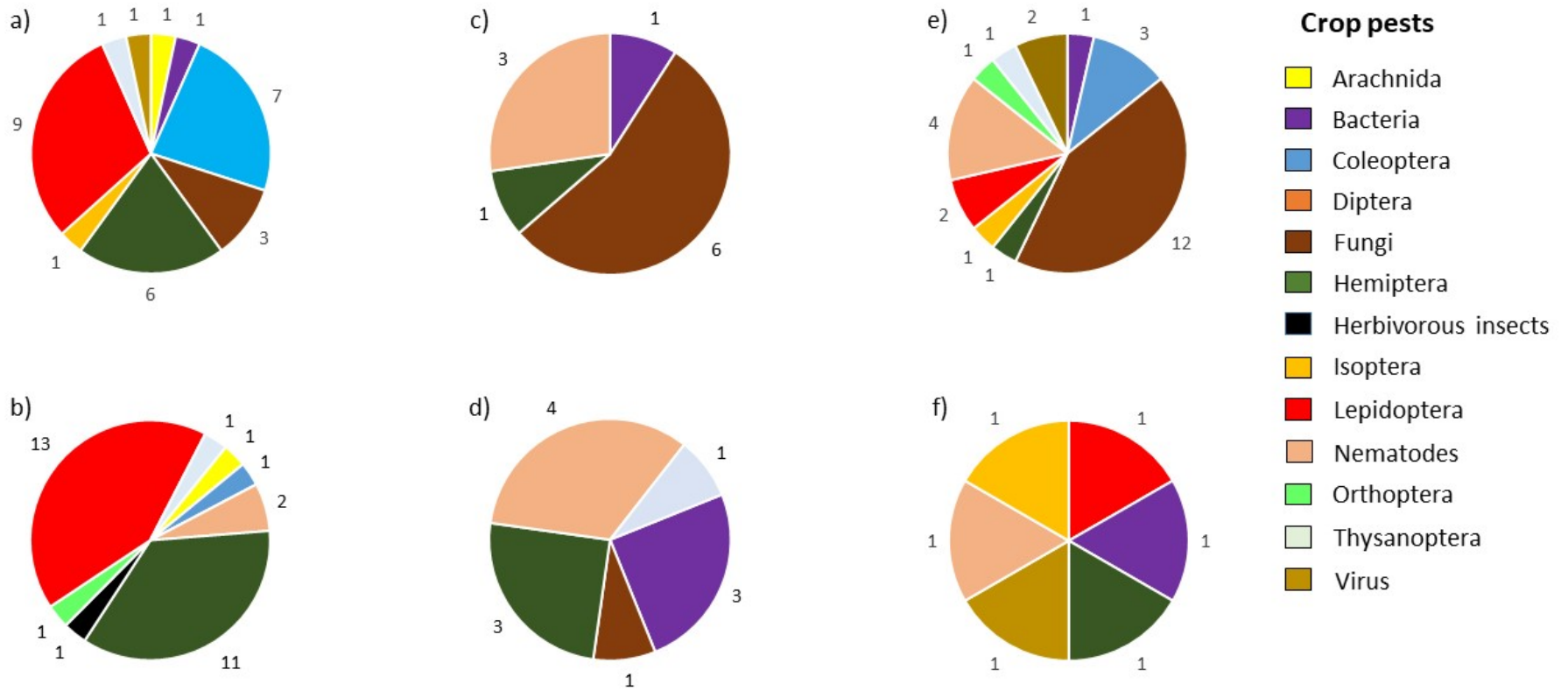


Fig.4. Distribution of the number of research articles that focus on different pest taxa for, in the first row, agricultural techniques producing a bottom-up effect on crop pests through a) spatial diversification, c) temporal diversification, e) soil management and, in the second row, agricultural techniques supporting a top-down regulation by bioprotection agents on crop pests through b) spatial diversification, d) temporal diversification, and f) soil management. The number next to each slice of the pie chart represents the number of research articles representing each crop pest. Herbivorous insects encompass unspecified pest taxa.

### 3.4 Geographical origin of the reviewed literature

Asia was the continent of origin of most of the articles focusing on crop spatial diversification techniques, whether they produced a bottom-up effect (Fig. 5a) or supported a top-down regulation of pests by bioprotection (Fig. 5b). These techniques were reported in 11 out of 29 and 14 out of 26 articles. The continents with the second-highest number of articles for crop spatial diversification techniques with a bottom-up effect on crop pests were Africa and North America, both with 6 out of 29 articles (Fig. 5a). Europe was the continent of origin of most of the articles investigating crop spatial diversification techniques supporting a top-down regulation of crop pests by bioprotection, with 4 out of 26 articles in both cases (Fig. 5b).

When investigating crop temporal diversification techniques producing a bottom-up effect on crop pests, North America was the most represented continent with 5 out of 10 articles, followed by Europe, Asia and Africa (Fig. 5c). Instead, articles focusing on crop temporal diversification techniques supporting a top-down regulation of crop pests by bioprotection originated from Asia, with 5 out of 10 articles, followed by North America, with 3 articles (Fig. 5d).

For soil management techniques with a bottom-up effect on crop pests, Europe was the most represented continent of origin with 13 out of 25 articles, followed by North America, Asia and Africa respectively, with 5, 4 and 2 out of 25 articles (Fig. 5e). Asia and Europe, with 2 articles each, were the continent of origin of most of the articles investigating on soil management techniques supporting the top-down regulation of crop pests by bioprotection (Fig. 5f).

