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Do agroecological practices enhance the supply of ecosystem services? A comparison between agroecological and conventional horticultural farms

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ABSTRACT

Agricultural intensification has strongly impacted ecosystems and accelerated the process of global change. Consequently, agroecological practices are being increasingly adopted. Agroecological practices are biodiversity-based solutions that aim to generate sustainable and resilient agroecosystems, which could enhance the supply of ecosystem services. This study compared agroecological and conventional horticultural farms in terms of agroecological practices and ecosystem services supply. We conducted biophysical samplings and interviews on 24 agroecological and conventional farms over two summers in the Madrid Region (Spain). We used multiple indicators as proxies of the supply of 12 ecosystem services, and we identified the agricultural practices applied at each farm. We found that agroecological farmers applied more agroecological practices compared to conventional farmers, and agroecological farms had a higher potential to supply regulating, provisioning, and cultural services. Some agroecological practices, such as crop diversification, light tillage, and the use of organic pesticides, were associated with enhancing soil fertility, pest control, and pollination services. Our study provided empirical evidence that agroecological practices enhance ecosystem services at horticultural farms, which is extremely relevant to upscaling agroecology in the current context of ongoing European policy reforms.

1. Introduction

In recent decades, agricultural intensification has strongly impacted ecosystems, and accelerated the process of global change (Ahmed and Stepp, 2016; Bohan et al., 2013). Consequently, there has been increasing awareness of the scientific community for the need to transform the industrial agricultural sector to a more sustainable system, with agroecology representing one such approach (Chabert and Sarthou, 2020). Although there is not a unified definition for the term, agroecology is widely perceived as a science, movement, and practice (Wezel et al., 2009) that emerged as an alternative to traditional conventional farm management (Hatt et al., 2016). Agroecology applies ecological concepts for the sustainable management of agrifood systems (Altieri, 1995; Wezel et al., 2009) and encompasses many practices, including reducing tillage, eliminating chemical synthesized fertilizers and pesticides, and implementing biodiversity-based solutions towards creating sustainable and resilient agroecosystems (Dendoncker et al., 2018; Duru et al., 2015a; Garbach et al., 2017).

Agroecosystems provide certain ecosystem services (ES) that often depend on other ES, such as soil fertility or pollination, to provide them (Zhang et al., 2007). For instance, agroecosystems depend on the specific biophysical characteristics of their location, in addition to on the type of management and practices adopted by farmers (Chabert and Sarthou, 2020; Garbach et al., 2017). Therefore, ES are co-produced by both natural and anthropogenic systems (Hatt et al., 2016; Palomo et al., 2016; Spangenberg et al., 2014). Thus, agroecology aims to enhance the supply of provisioning ES (such as food and fibre) through practices aimed at increasing several regulating ES, including soil fertility,

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pollination, and natural pest control (Bommarco et al., 2013).

Globally, studies have frequently reported that agroecological practices positively affect the supply of ES (Boeraeve et al., 2020; De Leijster et al., 2019; Harterreiten-Souza et al., 2014; Skelton and Barrett, 2005; Trichard et al., 2014); however, the multi-dimensionality of agroecological systems makes it difficult to empirically confirm this (Álvarez-salas et al., 2014). Consequently, research assessing the effect of agroecological practices on the supply of ES often use different methodological approaches to simplify how these systems are studied. As a result, only one or a few ES are typically evaluated, using single indicators for each ES, or working on experimental fields (Blubaugh and Kaplan, 2015; Lorin et al., 2015; Pennington et al., 2017). To improve our understanding on the complex nature of agroecosystems, complex methodological approaches are necessary. Given that ES are the result of convergent biological and anthropogenic processes, it is necessary to assess multiple ES with multiple indicators on productive farms, as opposed to experimental settings, to elucidate how agroecosystems function (Kremen et al., 2012; Ponisio et al., 2015).

Within this framework, this study aimed to compare agroecological and conventional horticultural farms in terms of agroecological practices applied and ES supplied. We used multiple indicators for several ES. These indicators were assessed by collecting biophysical samples on horticultural farms and via interviews with farmers. Similar studies have been conducted on cereal fields (Boeraeve et al., 2020); however, this is the first study exploring the supply of multiple ES on productive horticultural farms through multiple indicators. Our main objectives were to: (1) identify the agroecological practices being applied by agroecological and conventional horticultural farmers, and (2) assess differences in the supply of regulating, provisioning, and cultural ES between these two management types. We hypothesised that agroecological horticultural farmers would apply more agroecological practices, leading to a higher supply of ES. Our results are expected to provide new insights on the linkage between agroecology and ES, contributing information for the ongoing European Agricultural Policies reform within the framework of the European Green Deal, and the Farm to Fork Strategy.

2. Study area and methods

2.1. Study area

The study was conducted in eight municipalities in the south-eastern region of Madrid, where most agroecological initiatives in the horticultural sector are located (del Valle and Jiménez, 2019; Yacamán Ochoa et al., 2015). Three of the eight municipalities belong to *peri*-urban areas (areas with a population density of > 10 inhabitants/ha and/or population of > 20000 inhabitants), with an important agricultural tradition. The remaining five municipalities are rural municipalities (areas with a population density of < 10 inhabitants/ha and/or population of < 20000 inhabitants) that belong to the Las Vegas rural agrarian district, located in the Tajo Watershed, and are traversed by the Jarama and Tajuña rivers. This area is characterized by fertile soils that contribute to the territory's strong agricultural tradition, which persists to today (García-Llorente et al., 2019; Pérez-Ramírez et al., 2019). Within the Las Vegas rural agrarian district, we selected three municipalities of the Tajuña River, and two municipalities in the vicinity of the Tajo River. The three areas have riparian vegetation interspersed with patches of irrigated and rainfed crops. Climate conditions are similar throughout the territory (Table 1).

2.2. Horticultural farms selection

Within each area, we selected a balanced number of agroecological and conventional horticultural farms. The main crops grown on these horticultural farms were: tomato, pepper, onion, potato, lettuce, zucchini, eggplant, and melon. We used the term "conventional" to refer to farms that applied at least one input prohibited under the organic agriculture regulations. Given that there are multiple definitions of agroecology, and that this term is continually evolving (Gallardo-López et al., 2018), we considered agroecological farms to be those that the farmer self-defined as such, and that did not apply any prohibited inputs under the organic agriculture regulations. We obtained the contact information of farmers through visits to city halls, agrarian parks, and communal or cooperative initiatives that were self-defined as agroecological in the selected municipalities, and by snowball sampling. Overall, 13 agroecological and 11 conventional horticultural farmers agreed to participate in the study (Table 1; Fig. 1).

Table 1
Study areas including the selected municipalities, their mean population size and density (data from National Statistics Institute, year 2019), dominant geomorphology and soil types (data from IGME), mean annual temperature and precipitation (data from Climate-Data.org; years 2014–2019), and the number of agroecological and conventional farms included in the study.

