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Greenhouse gas emissions from Mediterranean agriculture: Evidence of unbalanced research efforts and knowledge gaps

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ABSTRACT

Designing effective mitigation policies for greenhouse gas (GHG) emissions from agriculture requires understanding the mechanisms by which management practices affect emissions in different agroclimatic conditions. Agricultural GHG emissions and carbon sequestration potentials have been extensively studied in the Mediterranean biome, which is a biodiversity hot spot that is highly vulnerable to environmental changes. However, the absolute magnitude of GHG emissions and the extent to which research efforts match these emissions in each production system, are unknown. Here, we estimated GHG emissions and potential carbon sinks associated with crop and livestock production systems in the Mediterranean biome, covering 31 countries and assessing approximately 10,000 emission items. The results were then combined with a bibliometric assessment of 797 research publications to compare emissions estimates obtained with research efforts for each of the studied items. Although the magnitude of GHG emissions from crop production and the associated carbon sequestration potential (261 Tg CO_2eq yr^{-1}) were nearly half of those from livestock production (367 Tg CO_2eq yr^{-1}), mitigation research efforts were largely focused on the former. As a result, the relative research intensity, which relates the number of publications to the magnitude of emissions, is nearly one order of magnitude higher for crop production than for livestock production (2.6 and 0.4 papers Tg CO_2eq^{-1}, respectively). Moreover, this mismatch is even higher when crop and livestock types are studied separately, which indicates major research gaps associated with grassland and many strategic crop types, such as fruit tree orchards, fiber crops, roots and tubers. Most life cycle assessment studies do not consider carbon sequestration, although this single process has the highest magnitude in terms of annual CO_2eq. In addition, these studies employ Tier 1 IPCC factors, which are not suited for use in Mediterranean environments. Our analytical results show that a strategic plan is required to extend on-site field GHG measurements to the Mediterranean biome. Such a plan needs to be cocreated among stakeholders and should be based on refocusing research efforts to GHG balance components that have been afforded less attention. In addition, the outcomes of Mediterranean field studies should be integrated into life cycle assessment-based carbon footprint analyses in order to avoid misleading conclusions.

1. Introduction

Agriculture is an important source of greenhouse gas (GHG) emissions globally, not only because of its direct contribution to methane (CH_4) and nitrous oxide (N_2O) emissions but also because of emissions associated with land use change, industry, and transport (through inputs such as fertilizers, pesticides, fuel, electricity, and machinery). Knowledge about GHG emission patterns in agriculture has advanced enormously in recent decades, and the associated publication rate has increased exponentially (Aleixandre-Benavent et al., 2017). In addition, numerous global syntheses have compared conventional production with alternative production methods that could help mitigate emissions, such as organic farming (Gattinger et al., 2012; Muller et al., 2017; Poore and Nemecek, 2018; Skinner et al., 2014) or conservation agriculture (Antle and Ogle, 2012; van Kessel et al., 2013). However, the reviews above also report wide variabilities in the systems studied owing

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to their great complexities, diverse real-world situations, and use of different methodologies to conduct evaluations. Consequently, these studies show the need to conduct specific analyses in each agroclimatic region, as many of the results cannot be extrapolated to different conditions.

The Mediterranean biome is found in the Mediterranean basin and in four other areas globally, covering an area of 326 Mha (Table S1). Approximately 310 million people live within the biome, and its population density is approximately double that of the world average (Table S2). It holds 6.6% of the global cropland area and 3.7% of the grassland area in only 2.5% of the total global land area (Table S2). In addition, many characteristic crop types are cultivated within the biome, such as olives (88% of the total global olive growing area), almonds (81%), and grapes (44%), although the dominant crops are wheat (30% of Mediterranean cropland and 10% of the global wheat area) and barley (17% and 26%, respectively) (Table S3). Agriculture within the Mediterranean biome is highly vulnerable and is already impacted by climate change and other global change processes (Aguilera et al., 2020a; Cramer et al., 2018; Malek et al., 2018; MedECC, 2019). However, it is also an important source of GHG emissions (Sanz-Cobena et al., 2017). Winters are typically mild and humid and summers are hot and dry (Aschmann, 1973), and this type of climate influences not only the productivity and varieties of crops and livestock production systems but also the GHG emissions, which are shaped by the soil biogeochemical processes and the specific inputs. Recent meta-analyses under Mediterranean conditions have shown well-defined N_2O emission patterns, that vary depending on the water management system and type of fertilizer used (Cayuela et al., 2017), and large changes in soil organic carbon (SOC) have been shown to occur with differing management practices (Aguilera et al., 2013a; Morugán-Coronado et al., 2020; Vicente-Vicente et al., 2016). However, less research has focused on other key processes, such as GHG emissions from livestock production, and a quantitative synthesis of information has not been obtained to date (Aguilera et al., 2020a). In addition, research gaps have not been identified, which makes it difficult for researchers to select the most urgent subjects to investigate to facilitate climate change mitigation efforts.

In the present study, our aim was to provide an analysis to address the challenges mentioned above through an assessment of GHG emissions and potential C sequestration associated with Mediterranean agriculture at the biome scale. In order to identify the research gaps, we also quantified the results published research examining such emissions. The two datasets (emissions and publications) were then combined to assess the quantity of research (classified by quality classes) against the magnitude of emissions or sequestration potential of each process and emission type. This procedure allows identifying the components of the GHG budget in Mediterranean agricultural systems that have attracted considerable research attention, as well as the emission hotspots. This way of addressing gaps in research could enable the design and implementation of policy actions that adequately address persistent challenges, such as environmental problems associated with food production systems, in the present case.

2. Methods

2.1. Overview of methods employed and study area

To determine the amount of emissions and potential soil C sinks occurring under a Mediterranean climate, we first gathered emission data (or estimated emissions) for the year 2010 in all countries with land areas greater than 10,000 ha (31 countries, Table S1) and then used spatially explicit datasets to estimate the share of each emission type. Mediterranean climate areas were defined according to the boundaries of the Mediterranean biome reported in the Global 200 assessment (Olson et al., 2001). We also included the Central Valley of California because it has a Mediterranean climate, although it was excluded from the Global 200 Mediterranean biome (Fig. 2). The population living in the Mediterranean biome was calculated by combining this map with a population distribution database (CIESIN, 2016) and population by country data (OECD, 2019) (Table S2). All calculations were made in R version 4.0.3 with RStudio version 1.2.1093, and the codes and relevant data are available from the authors upon request. Data processing and plotting were conducted with the R library Tidyverse (Wickham et al., 2019). Geoprocessing operations were performed using R packages raster (Hijmans, 2020) and sf (Pebesma, 2018). World maps were obtained from the NaturalEarth database using the R package rnaturalearth (South, 2017).