## 4 Probability of success of agricultural techniques and bioprotection in pest control

We found that 24 out of 29 articles on crop spatial diversification techniques producing a bottom-up effect reported a significant positive effect on pest control ( $p$ -value  $< 0.001$ , Fig. 6a). Similarly, 21 out of 26 articles on crop spatial diversification techniques supporting top-down regulation of crop pests by bioprotection reported efficient pest control ( $p$ -value  $= 0.001$ , Fig. 6a). Of these 21 findings, 20 focused on bioprotection according to a conservation biological control approach, while 4 followed an augmentation biological control approach. However, there was no difference in the probability of having a positive effect on pest control between crop spatial diversification techniques producing a bottom-up effect or supporting a top-down regulation ( $p$ -value  $= 1$ , Fig. 6a). The same patterns were observed when comparing the probability of having a positive effect on pest control when considering the treatments (Supplementary material: Additional results S1, Fig. S5a).

In crop temporal diversification techniques producing a bottom-up effect on crop pests, 8 out of 10 articles reported a positive effect on pest control (Fig. 6b). When analyzing articles on crop temporal diversification techniques that support the top-down regulation of crop pests by bioprotection, 7 out of 10 articles reported a positive effect on pest control (Fig. 6b). Of these 7 articles, 5 focused on bioprotection involving a conservation biological control approach, while 2 focused on an augmentation biological control approach. In addition, there was no significant difference when comparing the probabilities of having a positive effect on pest control between crop temporal diversification techniques producing a bottom-up effect or supporting a top-down regulation ( $p$ -value  $= 1$ , Fig. 6b). The same patterns were observed when comparing the probability of having a positive effect on pest control when considering the treatments (Supplementary material: Additional results S2, Fig. S5b).

With regard to soil management techniques focusing on a bottom-up effect on crop pests, we found that 15 out of 25 articles reported a positive effect on pest control (Fig. 6c). Furthermore, when considering soil

management techniques that favor a top-down regulation on crop pests, 3 out of 6 articles reported a positive effect on pest control (Fig.6c). Of these 3 articles, 1 focused on bioprotection according to a conservation biological control approach, and 2 on an augmentation biological control approach. When comparing the probabilities of having a positive effect on pest control between soil management producing a bottom-up effect or supporting a top-down regulation, there were no statistical differences ( $p$ -value=0.67, Fig.6c). The same patterns were observed when comparing the probability of having a positive effect on pest control when considering the treatments (Supplementary material: Additional results S3, Fig. S5c).



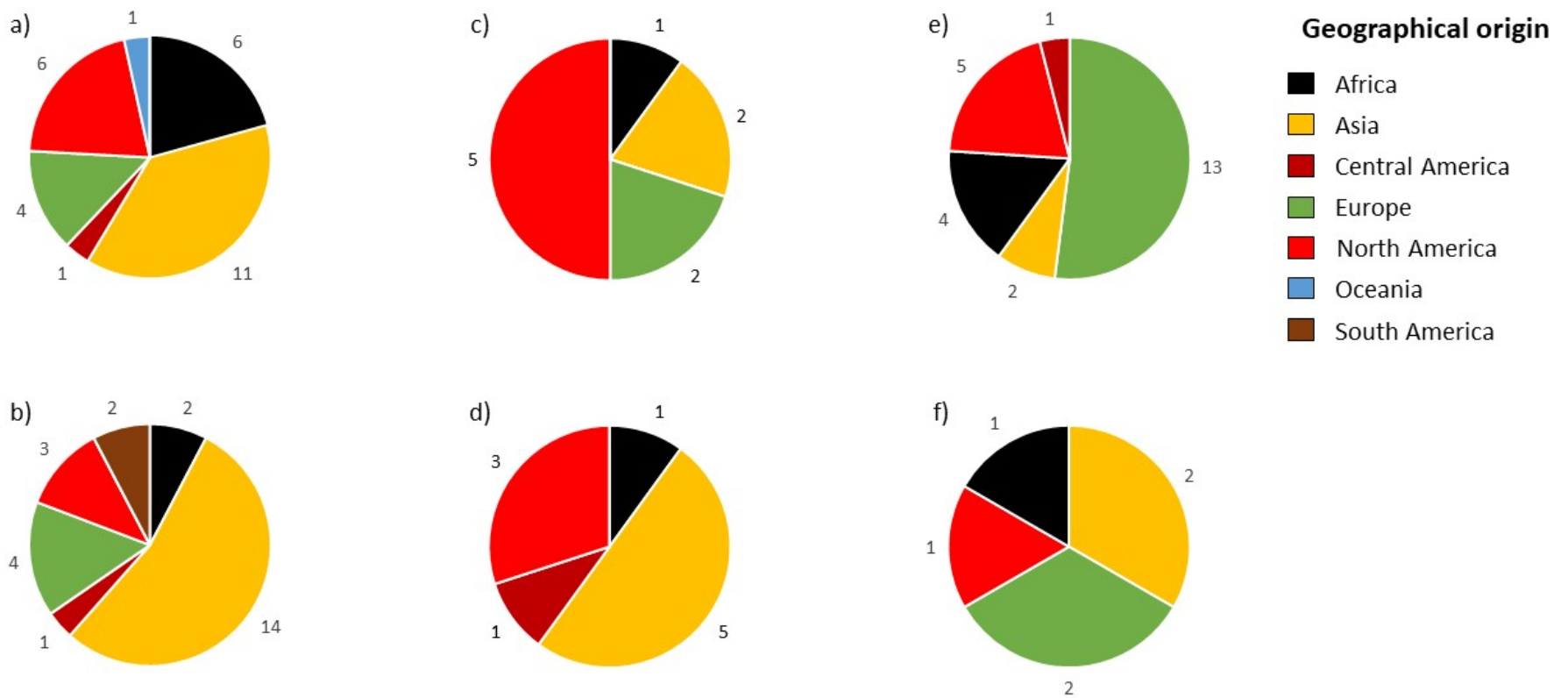


Fig.5. Distribution of the number of research articles across different continents for, in the first row, agricultural techniques producing a bottom-up effect on crop pests through a) spatial diversification, c) temporal diversification, e) soil management and, in the second row, agricultural techniques supporting a top-down regulation by bioprotection agents on crop pests through b) spatial diversification, d) temporal diversification, and f) soil management. The number next to each slice of the pie chart represents the number of research articles reporting studies carried out on the continent.