	***Peri*-urban area**	**Tajuña River**	**Tajo River**
Selected municipalities	Fuenlabrada, Rivas-Vaciamadrid, Mejorada del Campo	Chinchón, Perales de Tajuña, Orusco de Tajuña	Villamanrique de Tajo, Fuentidueña de Tajo
Mean population density (inh/ha)	25.22	0.54	0.29
Mean population (inh)	100,907	3091	1342
Geomorphology	Feldespathic sandstones; polygenic gravel and ridges, sand, and silt-clayey sands on the floodplains	Low terraces of brown silt and gravel; floodplains of gravel, sand and silt	Gravel, sand, silt and gypsum clay at the bottom of the alluvial valley; gravel, sand and silt on the floodplains
Soil type	Alfisols; entisols	Entisols, inceptisols, enticeptisols	Inceptisols, enticeptisols
Mean annual temperature (°C)	13.8	13.6	14.3
Mean annual precipitation (mm)	436.5	435.3	408.0
Agroecological farms selected	3	7	3
Conventional farms selected	4	4	3

Acknowledging that the a priori delineation between agroecological and conventional farms may overlook the fuzzy gradient of intermediate agricultural management typologies, we conducted various statistical analyses to assess whether the initial selection of agroecological and conventional farms was accurate in terms of practices. First, we conducted a Principal Component Analysis (PCA) on the practices applied at each farm. Then, we performed Ward's Hierarchical Cluster Analysis (HCA) using PCA factors that had an eigenvalue > 1 to cluster farms according to the applied agroecological practices. Finally, we performed Kruskal-Wallis analyses and Dunn's tests to evaluate differences between the groups that emerged from the HCA. The analyses revealed a high coherence between the a priori delineation of agroecological versus conventional farms, and the results of the HCA in terms of the different practices applied (see Supplementary data: Appendix A for detailed results).

Eight of the agroecological farms were private plots, while five were cooperatives, social projects, or were located on agrarian parks. The Agrarian Park is a municipal or regional public body designed to protect and manage agricultural land (mainly in urban and *peri*-urban environments), where food production and the conservation of the agricultural landscape are key aspects for strengthening the link between the countryside and the city (Yacamán Ochoa, 2018). Only one of the

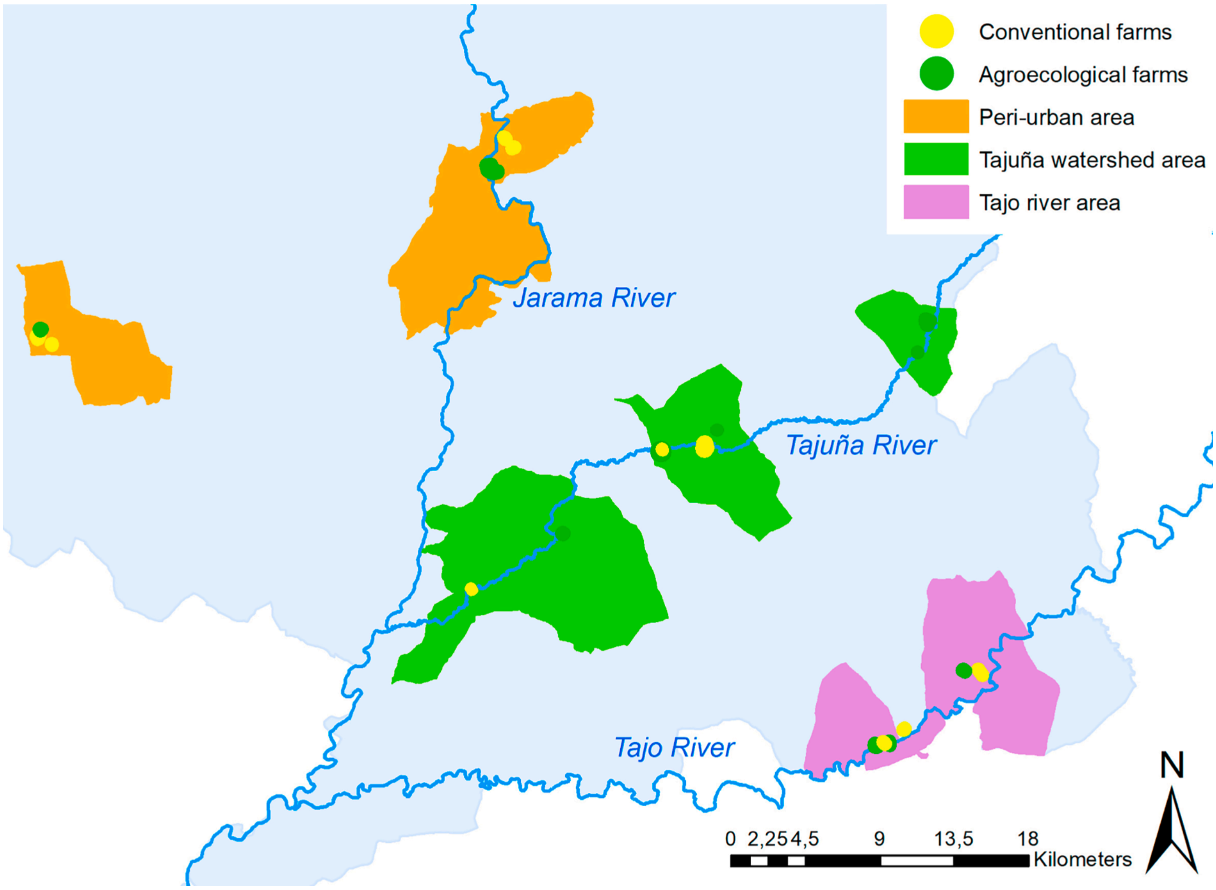

Fig. 1. Map showing the selected municipalities (orange for *peri*-urban, green for Tajuña, and purple for Tajo areas) and farms (yellow dots for conventional and green dots for agroecological farms).

selected agroecological farms was partially certified as organic agriculture; however, we excluded the certified sector of the farm when performing sampling, to avoid introducing heterogeneity in our sample. Nine of the conventional farms were private plots, while two were located in an agrarian park. On average, the agroecological farms had been active for three years, whereas conventional farms had been active for 22 years. Agroecological farms were located in areas that were previously abandoned or under non-agricultural use, whereas every conventional farm was located in areas that were previously conventional farming systems. The farm surface was similar for both management types. Agroecological farms covered an average surface of 1.5 ha (SD = 2.4), while conventional farms covered 1.4 ha (SD = 1.4).

2.3. Description of general sampling design and agroecological practices

We conducted biophysical sampling on farms from June to September 2019 and July to September 2020. We conducted semi-structured interviews with the farmers from each selected farm during September 2019 (see Supplementary data: Appendix B for information on sampling at each farm and year). We selected 17 ES indicators as proxies of 12 ES. Eleven indicators were measured through biophysical field sampling, and the remaining six indicators were assessed through interviews (Table 2).

We selected 13 practices that have been previously identified in the published literature as practices that have a potential effect on our selected ES (Palomo-Campesino et al., 2018; Table 3). The practices included were animal breeding, crop association, crop diversification, crop rotation, beehives installation, aromatic plants, drip irrigation, fallow, light/no tillage, nest-boxes for insects, organic/no fertilizers, organic/no herbicides and organic/no pesticides. The interviews with farmers included a table containing these 13 practices, for which farmers were asked if they applied them and, where applicable, provide the details of their application and if they applied them with the aim of enhancing the supply of one or more ES. Farmers could also add other practices not provided in our initial list. We synthesized the compiled information based on the reasons given by farmers for the application of each practice.