To enable comparisons between bibliometric data and data on estimated emissions and potential sequestration levels within Mediterranean climate areas, a “research intensity” indicator was constructed for the number of articles published per teragram ($Tg = 10^{12}$ g) of annual CO_2 equivalent (CO_2eq) quantified in each of the categories defined in section 2.2. The GHG emissions assessed included biogenic agricultural emissions from the soil, animals, and manure in addition to energy-related emissions and life cycle emissions from industrial inputs, which were grouped into the “inputs” category. We also included soil carbon (C) sequestration in the total GHG emission budget. For life cycle assessments (LCAs), the number of studies was compared with the emissions associated with inputs; however, biogenic emissions and C sequestration from the total C footprint were discounted, as these emissions were already studied in relation to their corresponding indicators.

2.2. Compilation and classification of studies

A bibliographic search was conducted through the Web of Science database, and the search criteria included all works published until 2017 and relating to GHG emissions from crops, pastures, and animal husbandry in areas with a Mediterranean climate. In the first step, several keywords were inputted in the search engine. See Supplementary Materials for a full description of the terms employed and the full list of references. The results were then searched for papers that met the search criteria, and these papers were then included in the database. The second step involved screening the reference lists of papers to find additional papers meeting our selection criteria. The full bibliometric dataset is provided in Table S5.

Table 1 summarizes studies according to the type of production, emissions, accounting method used, and study type. Studies in which estimates were made using more than one method were classified by the most accurate method employed. Studies covering more than one category were included in each category: for example, an LCA could include a Tier 1 estimation of N_2O emissions and a Tier 3 estimation of SOC sequestration, or it could even include more than one crop or animal type. Some studies included several crops with respect to one rotation but not separate data for each one. This was the case for most studies on C sequestration in herbaceous cropping systems and for some studies on N_2O and some LCAs. In the case of C sequestration, studies were included in all corresponding categories under the assumption that it is not possible to conduct specific studies of each crop in long-term experiments in which the unit of analysis is rotation as a whole and not the crop species. However, N_2O and LCA studies were only classified into categories for which they offered specific data. GHG accounting methodologies were classified by accuracy and relevance level in a hierarchical way, based on the IPCC-tiered approach (IPCC, 2006).

2.3. Farm greenhouse gas emissions

GHG emissions from agriculture in Mediterranean areas occurring in around the year 2010 were retrieved from several sources. We applied 100-yr global warming potentials (GWPs) that included climate feedbacks from the IPCC (IPCC, 2014) to convert N_2O emissions ($GWP = 298$) and CH_4 emissions ($GWP = 34$) to CO_2eq. When possible, we used

Table 1
Classification of reviewed studies.

Categories	Sub-categories	Description/Clarifications
Production	See correspondence with FAOSTAT categories in Table S6	"Green fodder" category includes all herbaceous crops harvested for biomass (generally green) and used as fodder or energy. This can include cover crops when they are studied specifically. The "grassland" category covers treeless and wooded pastures (such as dehesa) as well as scrublands when grazing is reported.
Emissions	Direct soil N_2O Soil CH_4 SOC Enteric CH_4	Our analysis is not exhaustive. Some emission sources are excluded for simplification, such as the burning of residues and savanna, emissions from organic soils (which are very scarce under Mediterranean conditions), carbon storage in biomass of woody perennial crops, and indirect N_2O emissions.
	Manure management	Includes studies reporting CH_4 and/or N_2O emissions.
	Inputs	Includes (i) direct emissions from energy use, (ii) manufacture and transport emissions, and (iii) emissions from infrastructure construction and maintenance.
GHG accounting methods	Tier 1	Default IPCC method with a global general factor.
	Tier 2	Region-specific factors are applied using the same equations as in Tier 1.
	Tier 3	Includes more detailed estimations usually based on process-based modeling.
	High-quality	Studies in which GHG emissions are measured in the field. The "Inputs" emission category includes LCAs, and the "SOC" category includes studies in which SOC was measured in differentiated treatments in experiments spanning 10 or more years.
	Other measurements	Studies conducting measurements in the following situations: (i) mesocosm conditions; (ii) CH_4 in upland soils; (iii) farm-level emission measurements in livestock farms (not distinguishing enteric CH_4 emissions from manure management emissions); (iv) experiments spanning <3 years that measure SOC or CO_2 fluxes from the soil or agroecosystems.
	SOC 3–10 years	Studies in which SOC is measured under different treatments over 3–10 years.
	Repeated	In cases where long-term experiments on SOC data were conducted, and the results were reported by more than one study, all the studies but the last one were included in this category.
	Review	Includes meta-analyses and descriptive reviews.
Management	Organic	Treatments that comply with organic farming regulations.
	Conventional	All non-organic treatments, even those that include practices that are usually applied in organic farming.
Study type	Trials	Randomized field experiments.
	Farms	Studies conducted in real commercial farms.
	Mesocosm	Experiments conducted under controlled environments simulating Mediterranean conditions.

GHG, greenhouse gas; SOC, soil organic carbon; LCA, life cycle assessments.

data of 2008–2010 average emissions from the FAOSTAT GHG emissions database (FAO, 2019), and soil CH_4 emissions, manure management, and enteric fermentation emissions were also obtained from this source. Following other studies (Bennetzen et al., 2016; Pellegrini and Fernández, 2018), we assumed that diesel and gasoline were used for crop production and all other fuels (natural gas, liquefied petroleum gas, fuel oil, coal and biomass) were used in livestock production. FAOSTAT data on fuels allocated to livestock were discarded because they had already been accounted for in the input emission factors that we used for livestock. Soil N_2O emissions reported by FAOSTAT were corrected using Mediterranean region-specific N_2O average emission factors (N_2O-N N applied^{-1}) of 0.5% for synthetic fertilizers and 0.5% for organic fertilizers (based on the average of organic solid and organic liquid) (Cayuela et al., 2017). As FAOSTAT data are limited to a small number of crops, data for crop residues were estimated by calculating the residue and root production in terms of N and then subtracting 50% of the aboveground residue biomass, which was assumed to be either harvested or burned and therefore not applied to soil. We applied the harvest index and dry mass content coefficients (Table S7) to FAOSTAT Commodity Balances production data to estimate total aboveground production. In addition, we applied root:shoot ratios (Table S7) to the aboveground biomass data to calculate belowground biomass. The N content per unit dry biomass coefficient (Table S7) was applied to aboveground and belowground residues to estimate residue and root N production and soil N inputs. A direct N_2O emission factor of 0.18% was applied to crop residues based on organic fertilizers under Mediterranean conditions (Cayuela et al., 2017). Indirect N_2O emissions were not included in the assessment, due to the inherent uncertainty derived from the complexity of their assessment. Given that the calculation of these emissions involves at least two steps (quantification of NH_3 and NO_3^- losses and emissions of N_2O derived from these compounds), it is not straightforward to classify papers addressing these emissions.