Probability of success

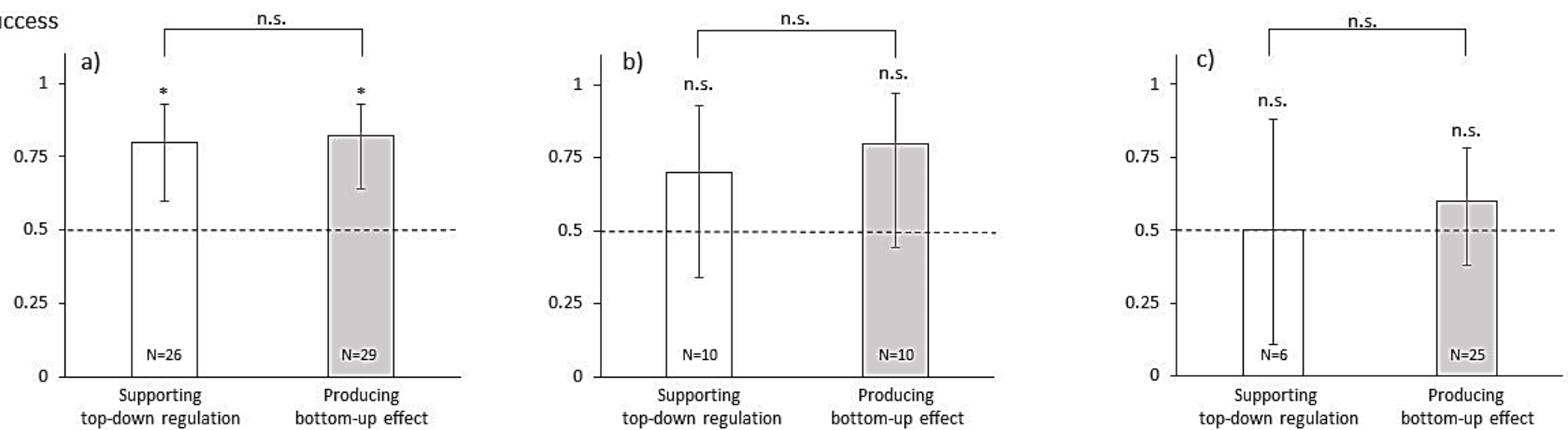


Fig.6. Probability of success ( $\pm$  95% CI) of pest control for research articles interested in: a) crop spatial diversification, b) crop temporal diversification and c) soil management based on agricultural techniques producing a bottom-up effect on crop pests and agricultural techniques that support a top-down regulation by bioprotection agents. Dotted lines represent a probability of 50%. Above each CI bar, an asterisk indicates a success probability significantly higher than 50% (exact binomial test,  $P < 0.05$ ). Horizontal brackets above the bars indicate the statistical difference (Pearson's  $\chi^2$ ,  $P < 0.05$ ) between the probability of having a positive effect on biocontrol between research articles focusing on indirect top-down regulation and direct bottom-up effects on crop pests. n.s.: non-significant.

## **5 Integration of agricultural techniques producing a bottom-up effect or in support of top-down regulation of crop pests by bioprotection**

### **5.1 Summary of the results of the literature review and ecological mechanisms underlying pest control**

This review shows that agroecological research has mainly been interested in crop spatial diversification where pest control is achieved through the integration of companion plants in intercropping or on-field margins. The integration of companion plants can result in a direct bottom-up effect on crop pests by disrupting their host plant location capacity. For instance, Mohammadi et al. (2021) reported that the use of garlic intercropped with green beans decreases the population of *Tetranychus urticae* (Arachnidae) through the release of repellent odors emitted by garlic plants. The integration of companion plants can also support the top-down regulation by bioprotection agents, especially macro-organisms, by providing them with food resources and shelters. For instance, Abad et al. (2020) showed that Persian clover intercropped within tomato provides a supply of pollen, nectar, shelters and alternative preys that enhance the efficacy of parasitoid wasps against *Helicoverpa armigera* (Lepidoptera). This strong interaction between crop field modification and the recruitment of bioprotection agents explains why crop spatial diversification provides a fertile technique to support top-down regulation of crop pests.

There were half as many studies concerning crop temporal diversification. Historically, the main idea of pest control by crop temporal diversification consists in breaking the life cycle of pests, mainly those found in the soil (Bullock 1992). In this respect, Xie et al. (2016), have shown that crop rotation between *Angelica sinensis* (host plant) and marigold (nonhost plant) resulted in a lower harmful nematode density in the soil and a higher Angelica yield. Recently, interest has grown in crop temporal diversification for pest control via the recruitment of beneficial micro-organisms in soils. For instance, Yang et al. (2020) showed that planting soybeans before oilseed rape significantly increased the population density of beneficial microorganisms that inhibit the performance of the pest *Plasmodiophora brassicae*. However, the few articles found in this review suggest the need for a surge in interest to enlarge the agenda of agroecological research on crop temporal diversification for pest control purposes.

Some research has also been undertaken to establish how soil management can foster the top-down regulation on crop pests by means of bioprotection. One example is Chen et al. (2020), who showed how biochar application increased soil carbon and nitrogen content which in turn stimulated beneficial soil microbial pest control activity against bacterial wilt disease. Pearsons and Tooker (2017) showed that tillage reduction increases soil habitat stability, enhancing the presence of bioprotection agents and thereby promoting pest control. The few articles found in our literature review indicate, however, that additional research efforts are required to foster the integration of soil management techniques in support of top-down regulation of crop pests by means of bioprotection.