Because the application of the same agroecological practice differed across farms, we calculated an index of each practice for every farm with the application details given by farmers during the interviews. To calculate these indexes, we first categorised each agroecological practice based on its degree of application, ranking from 0 (the practice was not applied at the farm) to 1 (the practice was applied in the most sustainable way) (see Supplementary data: Appendix C for details). Then, we multiplied the degree of application and the time period that the practice had been applied at each farm (weighted from 0 to 1). In this way, we obtained an index for each agricultural practice and farm, with a rank from 0 to 1, in which 0 was a practice not applied at the farm, and 1 was a practice applied in the most sustainable way for>10 years at the farm. These indexes were later used in a redundancy analysis (RDA) to explore the relationship among the application of practices and the supply of provisioning and regulating ES.

2.4. Regulating ES: Biophysical data collection

We assessed 11 indicators selected as proxies to explore the supply of five regulating ES: soil fertility, soil formation, erosion control, pest control and pollination (Table 2). Biophysical sampling methods for each indicator are provided in the subsequent subsections.

Table 2
List of ESs assessed, indicators and methods used, units, and number of years sampled.

ES	Indicator	Method	Unit	Years
Soil fertility	Nitrogen	Soil sampling	Percentage	2
Soil fertility	Organic material	Soil sampling	Percentage	2
Soil fertility	Phosphorous	Soil sampling	mg/kg	2
Soil fertility	Potassium	Soil sampling	mg/kg	2
Soil formation	Stabilisation factor	Tea Bag Index		2
Soil formation	Decomposition rate	Tea Bag Index		2
Erosion control	Aggregate stability	Soil aggregate immersion	Stability class	2
Pest control	Damage by *Tetranychus urticae*	Visual	Degree of infestation	2
Pest control	Presence of *Macrolophus pygmaeus*	Visual	Number of plants	2
Pest control	Abundance of *Tuta absoluta*	Delta traps	Number of individuals	1
Pollination	Wild bee diversity	Pan traps	Species richness	1
Food	Diversity of crops	Interview	Number of crops	1
Food	Diversity of traditional varieties	Interview	Number of traditional varieties	1
Gene pool	Diversity of crops	Interview	Number of crops	1
Gene pool	Diversity of traditional varieties	Interview	Number of traditional varieties	1
Gene pool	Diversity of medicinal plants	Interview	Number of medicinal plants	1
Natural medicines	Diversity of medicinal plants	Interview	Number of medicinal plants	1
Local ecological knowledge	Exchange of traditional varieties	Interview	Yes/No	1
Local ecological knowledge	Interaction with other farmers	Interview	Free listing	1
Recreation	Visits to the farm	Interview	Free listing	1
Environmental education	Visits to the farm	Interview	Free listing	1
Cultural identity	Interaction with other farmers	Interview	Interaction with other farmers	1

2.4.1. Chemical soil composition

Following the protocol of the Madrid Institute for Rural, Agricultural and Food Research and Development (IMIDRA) Soil Laboratory, we took three soil subsamples at root depth (approximately 15–20 cm soil depth) from each farm. The subsamples were taken from dry soil after removing adventitious plants from the soil surface. We mixed the three soil subsamples to create a unique homogeneous sample of at least 1 kg. We sent all soil samples to the accredited IMIDRA Soil Laboratory where nitrogen (N), organic material (OM), phosphorous (P) and potassium (K) were measured (see Supplementary data: Appendix D).

2.4.2. Soil decomposition data

We applied the Tea Bag Index method to estimate the stabilisation factor (S) and decomposition rate (k) of the soil from each farm (Costantini et al., 2018; Keuskamp et al., 2013; Tóth et al., 2018). We buried five green tea bags and five rooibos tea bags at approximately 8 cm depth at five different points on each farm. The burial sites were selected with the collaboration of the farmers to avoid places that would be ploughed or that could obstruct the farmers' work. Every tea bag was previously marked and weighted. Then, the weight of an empty bag was subtracted to establish the weight of tea inside each buried tea bag. The tea bags were recovered from the farms after 90 days and dried in a stove for 48 h at 70 °C. The weight difference between bags before and after burial in fields provided an estimation of S and k.

2.4.3. Soil aggregate stability

We randomly collected nine soil fragments of 6–8 mm diameter from each farm, and air dried them for 24 h. Then, we placed each sample in a separate sieve and immersed it in distilled water for a maximum of 5 min. After the first immersion, if the sample remained on the sieve, we repeated the process up to five more times. We qualitatively classified each sample based on the time required to lose its structural integrity after immersion (see Supplementary data: Appendix D) (Grønsten and Børresen, 2009; Seybold and Herrick, 2001). We calculated the average of the nine samples to generate a unique value for the degree of soil stability on each farm.

2.4.4. Plant damage and presence of beneficial insects

The red spider mite *(Tetranychus urticae*) is a plant-feeding mite of the Tetranychidae family. This species is a pest that is frequently found on tomato plants. Red spider mites place their eggs on and suck the fluids of the plant leaves which, if not controlled, can lead to plant death (Ferrero et al., 2011). One of the natural enemies of this species is *Macrolophus pygmaeus*, a plant bug in the Miridae family that feeds on the eggs of red spider mites (Zhang et al., 2018).

To assess damage to tomato plants by red spider mites and the presence of *Macrolophus pygmaeus*, we randomly selected 20 tomato plants on each farm. Using a ruler, we selected five leaves from a single plant separated by 20 cm distance, starting from the bottom of the plant and moving upwards. A pest control expert helped to classify each leaf from 0 to 4 according to the degree of infestation by red spider mites (see Supplementary data: Appendix D) (Murage et al., 2013). We repeated this process on the same plant, but on the opposite side, thus assessing a total of 10 leaves per plant. We calculated the average degree of infestation of all selected leaves to obtain a unique value of tomato plant damage by red spider mites at each farm. We also counted the number of selected tomato plants on which presence of any *Macrolophus pygmaeus* individual was detected.

2.4.5. Presence of Tuta absoluta

The tomato leafminer (*Tuta absoluta*) is a moth of the Gelechiidae family. As its common name indicates, tomato leafminer larvae penetrate and feed on the leaves, stem and tomato fruit, leading to the death of the fruit (or even the plant) (Tropea Garzia et al., 2012). To assess the presence of *Tuta absoluta*, we placed four delta traps per hectare, each with a pheromone capsule of *Tuta absoluta,* at each farm. The capsules attract male specimens, and a sticky card placed on the base of the delta trap captures every individual that perches on it. The traps were hung at the height of tomato crops, and were removed after 28 days. We counted the number of male individuals of *Tuta absoluta* that were glued to every collected trap. Finally, we calculated the average number of individuals per farm (Caparros Megido et al., 2013). This sampling method was carried out in 2020 only.

2.4.6. Diversity of wild bees

To assess the diversity of wild bees, we established six pan trap stations on sunny non-windy days at each farm. Each pan trap station consisted of three plastic bowls painted with ultraviolet reflecting paint: yellow, blue and white. The pan trap stations were randomly placed, at least 10 m from each other. The traps were placed at the same height as surrounding vegetation, avoiding shaded places. Then, we filled each bowl with soapy water, and left the traps for 48 h, making sure that the water did not evaporate during this time. After the 48 h, we collected the

Table 3
List and description of the agroecological practices included in the interview. Main provisioning and regulating ES potentially linked to each practice and literature references supporting these relationships are provided.