2.4. Emissions from energy use and input production

Direct emissions from energy use were estimated using energy use data from FAOSTAT. The values were multiplied by CO_2, CH_4, and N_2O emission factors associated with mobile combustion (diesel and gasoline) and stationary combustion (coal) in agriculture obtained from the IPCC (Eggleston et al., 2006), to obtain total GHG emissions. Input production emissions were estimated by multiplying the input use activity data reported in FAOSTAT (fuels, electricity, fertilizers, and pesticides) by the LCA emission factors obtained from various sources.

Emissions associated with synthetic fertilizer (N, P, and K) manufacturing as well as with soil N_2O owing to synthetic N fertilizer application were determined for crops based on various sources. The main source was a global, spatially explicit, five-by-five minute resolution (~10 km × 10 km at the equator) database that includes 17 major crops (Mueller et al., 2012). Data for these crops were then aggregated into several categories (Table S6). For the crop categories in which no data were available, the database was complemented by Spanish-specific application rates for olives, tree nuts, fruits, citrus, grapevines, pulses, and vegetables (Alonso and Guzmán, 2010) as well as the averages for all-crops (other crops and green fodder). These data were expressed as yield-scaled nutrient application rates per crop and country, and they were then scaled to match the total nutrient application per country, as reported by FAOSTAT (FAO, 2019). To account for the different emission factors of various fertilizer types, we used the FAOSTAT "Fertilizers by Product" dataset. Nutrient application values in this dataset were scaled to match the "Fertilizers by Nutrient" totals; however, although these were considered to be more reliable, they did not differentiate between fertilizer types. Pesticides were assumed to be applied to crops based on the relative N application rates. The emission factors for fertilizers and pesticides were obtained from the Ecoinvent 3.5 database (Wernet et al., 2016) using SimaPro software.

Electricity production-related emissions were estimated based on the average electricity mix of each country during 2008–2012 (World Bank, 2019) (Table S8). Electricity production emission factors at the farm gate were primarily obtained from Ecoinvent (Wernet et al., 2016), which mainly provides global factors but distinguishes specific factors for some countries in relation to solar and coal-based electricity. Hydroelectricity emission factors were complemented using estimations of reservoir emissions (Li and Zhang, 2014), and nuclear energy emission factors were obtained from Lenzen (2008) and Sovacool (2008). Electricity distribution losses were assumed to be 8% (Aguilera et al., 2015b), and it was assumed that all agricultural electricity was used for irrigation.

Emissions from irrigation infrastructure and waterbodies were estimated using total irrigated area data by country from FAOSTAT (FAO, 2019) "Land area equipped for irrigation". Shares of irrigated area per irrigation system (drip, sprinkler or surface) and per source (surface, groundwater or wastewater) in each country were calculated using data obtained from AQUASTAT (FAO-AQUASTAT, 2021). In the case of Spain, the irrigation system data was obtained from Aguilera et al. (2018) and the irrigation source data from INE (2008). The average of all Mediterranean countries was used in the remaining countries in which this information was not available. The resulting shares of irrigation systems are shown in Table S9, and the area irrigated with surface water in Table S10. The emission factors per unit area of each irrigation system were obtained from Lal (2004). Methane emissions from irrigation waterbodies were calculated by multiplying the area irrigated with surface water in each country by the average CH_4 emissions per unit area irrigated with surface water (1.16 Mg CO_2eq ha^{-1} yr^{-1}) calculated in by Aguilera et al. (2019). Electricity, irrigation infrastructure and irrigation waterbodies emissions were distributed among crops based on shares of irrigated areas per crop calculated using total cultivated area data from FAOSTAT (FAO, 2019) and irrigated area data per crop from AQUASTAT (FAO-AQUASTAT, 2021). The missing data were estimated based on the average share of irrigated area per crop of all Mediterranean countries. In the case of woody crops in California, we gathered the area data from Johnson and Cody (2015). The resulting irrigation shares per crop in each country are shown in Table S11.

Emissions from the manufactures of greenhouse and plastic materials were estimated based on various datasets reporting greenhouse area in the selected countries (Table S11) and distinguishing between plastic and glass greenhouses (fixed installations) based on global shares (Rabobank, 2018). The surface area of tunnels and plastic mulching, which are not reported in these sources, were estimated based on their relative area in Spain. Inventory data on materials used per unit area were obtained from Aguilera et al. (2015b) and emission factors of materials from Ecoinvent (Wernet et al., 2016). All greenhouse and plastic emissions were allocated to vegetables.

Feed production and energy use emissions in livestock production were estimated using product-based emission factors from an LCA of European livestock based on data harmonized using CAPRI model factors (Leip et al., 2010). The weighted average feed emission factor per unit product was applied to non-European areas. All factors were applied to FAOSTAT livestock production data.

2.5. Carbon sequestration potential

In contrast to the rest of the components of the GHG emission balance analyzed in this study, SOC is a stock, not a flux, and therefore expressing it as a flux introduces additional uncertainty. Here, we chose to estimate the SOC sequestration potential in cropland based on the combination of data from meta-analyses and modelling. In the case of grassland, meta-analyses were not available. Therefore, we used the 4 per 1000 objective as the reference for the estimation of potential C sequestration in grassland.

The values obtained from meta-analyses can be considered to be an upper boundary of the SOC sequestration potential, using current recommended management practices, given that: i) the baseline situation is unknown, and some of the recommended management practices are already applied to some degree; ii) some of the recommended management practices applied in the studies included in the meta-analysis depend on availability of organic materials that may not be generalizable to all agroecosystems (for example, manure application depends on local manure availability, therefore limiting the potential of this practice); iii) the length of the studies included in the meta-analysis is lower than 100 years, which is the time horizon used for estimating the GWP of the other components of the balance. SOC sequestration rates after a change in management tend to be highest during the first years, and then decrease when the SOC content approaches a new equilibrium. The first two problems described above are difficult to solve at the scale of our study. Therefore, we did not aim to correct them. In the case of the third one, i.e. length of the study, we used a modelling approach to estimate the difference between C the average sequestration rate during the average length of the studies in the meta-analyses and during 100 years of a change in management. That way we expressed the global warming potential of all the components of the annual GHG budget within a common time horizon of 100 years.

Two meta-analyses under Mediterranean conditions were used to derive C sequestration rates using combined recommended management practices in cropping systems. The meta-analysis by Aguilera et al. (2013a) was used for herbaceous crops, and the meta-analysis by Vicente-Vicente et al. (2016) was used for woody crops. In the case of herbaceous crops, no crop-specific data was available in the published article, and the available data was too limited to differentiate between crop types. Therefore, we used the average C input rate in each crop type to scale the C sequestration rates in our own crop categories, when available. We used the average of herbaceous crops, when crop category-specific data was not available. The C sequestration rates thus obtained are shown in Table S13.