### **5.2 Differences between agricultural techniques, bioprotection, and targeted pests**

Our analysis of the literature reveals particularities of each of the three agricultural techniques with regard to the bioprotection agents that support top-down regulation, and the pest taxa targeted. Crop spatial diversification has mostly been employed in support of macro-organism bioprotection, such as insect predators and parasitoids, in turn targeting macro-organism pests such as herbivorous insects. One reason for this resides in the visual and chemical stimuli used by macro-organisms – both bioprotection agents and pests – to actively orientate within cropping fields and to locate food resources. For example, macro-organism bioprotection agents use visual or chemical stimuli to recognize companion plants used in crop spatial diversification to obtain alternative food resources and shelters (Giunti et al. 2015). Companion plants can also disorient or alter the visual and chemical stimuli used by macro-organism pests such as

herbivorous insects, thus reducing their chances of finding their target host plants (Potting et al. 2005). However, even if such bottom-up effects are assumed to be more efficient on pests with good sensory abilities, such as lepidopterans and coleopterans, our literature survey shows that companion plants are also used against pests with low dispersal and host detection ability, such as hemipterans (Potting et al. 2005). Microorganisms, on the other hand, which can also use chemical cues to locate hosts, might be highly influenced by their limited dispersal ability, thus diminishing the chances of locating suitable prey/hosts (Meyling and Eilenberg 2007; Pell et al. 2010). Microorganisms are therefore mainly used as bioprotection agent with crop temporal diversification and soil management targeting soil microorganism pests. We assume here that these two techniques modify the soil's physico-chemical characteristics, thus influencing biocontrol agents and pests inhabiting such environments (De Corato 2020).

### **5.3 Benefits in using bioprotection in combination with agricultural techniques**

So far, previous research has largely tested, assessed and demonstrated pest control efficacy by the bottom-up effect of agricultural techniques in annual cash crops (Lechenet et al. 2017). In this review, we have shown that top-down regulation by bioprotection in combination with agricultural techniques is just as effective in pest control as the bottom-up effect of agricultural techniques alone. Some evidence, however, suggests that the integration of bioprotection and agricultural techniques together could be more fruitful for pest control, compared to agricultural techniques alone. Examples are provided by Landl and Glauning (2013), and Blaauw et al. (2017), which investigated the efficacy of trap crops placed outside crop fields. Both claimed that since the attractiveness of trap crops for crop pests decreases with time, it is necessary to integrate bioprotection to avoid a subsequent return of pests in the crop fields. A second example is provided by López-lima et al. (2013), where the rotation of fava bean and potato has been shown to be more efficient to control the potato pest nematode *Globodera rostochiensis*, after inoculation of the fungal bioprotection *Metarhizium carneum*. Dupuis et al. (2017), demonstrated that the complementarity between mineral oil and straw mulching is more effective against the year-to-year variation of the potato virus Y, compared to mineral oil and straw mulching used separately. These examples indicate that bioprotection can be required to induce complementary and more efficient pest regulation when combined with agricultural techniques. However, there is a crucial need to determine the exact circumstances under which the integration of bioprotection succeeds or fails, if the genericity of this pest management strategy is to be improved. Understanding these circumstances can make available a tool that relies on different modes of actions to reach an efficient form of pest control and a reduction in synthetic pesticide inputs.

### **5.4 Participatory research and economic feasibility: enhancing the perceived value of farmers' role**

Our review also reveals a general lack of farmers' participation in the design and evaluation of trials testing alternative pest management strategies (i.e., choice of secondary plants in intercropping, species sequence in crop rotation, or ways to increase soil organic matter). Only Midega et al. (2018), reported a direct involvement of smallholder farmers in the evaluation of a push-pull strategy to control armyworm in maize plantations. In Midega et al. (2018), farmers helped researchers regarding the perception of the on-field efficacy and feasibility of the tested strategy in comparison with a control monoculture field. This example provides support for direct farmer involvement to increase the positive perception about the switch from conventional to alternative cropping systems, which is often considered to be complex, time-consuming, difficult to implement, and linked to lower yields or to unpredictable advantages (Lechenet et al. 2014).

Previous research has also shown that agricultural techniques alone or in combination with bioprotection can provide economic benefits through a significant reduction in synthetic pesticide inputs (Colnenne-David and Doré 2015; Hossard et al. 2016; Colnenne-David et al. 2017; Lechenet et al. 2017). However, no article in our review has provided economic information pertaining to the cost of integration of agricultural techniques and bioprotection, or to their potential economic advantage once they are fully

integrated into the cropping systems. The majority of the trials in the reviewed articles were performed in singular cropping fields and rarely involved the entire farming system. This makes it difficult to extrapolate a real cost of the complete integration of a sustainable pest management strategy on a large spatial scale.

To promote farmer participation in the design of trials testing alternative pest management strategies, workshops are a formalized method to explore a range of solutions and then flesh out the details of their implementation in different cropping systems (Reau et al. 2012). Methods that allow for the exploration of existing knowledge, whether scientific or empirical (Quinio et al. 2022), and the appropriation of the results of trials conducted by other farmers (Laurent et al. 2020), are essential to enable creativity. Secondly, workshops could empower farmers to propose cropping systems integrating bioprotection agents that are adapted to their own objectives (Leclère et al. 2021), allowing them to be direct contributors to agricultural knowledge (Hoffmann et al. 2007; Martínez-Sastre et al. 2020).

## **5. 5 Research agenda and caveats of the review**

Overall, our results show that the probability of successful pest control is similar for agricultural techniques with and without bioprotection indicating that there is still potential room for improvement. This probability is consistent with the results of a limited number of articles reporting negative or null effects when integrating agricultural techniques and bioprotection on pest control. This potential bias towards the tendency to publish positive results or results that confirm research hypotheses is a first caveat of our study. This could have influenced the pest control score used to calculate the probability of having a positive effect on pest control. To reduce the risk of a potential bias, we tested the probability of having a positive pest control effect based on each experimental treatment, thus giving more consideration to treatments with a negative or null pest control score. We showed that for crop spatial diversification, crop temporal diversification and soil management, with both a bottom-up effect and a top-down regulation of crop pests by bioprotection, the probability of success calculated with the pest control score of each experimental treatment had the same pattern of probability of success calculated with the overall pest control score (Supplementary material Fig. S5a,b,c). We argue that it is crucial to publish more results showing null or negative pest control effects to remove any bias and to advance the scientific research. This will help in revealing the reasons behind reduced efficiency in pest control, and with further our understanding of the mechanisms and limitations that influence the integration on a large scale of agricultural techniques and bioprotection.