Practice	Description	ES linked	Reference
Animal breeding	Horticultural farms where animals are also bred	Erosion control, food, pest control, soil fertility	Bernués et al., 2016; Theisen et al., 2017; Zhang et al., 2012
Aromatic plants	Cultivation of aromatic plants on the field, within the cropping area or as buffer strips	Erosion control, food, pollination, pest control, soil fertility	Gill et al., 2014
Beehive installation	Installation of honey beehives on (or near) the farm	Pollination	Yuan et al., 2016
Crop association	Joint cultivation of different crops aiming for positive ecological interactions	Food, pest control	Isaacs et al., 2016, Lopes et al., 2015
Crop diversification	Cultivation of different crops at the same farm simultaneously	Erosion control, food, pollination, pest control, soil fertility	Cerda et al., 2017; Forrest et al., 2015; Lugnot and Martin, 2013
Crop rotation	Cultivation of different crops on the same plot of a farm sequentially, alternating through years	Erosion control, food, pollination, pest control, soil fertility	Andersson et al., 2014; Diekötter et al., 2010; Scullion et al., 2002
Drip irrigation	Micro-irrigation directly in the area where each plant is located	Food, pollination	Julier and Roulston, 2009
Fallow	Plot of the farm left uncultivated for a year. This plot is rotated sequentially	Food, soil fertility	Liu et al., 2012, Torquebiau et al., 2012
Light tillage	Reduction in the frequency of tillage practices, and minimization of tillage depth	Erosion control, food, pollination, pest control, soil fertility	Degrune et al., 2017; Almagro et al., 2013; Kuntz et al., 2013
Nest-boxes for insects	Installation of boxes filled with sticks, pinecones, etc. to facilitate the creation of nesting sites by insects	Pest control	Thoming and Knudsen, 2021
No/natural fertilizers	Use of fertilizers allowed under certificated organic agriculture, or even no application of any fertilizer	Erosion control, food, pollination, pest control, soil fertility	Andersson et al., 2014; Birkhofer et al., 2008; Birkhofer et al., 2016
No/natural herbicides	Use of herbicides allowed under certificated organic agriculture, or even no application of any herbicide	Erosion control, food, pollination, pest control, soil fertility	Bonanomi et al., 2016; Diekötter et al., 2016; Holzschuh et al., 2008
No/natural pesticides	Use of pesticides allowed under certificated organic agriculture, or even no application of any pesticide	Erosion control, food, pollination, pest control, soil fertility	Bianchi et al., 2013; Holzschuh et al., 2008; Kremer and Hezel, 2013
Other	Free listing		

specimens that fell in the traps, and we stored them in 70 % alcohol. Finally, we dried and pinned the bees that fell on the pan trap stations (Hevia et al., 2016; Lebuhn et al., 2016; Westphal et al., 2008). The bees were identified to the species level by an expert taxonomist. The sampling of bees was carried out in 2019 only.

2.5. Provisioning and cultural ES: Collection of data from interviews

We included three questions in the interviews as indicators of the supply of three provisioning ES. Two questions were related to the provision of the food and gene pool: "*How many different crops do you grow at this farm?*" and "*Do you grow any traditional variety at this farm? Could you list them?*". The third question was related to the provisioning of natural medicines: "*Do you grow any medicinal plant at this farm? Could you list them?*" (Table 2).

We included three qualitative questions in the interviews as indicators of four cultural ES: "*Do you exchange any traditional variety with other farmers?*"; "*Do you receive visits to the farm? For what purpose? Could you list them?"; and "For what reasons do you interact with other farmers? Could you list them?*". The first question was related to local ecological knowledge, the second to recreation and/or environmental education, and the third to cultural identity and local ecological knowledge (Table 2). The answers given to the last two questions were categorised to simplify the analyses.

2.6. Statistical analyses

We performed a Mann-Whitney test to explore the differences between the number of agroecological practices applied by agroecological and conventional farmers. Then, we calculated the percentage of farmers applying each practice and, for each practice, we calculated the percentage of farmers that linked them to the supply of specific ES.

To explore the relationships among our results for provisioning and regulating ES indicators and the application index of each practice (Supplementary data: Appendix C), we performed a redundancy analysis (RDA). We used the indexes of the practices as explanatory variables and the results on ES indicators as response variables. For cases where we had two sampling periods (2019 and 2020) (Supplementary data: Appendix B), we calculated the mean value of the two years for each biophysical indicator and farm to perform our statistical analysis with sufficient data.

We conducted generalized linear mixed models (GLM model) to explore the effect of management type (agroecological or conventional) on each of the regulating ES indicators (as response variables) assessed using an F test. We set the type of management (agroecological versus conventional) as a fixed effect, and the study area of the farm as a random effect, considering that the study area involves a multitude of biophysical dimensions, such as landscape, type of soil and surrounding vegetation.

Finally, to explore differences between agroecological and conventional farms regarding the indicators related to provisioning and cultural ES, we performed Mann-Whitney and Chi-Squared tests, respectively. All analyses were conducted in XlStat.

3. Results

3.1. Agroecological practices applied and reasons for their application

We found statistically significant differences between the two management types regarding the number of agroecological practices applied (Mann-Whitney test: $U = 133.5$, P-value < 0.001). Agroecological farmers applied an average of nine practices (out of the 13 we asked about), and every practice was applied by at least one agroecological farmer (Fig. 2). Conventional farmers applied an average of four agroecological practices, with eight of the 13 practices being applied by at least one conventional farmer. Every agroecological farmer used organic inputs or no external inputs, and practiced crop diversification. Other practices frequently used by agroecological farmers were crop rotation, reduced tillage and growing aromatic plants. All of the conventional farmers performed crop rotation on their farms, and the most frequently applied practices were fallow, crop diversification, and use of organic herbicides or elimination of the use of herbicides (Fig. 2). Some other practices were stated during the interviews, but none of them was being applied by more than one farmer, so we did not include these in the