We used the HSOC model (Aguilera et al., 2018) in a range of representative situations under Mediterranean conditions. In order to build this range of situations, we used the full range of mineralization rates modifying factors in the Mediterranean climate provinces in Aguilera et al. (2018), representing a complete gradient of precipitation and temperature within the Mediterranean climate, and including both irrigated and rainfed systems, and covered and bare soils. This range of modifying factors results in mineralization rates of the humus pool (K2) of 0.4–4.1% per year. The other set of parameters of the HSOC model affecting the relationship between short-term and long-term C sequestration is the humification coefficient. Therefore, we simulated a range of humification coefficients between the two types of inputs used in the combined management practices of the meta-analyses, i.e. herbaceous residues and manure. As a result of these simulations, we concluded that the average C sequestration rate after 100 years represented 25% (SD = 6%) of the C sequestration rate in the average time period of the herbaceous meta-analysis studies (7 years) and 32% (SD = 6%) of the C sequestration rate in the meta-analysis group with the longest average study period (vineyards, 12 years). These values are in line with other published modelling studies (Álvaro-Fuentes and Paustian, 2011; Hansen et al., 2006; Powlson et al., 2008). The values were used to correct the C sequestration rates from the *meta*-analyses in each crop category, in order to equate the time horizon of the C sequestration potential with the time horizon of the global warming potentials of the GHG used in the study.

The effect of the correction of the study length on the C sequestration potential in each crop type in the Mediterranean biome was tested in a sensitivity analysis (Fig. S1). This sensitivity analysis also includes a comparison with the C sequestration values obtained assuming the objective of the 4 per 1000.

In order to calculate potential C sequestration with the 4 per 1000 goal, current stocks of topsoil (30 cm) SOC in croplands and pastures of selected Mediterranean territories, as reported by the Harmonized World Soil Database (HWSD) v 1.2 (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012), were used as a reference. The pastureland SOC stock was distributed among animal types based on N excretion on grassland from FAOSTAT (FAO, 2019). The resulting SOC stock values by crop and animal types are shown in Table S14. Despite criticism about the feasibility of the 4 per 1000 objective on a global scale (Poulton et al., 2018; Rumpel et al., 2020), a recent assessment showed that typical SOC sequestration rates associated with recommended management practices in croplands under a Mediterranean climate are well above (nearly one order of magnitude) this objective (Francaviglia et al., 2019). This also agrees with our sensitivity analysis (Fig. S1), and our assumption of using the 4 per 1000 objective is thus likely to be conservative.

2.6. Allocation of emissions to Mediterranean areas

Most crop-related emissions were allocated to Mediterranean areas using crop area distribution maps (Monfreda et al., 2008), which have a five-by-five minute resolution and represent the distribution in the year 2000 (average of 1997–2003 census data) for 175 crops that match those of the FAOSTAT Crop production module (FAO, 2019). The complete database of crop areas in the studied countries and in the Mediterranean areas of these countries is shown in Table S3. These crop types were then aggregated in our studied categories (Table S6) by summing their corresponding crop areas and production values. The spatial allocation of synthetic nutrients and their corresponding emissions were based on our estimations of their crop-wise yield-scaled application rates. Fertilizer applications in each crop were then distributed among Mediterranean and non/Mediterranean areas of each country using crop production distribution maps (Monfreda et al., 2008) of 175 crops. Irrigation emissions were allocated to Mediterranean areas based on the distribution of irrigated area in each country, which was obtained from the HWSD (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). Livestock-related emissions were allocated to Mediterranean areas based on livestock numbers distribution data, which were obtained from global maps (Gilbert et al., 2018) based on the year 2010. The maps include cattle, buffalo, horse, sheep, goat, pig, chicken, and duck distributions at similar resolutions as those for crops. The corresponding number of animals and shares in the studied countries and their Mediterranean areas are shown in Table S12. In addition, we used land use (FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012) and crop area distribution (Monfreda et al., 2008) maps to allocate C stocks and sequestration potentials to pasture areas and to each crop type in the selected countries and in the Mediterranean areas of these countries (Table S11).

3. Results

Total agricultural GHG emissions in the Mediterranean biome (Fig. 1a) were estimated as 281 Tg CO_2eq yr^{-1} from livestock production and 174 Tg CO_2eq yr^{-1} from crop production. When potential soil C sequestration was included in the GHG budget, these values were 367 and 261 Tg CO_2eq yr^{-1}, respectively. Notably, these values were not additive, as feed production was included in both categories. The GHG budgets were dominated by the “inputs” category, both in crop (54%) and in animal (44%) production. This included emissions from direct energy use and the production of inputs. Emissions from the production of inputs are mostly related to electricity and synthetic fertilizers for crop production (Fig. S2) and feed for livestock production. The SOC sequestration potential, s also a very significant component of the balance, and it potentially compensates for approximately 50% of the estimated GHG emissions from crop production and 30% of those from livestock production.

SOC sequestration in croplands was the category with the largest number of published research papers. However, only 15% of papers compared SOC changes in long-term experiments (>10 years), which have the greatest relevance in gaining an understanding of the contribution of SOC to climate change mitigation. The highest number of high-quality studies (n = 108; including field measurements) belonged to the cropland soil N_2O emission category (Fig. 1b). In contrast, the livestock categories accounted for lower publication counts, ranging from 6 to 13 in the case of field measurements (Fig. 1b).

Such large differences between the focus of emissions and the publication patterns imply a significant variation in the research intensity between studied categories when expressed as the number of articles published per unit CO_2eq emitted or potentially sequestered (Fig. 1c). The largest disparity was between the livestock categories and plant production: livestock is associated with the greatest amount of emissions; however, it accounts for a very small fraction of the analyzed articles. The opposite is true for plant production. On average, 2.6 papers have been published per Tg CO_2eq annually emitted in crop production, compared to 0.4 papers per Tg CO_2eq in livestock production.

Studies have been strongly concentrated in a few geographical areas (Fig. 2). More than one third of the studies were carried out in Spain (37% of crop studies, 35% of animal studies, and nearly 50% of SOC studies in cropland and grassland) (Fig. S3), followed by Italy (21% in cropland and 18% in grassland). SOC studies in Spain alone represent 32% of all studies reviewed. Field N_2O emissions (Fig. S4) have been measured in very few countries: cropland and grassland have been the focus of field N_2O measurements in nine and five countries, respectively, compared to 17 countries in which SOC has been assessed (14 countries with high quality studies) in cropland. However, the situation in grassland is also poor for SOC, with high-quality studies being available in only three countries out of eight. Overall, 65% of field N_2O studies and 72% of rice paddy CH_4 measurements have been conducted in only two countries: Spain and the USA (Figs. S4 and S5). Studies performed in Spain also represent 71% of enteric CH_4-measurement studies (Fig. S6) and 62% of manure management and N_2O and CH_4 emission-measurement studies (Fig. S7). A large proportion of LCA studies have focused on agricultural systems in Italy (46% of livestock LCAs and 44% of crop LCAs), followed by Spain (27% and 24%, respectively) (Fig. S8). These patterns are contradictory with the distribution of agricultural GHG emissions across the Mediterranean biome. For example, Spain is associated with only 21% and 7% of the SOC sequestration potential and 23% and 9% of soil N_2O emissions in croplands and grasslands, respectively, whereas Italy is associated with 8% of both crop and livestock input emissions.