We found few articles investigating the supportive effect of agricultural techniques on bioprotection agents mobilized through an augmentation biological control approach. Natural substances and semiochemicals were the sole augmented bioprotection agents with crop spatial diversification techniques used to lure pests' natural enemies from the surrounding agroecosystem. Microorganisms (i.e., fungi and bacteria) were the only augmented bioprotection agents used with temporal diversification or soil management techniques. This result might indicate that augmented bioprotection agents are commonly integrated into conventional cropping systems, directly replacing synthetic pesticides according to the “silver bullet” concept and without the support of agricultural techniques (Hokkanen 2015). However, this integration can be considered as a short-term solution to the problem of a sustainable pest management strategy, as the lack of support by agricultural techniques might reduce bioprotection agent presence and persistence while remaining anchored in conventional agriculture (Michaud 2018). This suggests the need for a more systemic approach integrating augmented bioprotection within diversified cropping systems promoting bottom-up and top-down regulations.

A last caveat involves the success or failure of an experimental treatment against crop pests. There are potentially multiple reasons for an experimental treatment to succeed or fail. A positive or negative pest control score does not necessarily indicate general success or a dead end to the tested treatment, but it could highlight some limitations such as the environmental conditions in which it was tested. Accordingly, there is a need not only to improve our ability to identify treatments that work or fail, but also, above all, to

understand environmentally driven versatility in pest control. For instance, we should pay attention to large-scale environmental variations such as pedo-climatic context and changes in communities of biocontrol agents surroundings crops. For instance, Middleton and MacRae (2021) demonstrated that the potential beneficial effect of flower strips placed at the margin of crop fields to attract bioprotection agents (i.e., macro-organisms) was inhibited by the higher level of heterogeneity in the surrounding landscape. Following the intermediate landscape complexity hypothesis, landscapes might provide better habitats for bioprotection agents, in particular macro-organisms, above a given threshold of complexity, in comparison with the habitats managed at field scale (Tschardt et al. 2005). This means that local techniques promoting bioprotection must be tailored to the level of biological control already provided by the landscape context. In the same line, in this review, we did not take into account local factors related to cropping system management (e.g., organic or conventional) in which the experimental trials were performed. For the combination of bioprotection and agricultural techniques studied here, we might expect the effects to be strengthened or dampened by the management of the cropping system in which they are used. Designing multiscale experiments, where agricultural techniques at field scale are investigated in their potential role of bioprotection promoters in several gradients of landscape heterogeneity will enable to understand which level provides the most pest control benefits (Serée et al. 2022). This will, however, require collective choices among all farmers living in that context, to manage larger spatial scale experiments.

## 6 Conclusions

In this review, we showed that agricultural techniques regulating bottom-up pest control are as efficient as those regulating top-down pest control. This opens large avenues to design integrative crop protection strategies benefiting from both pest control forces. However, over the last decade, spatial and temporal diversification as well as soil management have poorly integrated the four categories of bioprotection agents. Although our literature survey points to studies mostly interested in bringing together agricultural techniques and conservation biological control, there are still major gaps in the literature, pointing to the need to develop holistic approaches based on the combination of agricultural techniques and augmented biological control. For example, despite a large body of literature about the natural substances and semiochemicals used, only 2, 1 and 1 articles reported advantages in augmenting natural substances in combination with spatial diversification, temporal diversification and soil management, respectively. This result shows that while bioprotection has sparked keen interest in recent years, it is rarely integrated into agroecological frameworks that are still considered as ‘silver bullets’, according to a substitution paradigm. This suggests that the Directive 2009/128/EC (European Parliament 2009) did not change the previous research agenda routine, and that despite good intentions, it seems to have failed in the endeavor to support some integrative perspectives to go beyond synthetic pesticide substitution paradigms. Here, we suggest that to foster this integration of alternative and sustainable pest management strategies, it is necessary to consider multiple changes in the process of innovation and integration involving multiple stakeholders, that is, in the design of experimental trials by researchers, involving farmers and economists to test real on-field feasibility. As global demand for food will increase in the next decades, unsustainable cropping systems still represent a threat to human and environmental health. Cropping systems based on agroecological strategies will provide benefits beyond pest control services alone, and will support other ecosystem services such as pollination (Kovács-Hostyánszki et al. 2017), climate change mitigation (Murrell 2017), risk reduction for humans, and environment health, thus representing a multiple-win solution.

## Declaration

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### Conflict of interest

All the authors declare that they have no conflict of interest.

### Authors' contributions

Foteini Pashalidou, Davide Bellone and Alan Kergunteuil contributed to the conception and design of the study. Material preparation, data collection and analysis were performed by Davide Bellone. The first draft of the manuscript was written by Davide Bellone and all the authors commented on previous versions of the manuscript. All the authors read and approved the final manuscript.