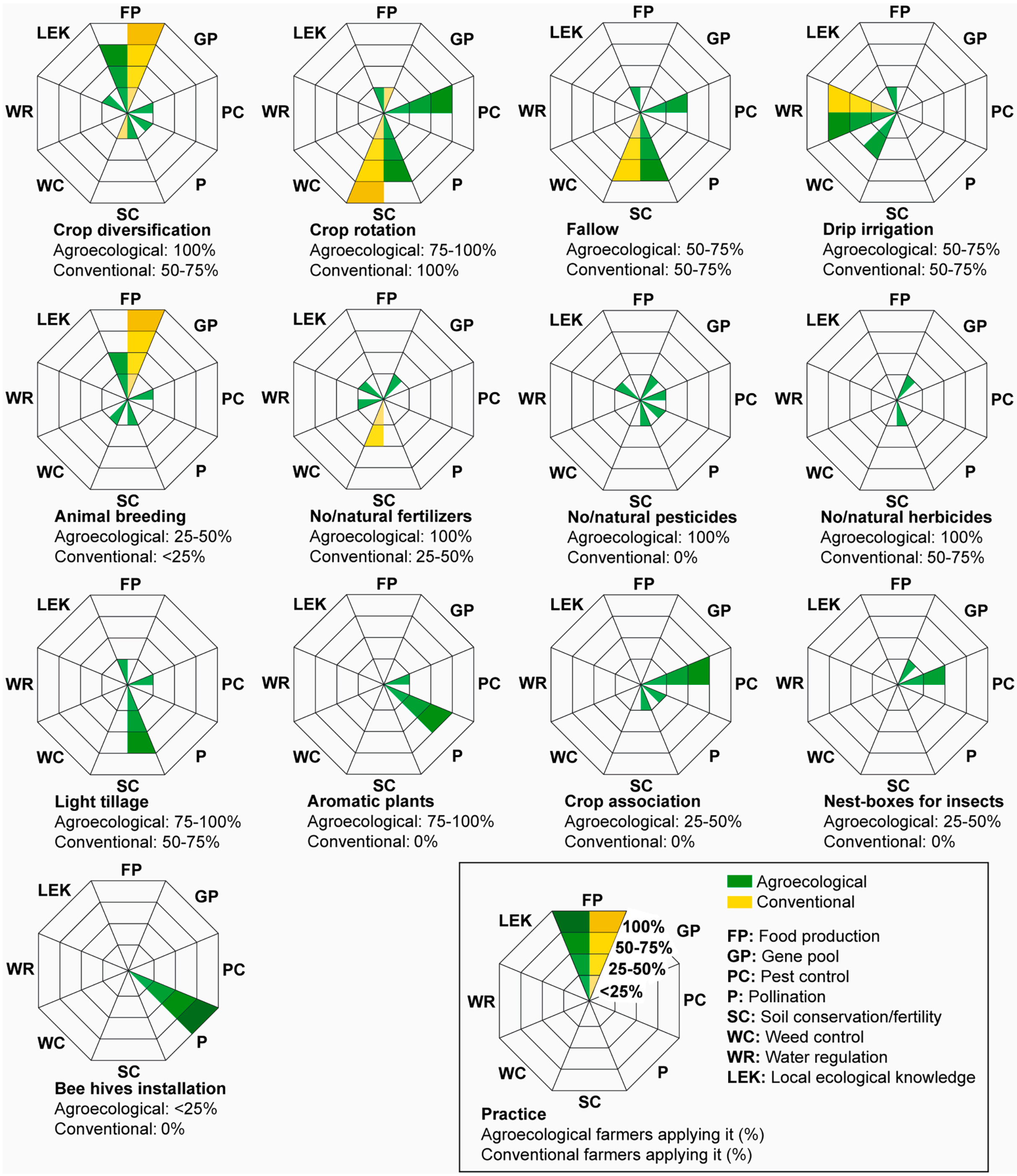

Fig. 2. Percentage of agroecological (green) and conventional (yellow) farmers applying agroecological practices, and reasons given for its application (we only included reasons aimed to enhance ES). For example, between 75 and 100 % of agroecological farmers grow aromatic plants; between 50 and 75 % of them did it to increase pollination, whereas < 25 % of them did it to enhance pest control.

analyses.

The reasons given for applying each practice differed widely between the two types of farmers. In general, agroecological farmers referred to a wider range of ES to justify the use of agroecological practices. In particular, agroecological farmers linked the application of agroecological practices to the fostering of eight ES: food production, gene pool, pest control, pollination, soil conservation/fertility, weed control, water regulation and local ecological knowledge. In comparison, conventional farmers linked the application of agroecological practices to the fostering of three ES: food production, soil conservation/fertility and water regulation. Considering the answers given by both types of farmers, crop diversification and animal breeding were mainly applied to enhance food production; crop rotation and crop association were mainly applied to enhance pest control; cropping aromatic plants and installing beehives were mainly applied to enhance pollination; crop rotation, fallow and light tillage were mainly applied to enhance soil conservation; and drip irrigation was mainly applied to enhance water regulation (Fig. 2).

3.2. Effect of practices and management type on regulating ES

RDA revealed that the relationships between practices and regulating ES indicators were mainly related to soil and biodiversity conservation. The first three axes of the RDA explained 66.95 % of variance. The first axis explained 37.33 % of variance, and was related to soil conservation. The second axis explained 16.45 % of variance and was linked to pest control. The third axis explained 13.17 % of variance and was associated to pollination. Positive scores on the first axis showed that indicators related to soil fertility (N, OM, P, and K) and the presence of *Macrolophus* were associated to the application of light tillage, fallow periods, use of organic inputs or no inputs, exclusion of chemical inputs, crop diversification, presence of nest boxes for insects and growing aromatic plants (Fig. 3; Supplementary data: Appendix E). The second axis showed, on the positive scores, an association between the degree of red spider mite infestation and the presence of *Macrolophus,* with the practices of light tillage, crop diversification, use of organic pesticides or no pesticides, presence of nest boxes for insects and drip irrigation (Fig. 3; Supplementary data: Appendix E). The positive scores on the third axis showed that light tillage, fallow, use of organic fertilizers and pesticides or none at all and animal breeding were associated to wild bee diversity (Fig. 3; Supplementary data: Appendix E).

GLM models showed that the degree of red spider mite infestation and the presence of *Macrolophus* were significantly higher on agroecological farms (GLM model, respectively: F = 8.664, *P*-value = 0.008; F = 6.882, *P*-value = 0.02), whereas the presence of *Tuta absoluta* was higher in conventional farms (GLM model: F = 22.483, *P*-value < 0.001). Soil stability class and wild bee diversity were marginally higher on agroecological farms (GLM model, respectively: F = 4.222, *P*-value = 0.05; F = 3.378, *P*-value = 0.08). Except for the stabilisation factor (*S*) and decomposition rate (*k*), all other indicators were higher, although not significantly, on agroecological farms (Table 4). The study area where farms were located had no significant effect on any of the models.

3.3. Effects of management type on provisioning and cultural ES

More provisioning and cultural ES were found on agroecological farms compared to conventional farms. The number of crops grown at the farm was significantly higher on agroecological farms (Mann-Whitney test: U = 133.5, *P*-value < 0.001). Although the average number of traditional varieties grown was higher on agroecological farms, we found no statistically significant differences (Mann-Whitney test: U = 96.5, *P*-value = 0.15). The number of medicinal plants grown