With respect to crop types, the GHG budget from crop production was dominated by winter cereals (27% of emissions), followed by olives (16%) green fodder (13%), vegetables (8%), and maize (7%), whereas in livestock production from the dominant categories were bovids (43%), sheep (20%), chickens (19%) and pigs (11%) (Fig. 3a). Producing agricultural inputs dominated emissions in most crop groups, with the exception of rice (soil CH_4) and pulses (SOC) (Fig. 3a). The pattern in livestock groups was largely shaped by the distinction between monogastric, where feed emissions clearly dominated, and ruminants, where enteric CH_4 (bovine) and SOC (sheep and goats) represented the major share. The input emissions were in turn dominated by direct energy emissions for mostly rainfed crops (such as cereals), while the balance was better distributed for irrigated crops, with important contributions of irrigation-related electricity and waterbodies in this balance (Fig. S2, Table S4).

The distribution of the GHG budget among different emission types

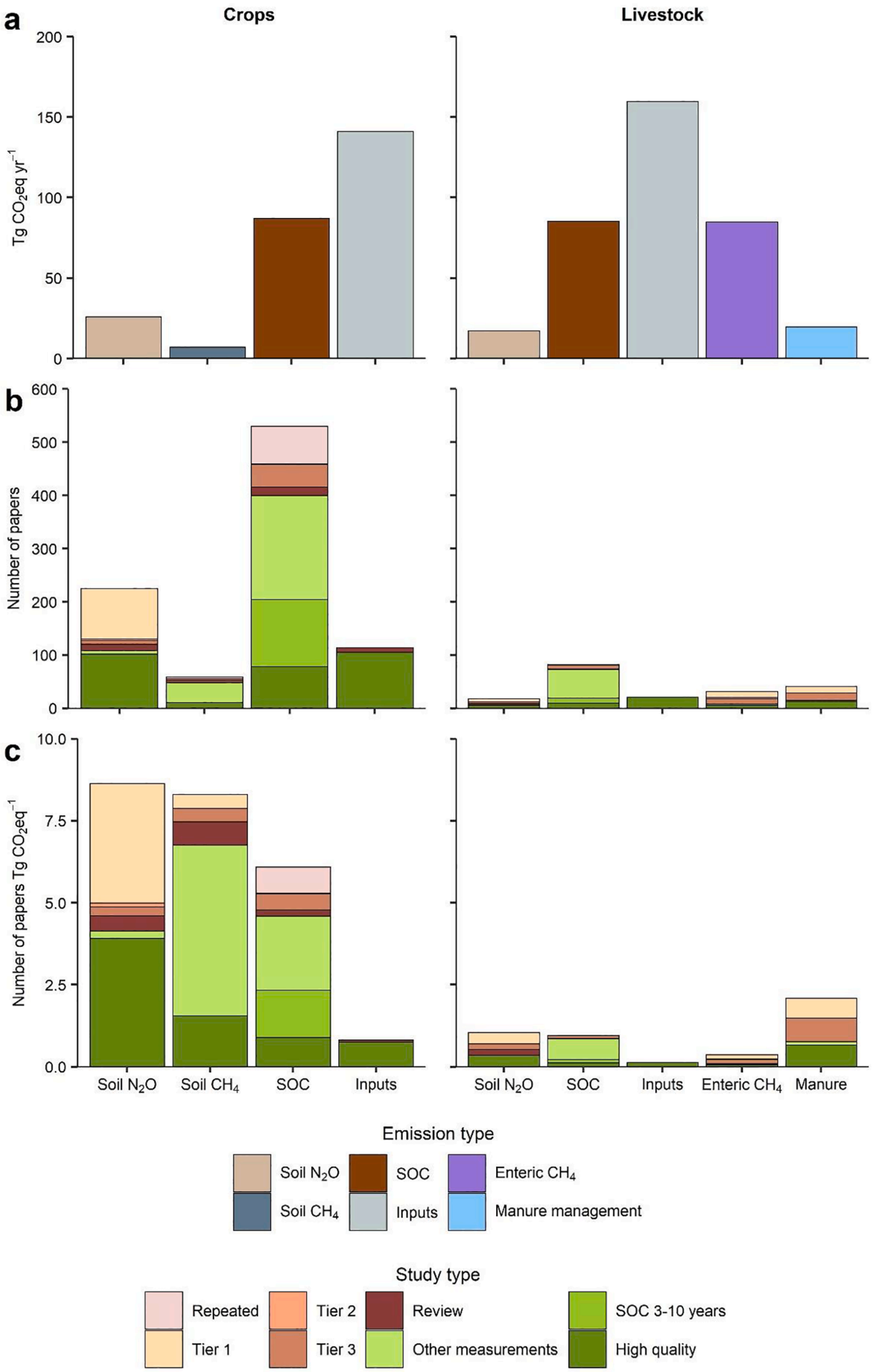

Fig. 1. (a) Agricultural greenhouse gas (GHG) emissions and carbon sequestration potential (jointly representing the GHG budget) in the Mediterranean biome, (b) number of papers, and (c) research intensity measured as the number of papers divided by the GHG budget and according to the type of emission and methodology used in the study.