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## Supplementary material

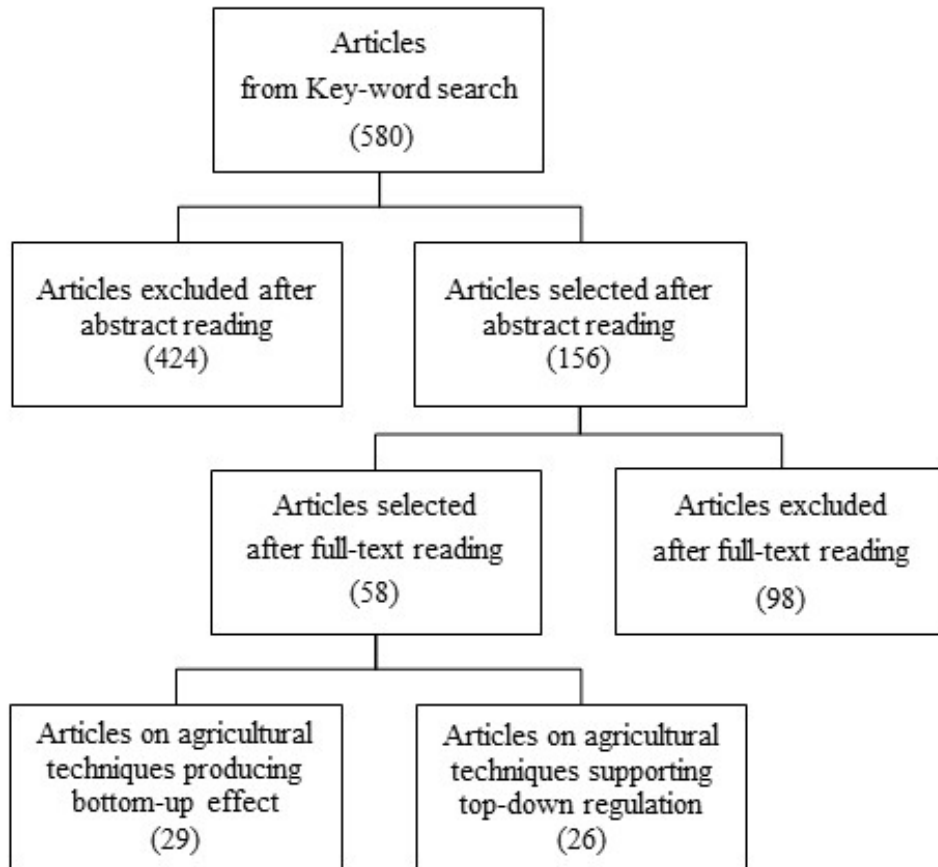


Figure S1. The steps for the literature review for crop spatial diversification. The number between brackets indicates the number of research articles selected for the step contained in the cell.

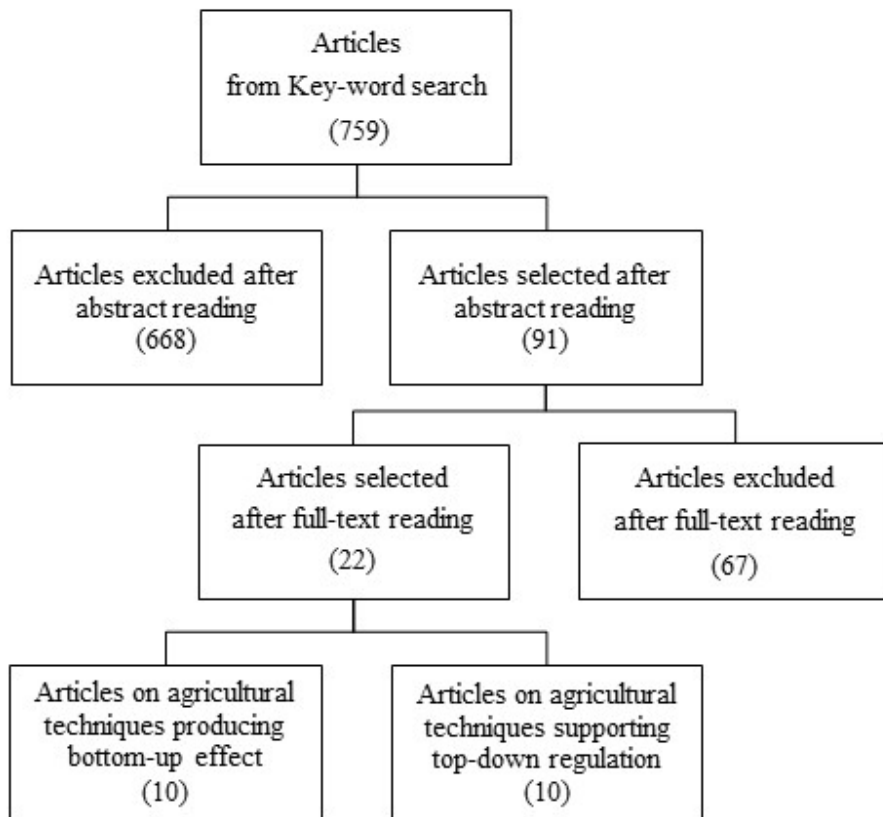


Figure S2. The steps for the literature review for crop temporal diversification. The number between brackets indicates the number of research articles selected for the step contained in the cell.