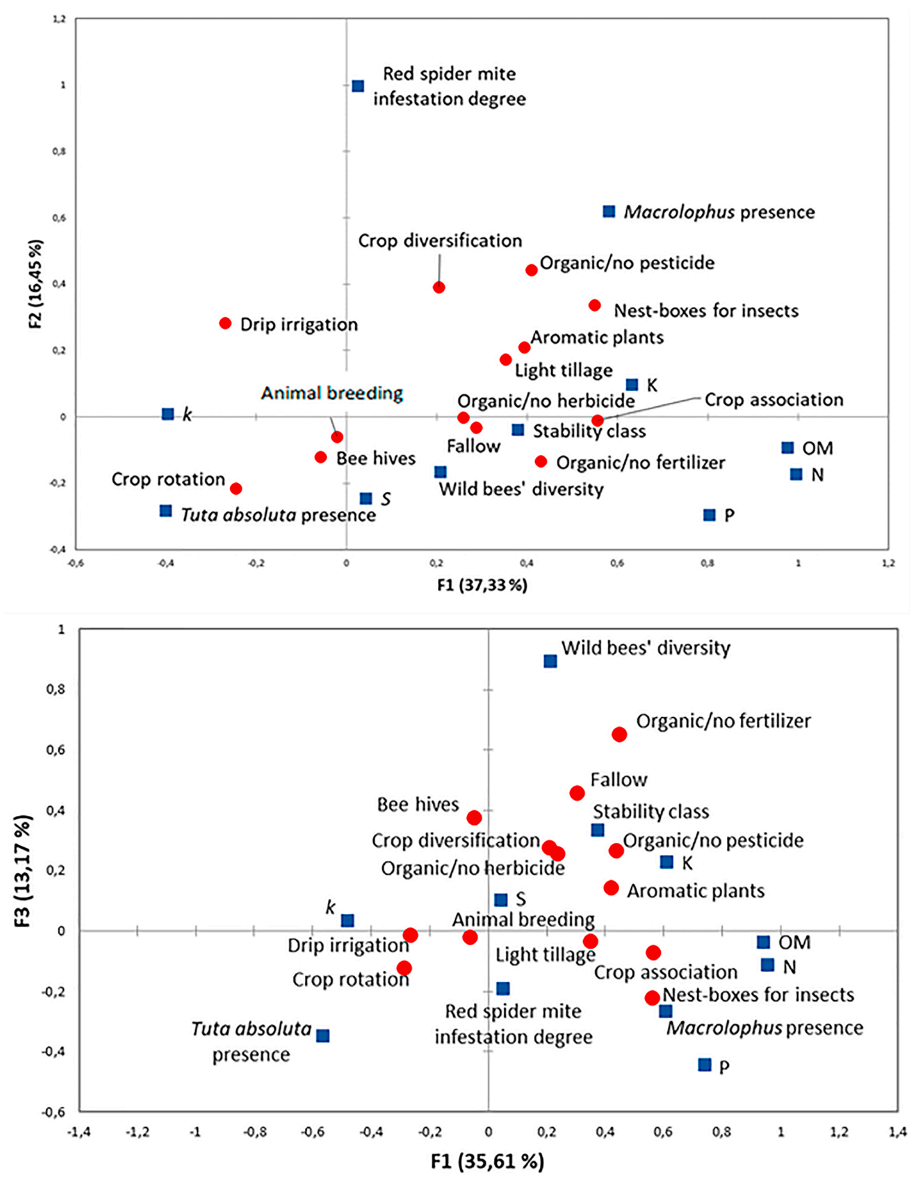

Fig. 3. Biplots resulting from redundancy analysis (RDA) performed to uncover the associations between agroecological practices (index) applied by farmers (red circles) and the indicators of regulating services (blue squares). Biplots for F1 and F2 (top) and F1 and F3 (bottom) are shown.

Table 4
GLM models analysing the differences between agroecological and conventional farms (explanatory variables) in the indicators of regulating ES (response variables). Mean values, and standard deviation for agroecological and conventional farms, F test, and p-values for each model are presented. Values in bold are significant (p-value < 0.05) or marginally significant (p-value < 0.1). Each row presents one GLM model.

	Agroecological		Conventional			
Indicator	**Mean**	**Std. deviation**	**Mean**	**Std. deviation**	**F test**	***P*-value**
N (%)	0.178	0.073	0.148	0.051	0.847	0.37
OM (%)	2.694	1.280	2.017	0.706	1.979	0.17
P (mg/kg)	70.808	52.950	66.545	45.983	0.033	0.86
K (mg/kg)	382.000	160.151	334.182	121.493	0.273	0.63
Stability class	3.175	0.825	2.441	0.994	4.222	**0.05**
S	0.222	0.161	0.319	0.145	2.438	0.13
k	0.013	0.005	0.017	0.015	1.470	0.24
Wild bee diversity (n species)	28.154	6.085	23.364	7.363	3.378	**0.08**
Red spider mite infestation degree	0.704	0.692	0.228	0.281	8.664	**0.008**
Macrolophus presence (n plants)	3.192	3.320	0.591	0.861	6.882	**0.02**
Tuta absoluta presence (n/trap)	42.236	21.098	81.773	38.903	22.483	**<0.001**

was significantly higher on agroecological farms (Mann-Whitney test: U = 106, *P*-value = 0.02) (Fig. 4); however, when asked about the reasons why they grew them, farmers stated it was to enhance pollination and pest control ES, not to obtain medicinal resources.

Although the number of traditional varieties grown by agroecological and conventional farmers did not noticeably differ, farmers exchanging traditional varieties with other farmers was significantly higher for agroecological farmers (Chi-Squared test: *P* -value = 0.02). The number of agroecological farmers receiving visits to their farms was significantly higher (Chi-Squared test: *P*-value = 0.004). Nevertheless, we found no significant difference between management types in the aims of the visits (Table 5). We found that relationships based on information exchange and collaboration were significantly higher for agroecological farmers (Chi-squared tests, respectively: *P*-value = 0.03; *P*-value = 0.003). In addition, agroecological farmers had a more collaborative relationship with other farmers when agreeing on using certain practices compared to conventional farmers (Chi-squared test: *P*-value = 0.09).

4. Discussion

4.1. Strengths and limitations of our study

Palomo-Campesino et al. (2018) found just 31 papers that have empirically analysed the effect of agroecological practices on the supply of ES on horticultural farms. Of these studies, just three assessed more than one ES on horticultural farms, and none assessed more than three ESs, with none evaluating cultural ES (Bonanomi et al., 2016; Kang et al., 2013; Sandhu et al., 2015). Thus, this study is the first to evaluate horticultural farms assessing multiple provisioning, regulating and cultural ES.

Most studies have focused on regulating and, to a lesser extent, provisioning ES when exploring the relationship between practices and ES (Brainard et al., 2016; Schipanski et al., 2014; Smith et al., 2008). These relationships are easily noticeable. For example, if floral margins are grown on a field to attract pollinators, pollination of crops could be improved, and crop production enhanced (Campbell et al., 2017; Grab et al., 2017). In contrast, studies reporting the relationship between agricultural practices and cultural ES are scarce (Calvet-Mir et al., 2012;

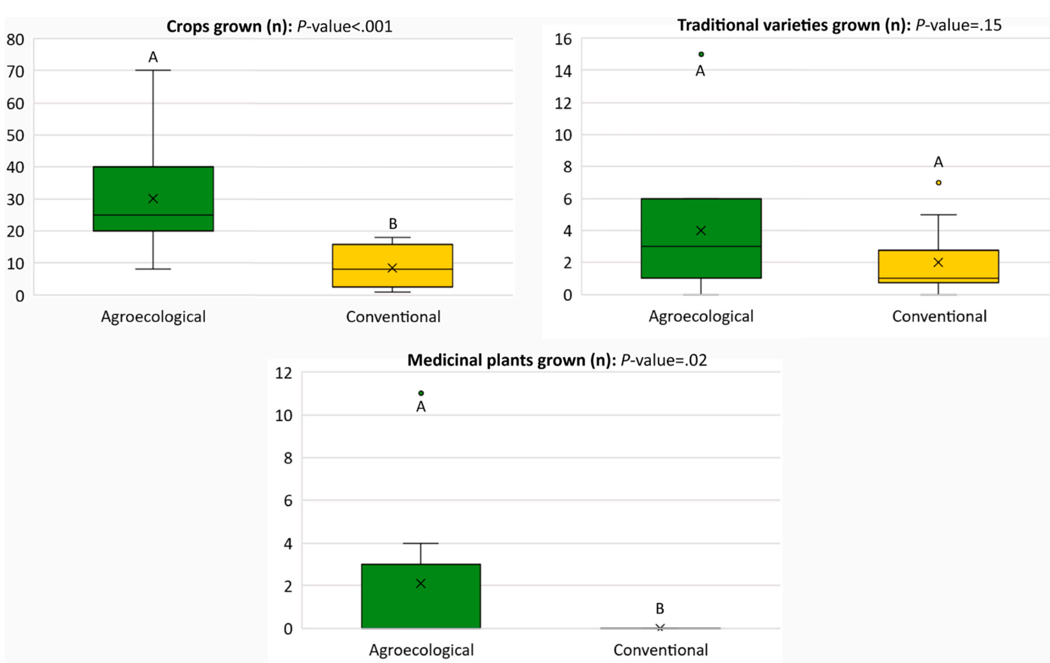

Fig. 4. Box plots of crops grown (top left), traditional varieties grown (top right), and medicinal plants grown (bottom) on agroecological (green) and conventional (yellow) farms. P-values of Mann-Whitney tests are given. Capital letters show whether management types are significantly different (different letter) or not (same letters) for the assessed indicators.