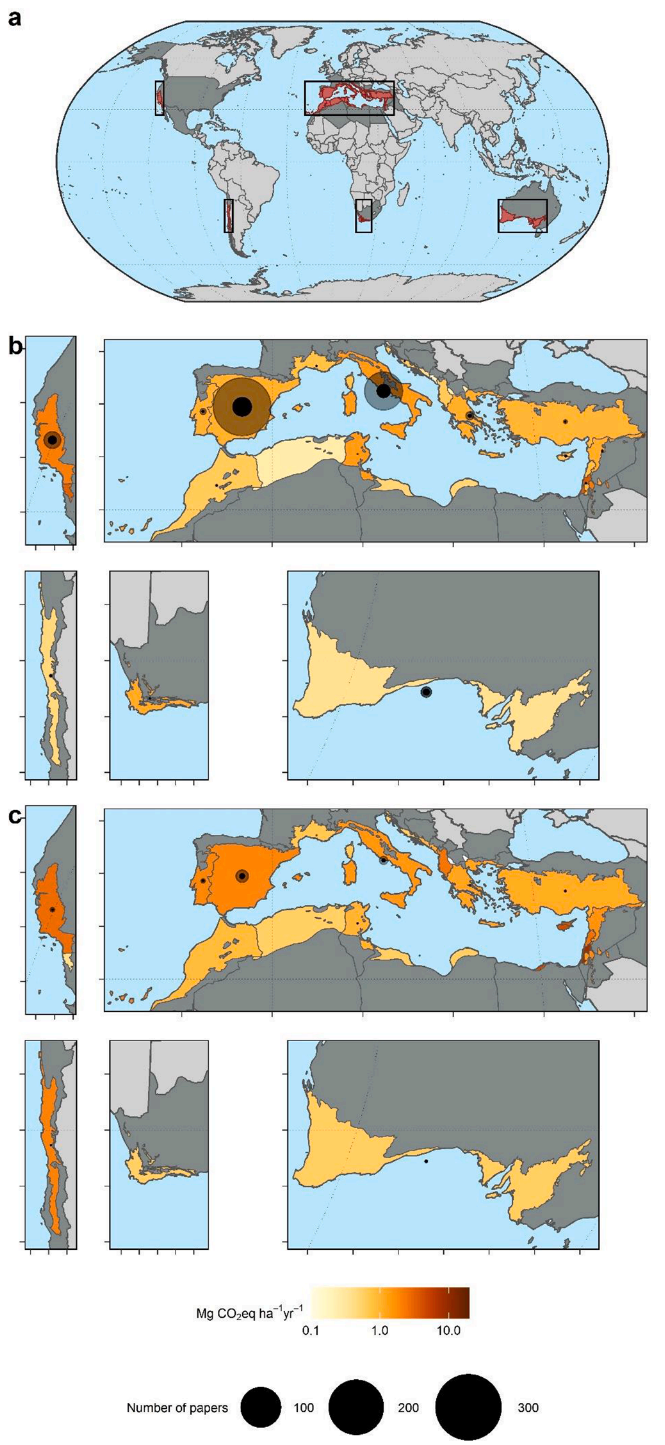

Fig. 2. Global distribution of the greenhouse gas (GHG) budget and number of research papers published relating to the Mediterranean biome. (a) The Mediterranean biome is marked in red, and the associated countries are marked in dark gray. The two lower panels show area-based GHG emissions (colors) and the number of publications (circles) relating to the Mediterranean areas of each country with respect to (b) crop production and (c) livestock production. Studies covering more than one country are excluded. Light circles represent all studies, and solid circles represent high-quality studies (field measurements of biogenic N_2O and CH_4, long-term >10 years SOC stock measurements, and life cycle assessments). A full disclosure of the GHG budget and the number of research publications by emission type are presented in Figs. S2–S7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

greatly differed from the distribution of publications among different emission types (Fig. 3a), and clear research gaps could be identified. For example, field measurements of GHG emissions from fruit tree orchards, fiber crops, and roots were lacking, as were long-term SOC studies of fibers, rice, and most animal species. In addition, there was a lack of LCA studies on root crops and goats. The research intensity indicator (Fig. 3a) revealed interesting patterns that could not be identified by bibliometric analysis alone. For example, although papers predominantly focused on cereals, the research intensity in this group was among the lowest with respect to the high emission share that it represents. In addition, although a relatively high number of studies focused on grassland, the number was not high enough with respect to the magnitude of the of this land use type in terms of annual Tg CO_2eq, resulting in a lower research intensity as compared to the other systems studied. In the case of chickens, the number of papers was relatively low; with respect to this group's high emission share, it had one of the lowest associated research intensities, with 0.2 papers per Tg CO_2eq, which was two orders of magnitude lower than that for grapevines (the group with the highest research intensity and 14.6 papers per Tg CO_2eq). This analysis of research intensity by group and emission type (Fig. 3b) verified the general trends observed in Fig. 1c, and it indicated a research deficit associated with all animal groups and most emission types. Grassland SOC sequestration and soil N_2O emissions were not linked to any livestock species, while "other animals" (mainly rabbits) was the only livestock category that was the subject of significant research intensity associated with estimations of input emissions, although it was the livestock group with the lowest GHG budget share.

We found 797 publications that assessed GHG emissions or the C sequestration potential in Mediterranean climate areas. Controlled randomized trials were the most common study type, followed by farm surveys (Table 2). However, LCA studies (shown in the "Inputs" category) of both crop and livestock products were mostly based on farm surveys, as these studies usually aim to characterize existing systems, rather than idealized ones. Farm-based studies were also predominant among livestock studies, representing 44–71% of the studies across emission types. Overall, 16% and 98% of the reviewed studies related to organic and conventional management, respectively. The share of studies referring to organic treatments was generally higher for crops (7–28% across emission types) than for livestock (0–8%) (Table 2). Nearly all research involving field measurements under organic management was focused on C sequestration, and no studies included field measurements of GHG emissions in organic rice paddies or in organic or extensive livestock systems (data not shown). The oldest research paper reviewed was published in 1986. The number of articles published during the 21st century has increased considerably (and more than 100 articles had been published by 2017) (Fig. S9). The number of long-term SOC studies peaked in 2010–2011, while the number of N_2O and LCA studies increased significantly after 2010 (and had surpassed or equaled the annual number of SOC studies by the end of the study period). For animal-related emissions, the first articles relating to enteric CH_4 and manure management under Mediterranean conditions were published as late as 2012. Overall, 90% of the reviewed studies were published after 2005.

Fig. 4 classifies the LCA studies in accordance with the method used to quantify key processes within the emissions' balance, particularly with respect to biogenic processes. Fig. 4a shows that most LCA studies relating to crops apply an IPCC Tier 1 method (the less detailed one, involving the highest uncertainty) to calculate N_2O, and do not consider SOC sequestration in the emissions' balance. Most articles that considered C sequestration did so by modeling (Tier 3), but most of these studies did not apply N_2O calculation methodologies adjusted to Mediterranean conditions. Therefore, only 24% of LCA studies included C sequestration and 5% included field measurements. Overall, only 6% of LCA studies relating to Mediterranean agricultural products reached Tier 2 when estimating N_2O emissions and included C sequestration. Similarly, for most LCA studies relating to animal products (Fig. 4b),