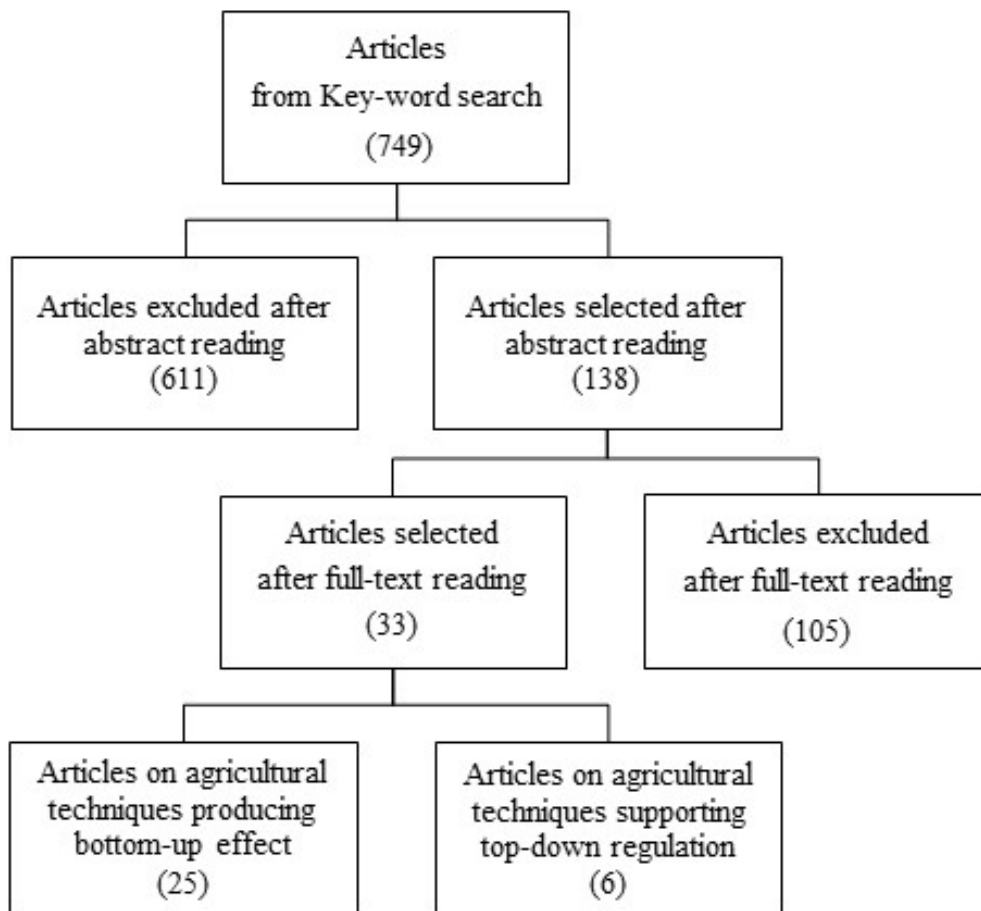


Figure S3. The steps for the literature review for soil management. The number between brackets indicates the number of research articles selected for the step contained in the cell.