Table 5
Differences between agroecological and conventional farms based on the indicators of cultural ES evaluated through the interviews. We present the number of positive answers (yes) to each variable as percentages to facilitate interpretation. *P*-values were the result of Chi-Squared tests comparing the number of agroecological and conventional farmers who gave the same answers (yes/no). Values in bold are significant or marginally significant.

Indicator	Agroecological farmers (%)	Conventional farmers (%)	*P*-value
Exchange of traditional varieties	78	33	**0.02**
Receive visits to farms	73	10	**0.004**
-Environmental education for schools	9	10	0.31
- Raise awareness in the population	18	0	0.14
- Workshops	9	0	0.31
- Recreation	9	0	0.31
Type of interactions with other farmers			
- Information exchange	69	27	**0.03**
- Collaboration (help each other)	59	6	**0.003**
- Collaborate to agree on practices	25	3	**0.09**

Kaufman, 2015; Tekken et al., 2017). Cultural ES must be considered in agroecological studies, given their relevance to the social system encompassing the agroecosystem (Teixeira et al., 2018; Van Berkel and Verburg, 2014). Furthermore, cultural ESs are also related to certain agroecological practices, and the supply of other ESs. For instance, the local ecological knowledge of farmers is often decisive in choosing which floral margins should be grown on their farms (Elisante et al., 2019; Hevia et al., 2021). Similarly, collaborations between farmers could lead to joint decisions on floral margins, improving pollination services at the landscape scale (Stallman, 2011). Although we did not evaluate cultural ES in detail, we explored this dimension and, combined with the results of the interviews, we obtained a broad picture of the social dimension in our study areas. We found that agroecological farmers generally contributed to the supply of more ES through the practices that they apply, and that their motivations for applying agroecological practices were frequently linked to the objective of ecosystem conservation. Nevertheless, conventional farmers also showed some concern about the conservation of rural landscapes and communities, revealing an opportunity to bring both types of farmers closer, and foster an agroecological transition in the region (Palomo-Campesino et al., 2021).

We acknowledge that research based on experimental fields has several advantages, such as the ability to control every aspect of the application of a certain agricultural practice, generating conclusions that are more robust. However, agroecosystems are complex social-ecological systems, with their functioning depending on environmental variables (e.g. type of soil, weather, surrounding landscape), on the agricultural practices applied, and on the social components of the system (e.g. farmer associations, consumer demand, farmer motivations and perspectives). Research conducted in the field may be less accurate when compiling empirical data; however, it provides a better understanding of the complexity of the social-ecological system under study, which is extremely relevant for systems where "one-size-fits-all" solutions do not exist (Clermont-Dauphin et al., 2014; Duru et al. 2015b; Boeraeve et al., 2020). Assessing productive farms allowed us to uncover the actual situation on farms with different characteristics, and where practices are applied in very different ways. Our methodological approach, which combined biophysical sampling and interviews with farmers, brought us closer to the reality of conventional and agroecological horticultural farms of southeast Madrid, and allowed us to differentiate the profiles of each type of farmer, uncover their motivations and perspectives towards agriculture, and elucidate the reality of agroecology in the study area (Palomo-Campesino et al., 2021).

Notwithstanding, working on productive farms limited the number of farms that could be selected and the duration of our study, since increasing these parameters would have required more human resources. Thus, the low number of farms and replicates, added to the absence of control plots (which are standard for studies in experimental farms) and the existence of uncontrolled parameters (e.g., pedo-climatic or environmental conditions), might have influenced our results. All of these factors could explain some of our low significant results; however, the specific characteristics of agroecological and conventional farming on our study area might also have been a determinant.

Both types of farms were small sized (unusually exceeding 2 ha), which is frequently linked to more sustainable management strategies, such as the use of less fuel and less mechanization (Ebel, 2020). Indeed, the conventional horticultural farms selected for our study differed widely from the traditional, large and highly technologized, monocultures that we picture when thinking of conventional farming. We found that the horticultural conventional farms in our study area were mainly small, family operated, slightly diversified, and minimally mechanized, being closer to low-input farms than to intensified conventional farms. Larger conventional farmers tended to own several farm plots that were rotated each year, with each plot being small and minimally mechanized. In comparison, the agroecological farming system in our study area is relatively recent, and our selected farms had been under that type of management for an average of three years. Knowledge about the period of time required for the benefits of applying ecological-based agricultural practices to show is limited; for instance, some experts state that 10-years is required for the benefits produced by these systems to be detectable (Giller et al., 2009). Therefore, our findings of positive effects (though not always significant) of agroecological systems on the supply of ES in a very short time period is remarkable.

Acknowledging these limitations, we designed our research with the aim of having a broad overview of our study area. The fact that we assessed multiple agroecological practices, added to the absence of control plots, hampered the possibility of linking specific practices to the supply of specific ES. However, given that agroecosystems embrace numerous practices that can have synergic or offsetting effects on the supply of ES (Power, 2010), it was important to study the set of practices applied on farms, rather than focusing on the specific effect of one or two practices. Therefore, we selected 13 agroecological practices that had been previously associated to soil quality and biodiversity conservation. Since farmers added few new practices to the list, and those which were added were not applied by more than one farmer, we considered that the selected list of practices was representative of our study area. Further, we explored the supply of multiple ES and used several indicators for some. ES are the result of multiple synergic or offsetting socio-ecological processes; thus, different indicators might have different results for the same ES (Boeraeve et al., 2020; Teixeira et al., 2021). For example, we used three indicators to assess pest control ES. The degree of red spider mite infestation was higher on agroecological farms, whereas *Tuta absoluta* infestation was lower and *Macrolophus* presence was higher. If we had only assessed the degree of red spider mite infestation, the conclusions of our study would have been that the agroecological farms performed worse for pest control compared to conventional farms. Thus, to explore complex multi-dimensional socio-ecological systems (such as the agricultural systems), a broad set of methods and indicators could result in more accurate findings.

4.2. *Potential effects of agroecological farming on the supply of ES*

As hypothesized, our results showed that agroecological farmers applied more agroecological practices compared to conventional farmers, which increases the potential of agroecological farms for the supply of ES in our study area. Given the multiple definitions and interpretations of the term "agroecology" (Loconto and Fouilleux, 2019), defining the criteria for the selection of this type of farm was challenging. Therefore, we considered agroecological farms to be those defined as such by their farmers, a decision that also informs us on how agroecology is perceived in our study area.