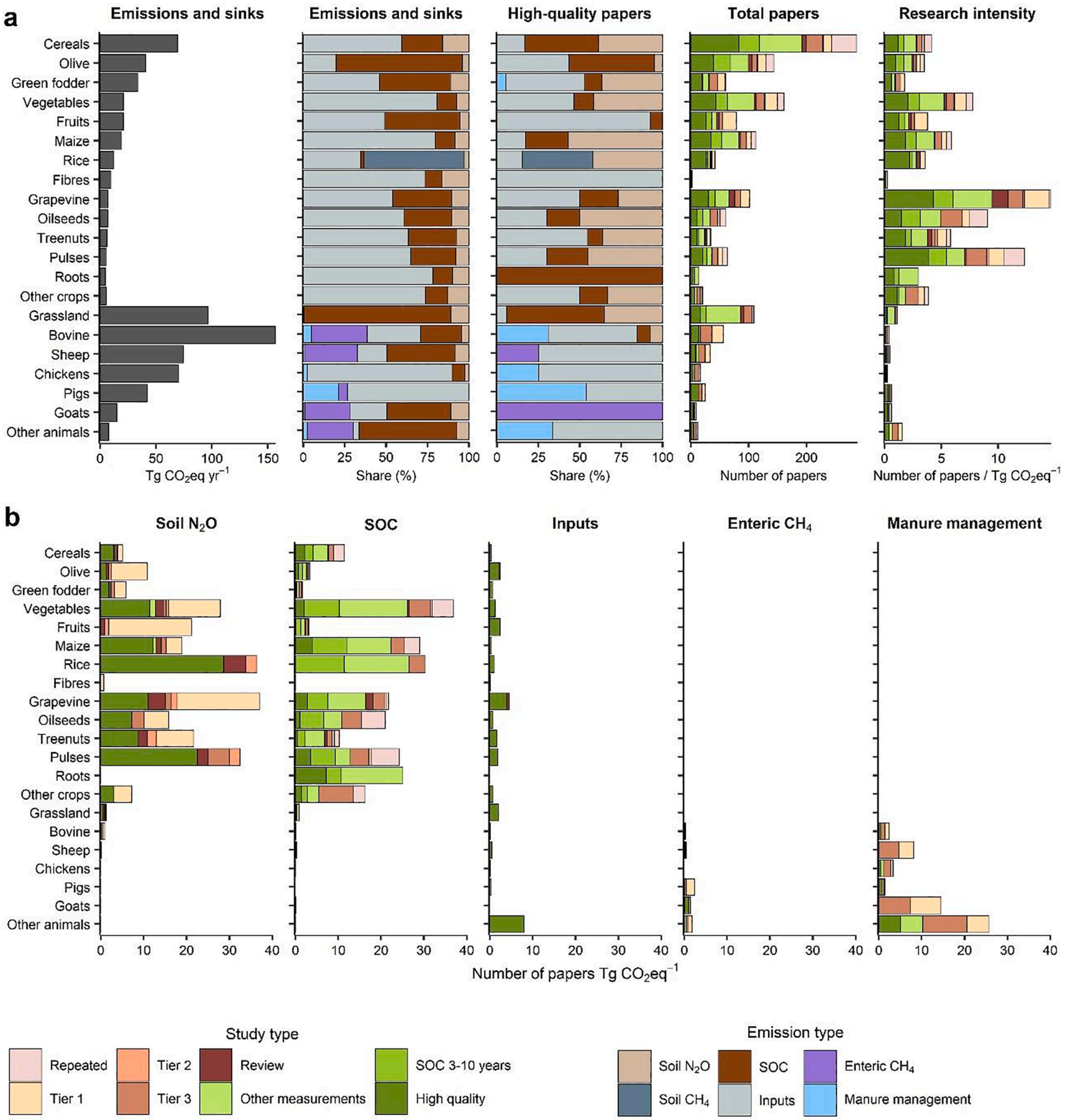

Fig. 3. Assessment of the greenhouse gas (GHG) budget and related articles in agricultural production in the Mediterranean biome classified by production type, emission type, and study type, including (a) GHG budget and number of publications and (b) research intensity measured as the number of papers per unit emission. The same paper may be included in more than one category. Grassland and crops used for fodder are shown both as a separate category and as a component of the balance of each livestock species.

emissions from manure management and enteric CH_4 emissions either were not included in the balance or were estimated using IPCC Tier 1 methods; however, an appreciable proportion of studies used Tier 3 methods for either of these emission categories. However, none of the livestock LCAs reviewed included direct measurements of these gases.

4. Discussion

Our results showed that the amount of research conducted on GHG emissions associated with agriculture in the Mediterranean biome was not proportionate with respect to the share of emissions from source categories and production systems. A previous study has shown that research, policy, and practice in Europe are misaligned (Scown et al., 2019); however, to the best of our knowledge, our study is the first to compare studies focusing on GHG measurement and assessment with the magnitude of emissions from each source category. We noted a strong bias in favor of crop research than in favor of livestock system research, although it is widely accepted that livestock dominates the agricultural GHG budget on a global level (Bennetzen et al., 2016; Springmann et al., 2018; Tilman and Clark, 2014), which was also verified in the present

Table 2

Number of articles assessing GHG emissions under a Mediterranean climate by emission, production, study, and management types.

		Total	Study type					Management type	
			Trial	Farm	Mesocosm	Regional	Review	Conventional	Organic
All studies									
Inputs	Crops	114	34	59	0	12	9	113	32
SOC	Crops	530	363	108	10	31	18	516	96
Soil CH_4	Crops	59	43	4	2	5	5	59	4
Soil N_2O	Crops	225	118	69	6	17	15	219	42
Enteric CH_4	Livestock	31	5	21	0	5	0	31	2
Inputs	Livestock	21	2	15	0	4	0	21	1
Manure management	Livestock	41	5	29	0	7	0	40	3
SOC	Livestock	82	25	41	0	15	1	82	3
Soil N_2O	Livestock	18	5	8	0	2	3	18	0
High-quality studies									
Inputs	Crops	105	34	59	0	12		104	29
SOC	Crops	78	55	22	0	1		77	12
Soil CH_4	Crops	11	10	1	0	0		11	0
Soil N_2O	Crops	101	88	12	0	1		99	8
Enteric CH_4	Livestock	6	5	1	0	0		6	0
Inputs	Livestock	21	2	15	0	4		21	1
Manure management	Livestock	13	4	9	0	0		12	1
SOC	Livestock	10	4	6	0	0		10	3
Soil N_2O	Livestock	6	3	3	0	0		6	0

SOC, soil organic carbon.