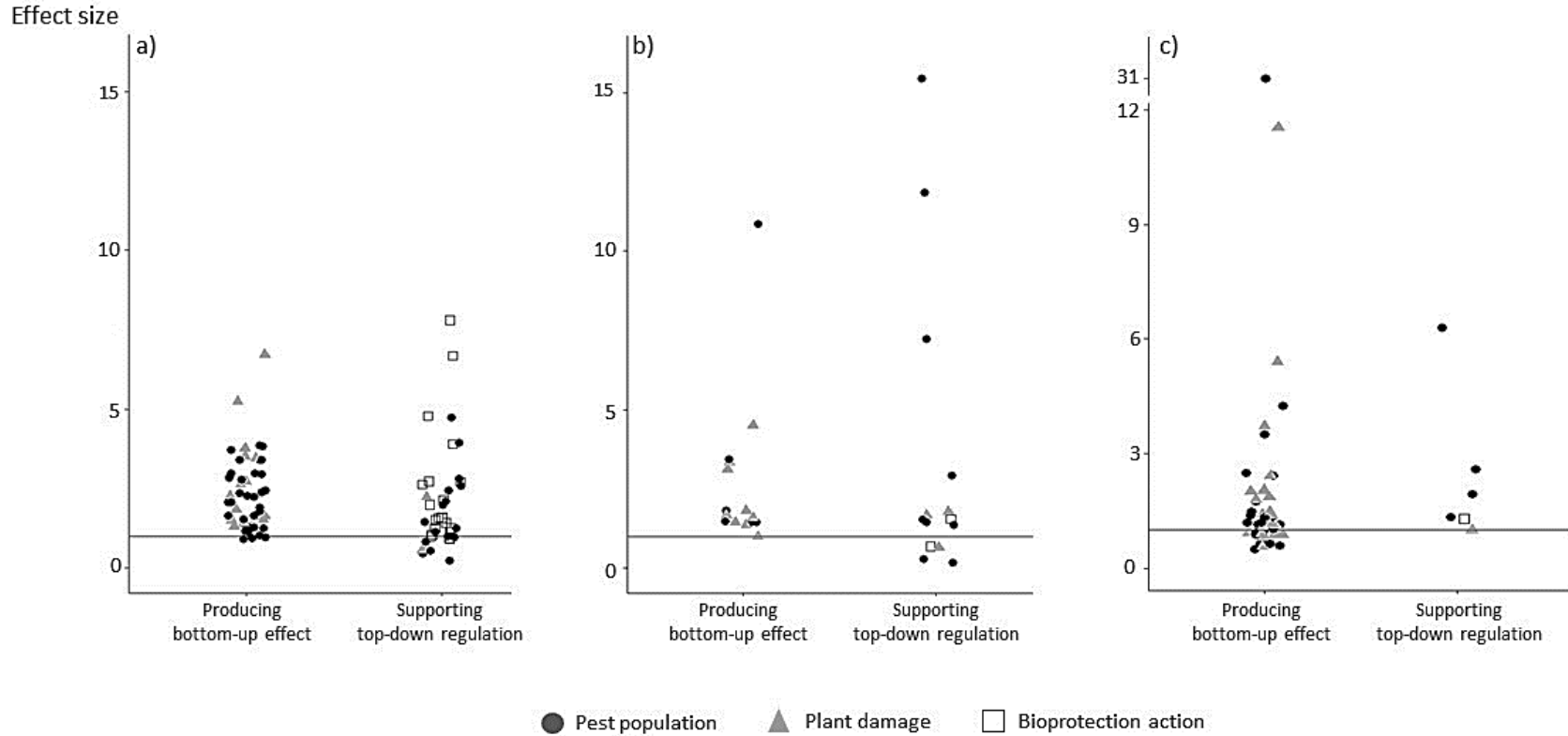


Figure S4. Effect size distribution of the pest control efficacy for each experimental trial within the articles used for the review. Effect sizes are presented on each agricultural technique a) crop spatial diversification, b) crop temporal diversification and c) soil management; producing a bottom-up effect on crop pests or supporting a top-down regulation by bioprotection agents. Each dot corresponds to an effect size calculated at the level of each experimental trial described in each article included on the review. An effect size above the horizontal line ( $y=1$ ) indicates a significantly better pest control (i.e. reduced population, reduced damage or higher regulation by bioprotection agents) in the experimental treatment compared to control plots. Pest population means a survey on pest population dynamic such as pest abundance, number or density. Plant damage means a survey on damage recorded on leaves, roots or fruit such as number of damage, index, severity, and bioprotection action means a survey on the activity of bioprotection influencing pest population dynamic such as predation, mortality or parasitism. For (a) crop spatial diversification producing bottom-up effect: n° of experimental trials = 53, n° of articles used for the review = 29, supporting top-down regulation n° of experimental trials = 47, n° of articles used for the review = 26; For (b) crop temporal diversification producing bottom-up effect: n° of experimental trials = 10, n° of articles used for the review = 15, supporting top-down regulation n° of experimental trials = 15, n° of articles used for the review = 10, For (c) soil management producing bottom-up effect: n° of experimental trials = 51, n° of articles used for the review = 25, supporting top-down regulation n° of experimental trials = 7, n° of articles used for the review = 6.

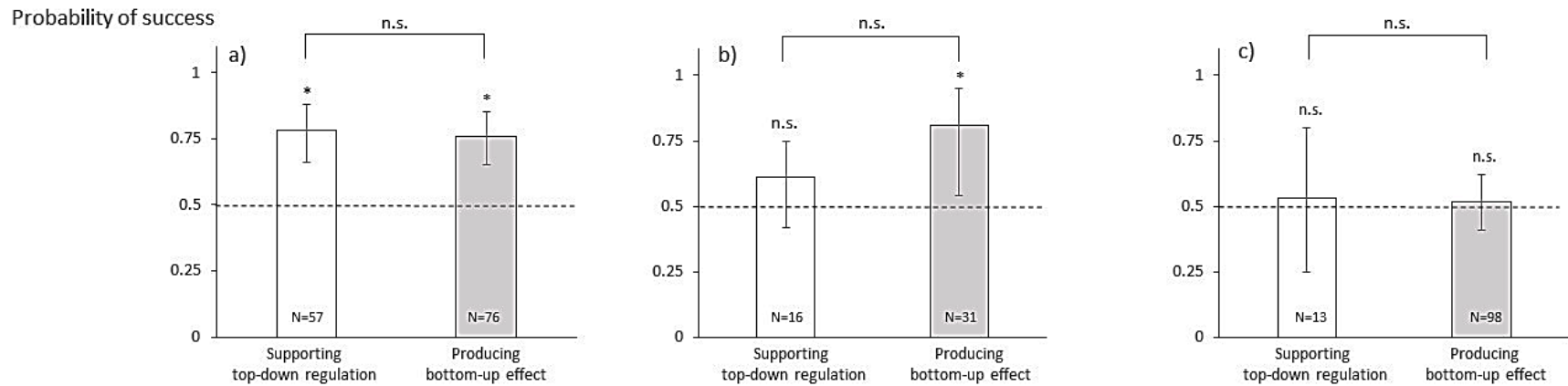


Figure S5. Probability of success ( $\pm$ CI) of pest control for experimental treatment within research articles interested in a) crop spatial diversification, b) crop temporal diversification and c) soil management based on agricultural techniques with a bottom-up effect on crop pests and agricultural techniques that support a top-down regulation by bioprotection agents. Dot lines represent probability of 50%. Above each CI bars, an asterisk indicates a success probability significantly higher than 50% (exact binomial test,  $P < 0.05$ ). n.s: non-significant. Horizontal brackets above the bars indicate statistical difference (exact proportional test,  $P < 0.05$ ) between the probability of having a positive effect on biocontrol between experimental treatments focusing on indirect top-down regulation and direct bottom-up effect on crop pests.

i) Additional results S1 : Crop spatial diversification

We found that 58 out of 76 treatments on crop spatial diversification techniques producing a bottom-up effect reported a significant positive effect on pest control ( $p$ -value  $< 0.001$ , Fig. S5a). Similarly, 45 out of 57 treatments on crop spatial diversification techniques supporting top-down regulation of crop pests by bioprotection reported efficient pest control ( $p$ -value  $< 0.001$ , Fig. S5a). However, there was no difference in the probability of having a positive effect on pest control between crop spatial diversification techniques producing a bottom-up effect or supporting a top-down regulation ( $p$ -value = 0.83, Fig. S5a).

ii) Additional results S2: Crop temporal diversification

In crop temporal diversification techniques producing a bottom-up effect on crop pests, 13 out of 16 treatments reported a positive effect on pest control ( $p$ -value = 0.02, Fig. S5b). When analyzing articles on crop temporal diversification techniques that support the top-down regulation of crop pests by bioprotection, 19 out of 31 treatments reported a positive but not significant effect on pest control ( $p$ -value = 0.28, Fig. S5b). However, there was no difference in the probability of having a positive effect on pest control between crop spatial diversification techniques producing a bottom-up effect or supporting a top-down regulation ( $p$ -value=0.2, Fig.S5b).

iii) Additional results S3: Soil management

With regard to soil management techniques focusing on a bottom-up effect on crop pests, we found that 51 out of 98 treatments reported a positive but not significant effect on pest control ( $p$ -value = 0.76, Fig. S5c). Furthermore, when considering soil management techniques that favor a top-down regulation on crop pests, 7 out of 14 treatments reported a positive but not significant effect on pest control ( $p$ -value=1, Fig.S5c). When comparing the probabilities of having a positive effect on pest control between soil management producing a bottom-up effect or supporting a top-down regulation, there were no statistical differences ( $p$ -value = 1, Fig.S5c).