Since our results and the HCA (see Supplementary data: Appendix A) highlight the striking differences in the number of agroecological practices applied by agroecological and conventional farmers, we concluded that the farm selection process was accurate, and provides us with two well differentiated systems to compare. Of note, agroecological farmers generally aim to improve several ES with each practice, whereas conventional farmers mainly focus on soil conservation and food production, rather than biodiversity-based services, such as pollination and pest control. Consequently, the interviewed agroecological farmers had a more holistic vision of the agroecosystem compared to conventional farmers. Previous studies stated that this holistic vision and knowledge of existing ecological networks within an agroecosystem (e.g., prey-predator dynamics, nutrient cycles) are necessary to apply various agroecological practices (Gaba et al., 2018; Gage and Schwartz-Lazaro, 2019; Lescourret et al., 2016).

Regarding the potential effect of agroecological farming on the supply of ES, we found positive results for regulating, provisioning and cultural ES. For regulating services, we found that pest control and, to a lesser extent, pollination and erosion control may be enhanced under agroecological management. In addition, and supporting previous studies (Birkhofer et al., 2008; Kuntz et al., 2013; Lugnot and Martin, 2013; Torquebieau et al., 2014), RDA showed positive relationships between the application of agroecological practices related to soil conservation (such as light tillage, fallow periods, use of organic or no use of fertilizers, and crop diversification) with the enhancement of soil fertility indicators (such as nitrogen, organic material, phosphorous and potassium on soil). We also found evidence of a positive relationship for practices intended to promote insects (such as the use of organic herbicides and pesticides or no use at all, crop diversification, nest-boxes for insects, and growing aromatic plants) with the presence of *Macrolophus,* a pest control indicator (Lugnot and Martin, 2013; Gill et al., 2014; Diekötter et al., 2016; Thoming and Knudsen, 2021). The fact that many species of wild bees nest on soils (Antoine and Forrest, 2020; Michener, 2007) might explain the association found between soil conservation practices and wild bee diversity. The lack of significant results for soil fertility indicators might be attributed to some agroecological farms from our sample only operating for a few years on average and/or to our small sample of farms. The Tea Bag Index results were difficult to interpret because, during the three month burial periods, the workers on some farms ploughed the soil, which unintentionally removed the teabags on some occasions, and lowered the number of samples.

Analysis of the interviews also showed that agroecological farms have a greater potential for the supply of provisioning ES. Opponents of agroecology often argue that only agroecosystems using intensive practices or high technology are capable of addressing the food demand of the global population (Borlaug, 2000; Tester and Langridge, 2010). Conversely, other authors showed that agroecological and other types of sustainable farming produce more food compared to conventional systems (Badgley et al., 2007; Pretty et al., 2011). Although we did not assess the supply of food in terms of crop production, we found that agroecological systems supply a wider variety of crops, which is essential for providing a healthy nutrition to the population (FAO, 2018).

Regarding cultural ES, we found that agroecological farmers received more visits to their farms; however, we did not find enough evidence to show that these visits contribute towards enhancing environmental education and recreation. Agroecological farmers significantly exchanged more traditional varieties and information with other farmers compared to conventional farmers. Thus, agroecological farmers contributed more towards maintaining local ecological knowledge and cultural identity. Of importance, agroecological farmers generally talked to other farmers to agree on best practices, as some ES (e.g. pollination) are greatly enhanced at the landscape scale, which can only be achieved through collaborative interventions among farmers (Stallman, 2011).

4.3. Implications for agroecological transition and perspectives for further research

Agriculture based on agroecological principles is key to slowing down the process of global change. Agroecology increases the diversity and supply of ES. In contrast to the systemic habitat destruction caused by industrialized agriculture, agroecological farmers adapt their practices to the landscape (Kmoch et al., 2018; Schoonhoven and Runhaar, 2018). Agroecological systems are essential to reconnect people with nature, and are key to providing accessible, healthy and affordable food to the global population (Altieri and Nicholls, 2020; Jumba et al., 2020). The Covid-19 crisis has clearly demonstrated how global functioning can change within weeks, and demonstrated the fragility of the productive sector in many countries (Altieri and Nicholls, 2020). Thus, now more than ever, the agricultural sector must be reviewed. Many economic, political and administrative barriers hinder the spread of agroecology (Dendoncker et al., 2018); however, a crisis like the one we are currently living through might be an inflection point, so it is time to urge decision makers to start the change.

Within this framework, several public policies recently started to promote sustainable agriculture and agroecology, such as the EU Common Agricultural Policy (CAP), European Green Deal, and Farm to Fork Strategy. Agri-environmental measures and future CAP Eco-Schemes allocate a proportion of payments to practices that could directly benefit the environment and climate. Therefore, studies providing evidence of the effect of certain agricultural practices on the supply of ES could be crucial in the design of new Eco-Schemes at a national scale. The ongoing CAP reform also aims to incorporate the sustainability ambitions of the European Green Deal. The European Green Deal was launched in December 2019, and aims to attain net zero greenhouse gas emissions by 2050 within the EU (Haines and Scheelbeek, 2020). The Farm to Fork Strategy was launched in May 2020, and is a broad approach to accelerate the achievement of a sustainable and healthy food system across Europe (Mowlds, 2020). At the global scale, the FAO's Scaling Up Agroecology Initiative aims to foster the transition of agroecosystems to agroecological systems to meet the Sustainable Development Goals of the 2030 Agenda. One of the goals of this initiative is to gather context-specific scientific evidence on agroecology, to identify what is needed to develop strategies to scale up agroecology (FAO, 2018). Although the agroecological transition must be a global process, it will only be achieved by adapting agroecology to each specific local context. Local, national and international policies are required for a coherent spread of agroecology across territories.

We shared our results with the farmers who participated in the study in the form of a document providing the results for their farms compared with the average data of all assessed farms. We provided explanations to help them understand the implications of the results, and some recommendations to improve the supply of ES with agroecological practices. Each farmer received a personalised report with the results from their farm (see Supplementary data: Appendix F for an example of the document we shared with one of the farmers). This knowledge exchange might serve as an incentive for conventional farmers to start the transition to adopt new agroecological practices on their farms. We found that agroecology is relatively recent in our study area, with agroecological farmers continuously learning how to improve their practices (Palomo-Campesino et al., 2021). Despite the significantly lower adoption of agroecological practices by conventional farmers compared to agroecological farmers, they were concerned about soil conservation and maintaining agricultural traditions. This motivation represents an opportunity for agroecology to spread and could be fostered if local and national institutions promote agroecological practices through innovative agroecological extension services and the development of appropriate policy regulations.

5. Conclusions

By assessing multiple biophysical indicators on productive farms, and performing semi-structured interviews with horticultural farmers, we showed the potential of agroecological practices to enhance the supply of provisioning, regulating and cultural ES. Agroecological farmers applied more agroecological practices compared to conventional farmers, which enhanced important ES, such as soil erosion control, pollination, pest control, food diversity, local ecological knowledge and cultural identity. Our results provide empirical evidence of the benefits of applying agroecological practices on horticultural farms, which is extremely relevant for promoting agroecology in the context of the ongoing reforms in European Agricultural Policies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Supplementary data

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