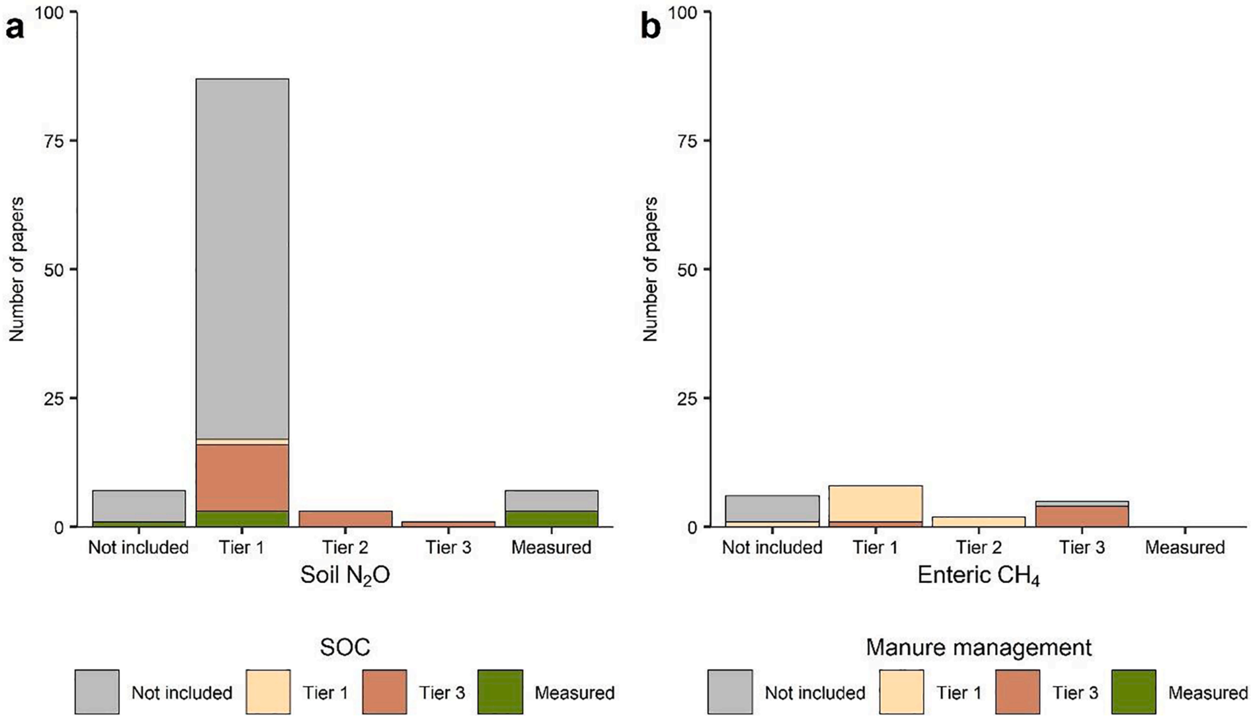

Fig. 4. Classification of LCA studies focusing on (a) crop and (b) livestock production in Mediterranean areas based on the method used to estimate key biogenic processes of emissions' balance.

study for the Mediterranean biome. The lack of field research for many studied crops and livestock groups, as well as for specific management types such as organic farming and extensive livestock, is particularly worrying, given that the technological components of the GHG balances of agricultural systems are generally well characterized (ecoinvent-Centre, 2007; Kim and Overcash, 2003), while biogenic GHG emissions are a major source of uncertainty. In the case of plant production, it has been shown that the average Mediterranean emission factors, particularly in rainfed systems and with solid organic fertilizers (Aguilera et al., 2013b; Cayuela et al., 2017), are lower than the default IPCC Tier 1 emission factor (IPCC, 2006) currently employed in national inventories, which is in line with the new IPCC revision of emission factors in water deficient areas (IPCC, 2019a). However, the results of our bibliometric analysis showed that the vast majority of LCA studies used the 2006 IPCC Tier 1 emission factor (Fig. 4a). This implies a bias against low input and organic management systems, where the N source is mostly solid organic fertilizers and N_2O emissions may play a relatively greater role. Uncertainty involved in estimating C sequestration favors the omission of SOC dynamics in agricultural GHG balances, even though this process has been identified as a major GHG mitigation option in agriculture (Bossio et al., 2020; Smith et al., 2008). In addition, the few LCA studies that include C sequestration usually show that the contribution of soil C dynamics to the GHG balance cannot be ignored (Lee et al., 2020). In the case of Mediterranean agricultural production, most LCA studies that assessed C balance showed that C sequestration achieved with recommended management practices might totally offset emissions in terms of 100-years CO_2eq, as determined with respect to organic (Aguilera et al., 2015a) or "sustainably managed" (Palese et al., 2013) olives, cover crops in irrigated herbaceous systems (Guardia et al., 2019), or old crop varieties that are organically managed in rainfed cereal rotations (Carranza-Gallego et al., 2018). Therefore, as in the case of N_2O, this methodological bias strongly penalizes agroecological practices. In addition, organic agriculture is usually misrepresented in LCAs, because LCAs: (1) do not include indicators for land degradation, biodiversity losses, and pesticide effects, (2) provide a narrow perspective on the functions of agriculture, and (3) inconsistently model indirect effects (van der Werf et al., 2020).

Most LCA studies conducted on livestock systems also used Tier 1 methodologies for key processes such as manure management and enteric CH_4 emissions, but none included direct field measurements. The scarcity of studies on GHG emissions in grasslands until 2017 provides a stark contrast with the magnitude of the potential SOC storage and N_2O emissions associated with this land use type, which could potentially offset a large fraction of livestock emissions. We found this fraction to be close to 100% of emissions for some species, such as small ruminants. However, some recent studies have shown the large effect of management practices on Mediterranean grassland GHG emission dynamics. For example, Verdú et al. (2020) found a decrease in CO_2 and CH_4 emissions from dung pats in the absence of ivermectin veterinary use, which was associated with a higher diversity and biomass of dung beetles. They also found that dung beetles had a larger effect on GHG emissions in this ecosystem than in colder temperate systems, underlining the need for Mediterranean-specific studies. These patterns suggest a need to incorporate field knowledge in LCA frameworks through the use of Tier 2 and Tier 3 approaches, which could be facilitated by referencing the available quantitative reviews synthesizing field findings under Mediterranean conditions. Another way of filling this knowledge gap would be using LCA analysis to complement the results of field studies that include measurements (Guardia et al., 2019; Sanz-Cobena et al., 2017), as this would help identify the outsourcing of emissions to off-farm components of the C footprint.

Our analyses have a number of limitations. For example, we have assessed current emission levels as a proxy of the climate change mitigation potential; however, as not all emissions can be abated, the emissions do not directly represent the mitigation potential. This fact may help to explain why some processes have received more research attention than others. Another limitation is that emission estimates are the result of available data generated by the research against which they are compared. For example, our estimation of direct N_2O emissions from soils using Mediterranean-specific emission factors was approximately 50% lower than that reported by FAOSTAT using the default Tier 1 approach (following the 2006 IPCC guidelines). In addition, research conducted to mitigate such emissions could facilitate a reduction in emission levels, if it generates appropriate policy and management recommendations, thus reducing the influence of the associated emissions category. Both the refinement of research methods and the effect of research on climate change mitigation would make the research intensity in that field seem excessive compared to the intensity in less-studied fields; however, such high research intensity values reflect the success of that research and do not represent an undue focus on a relatively minor emission contributor. Nonetheless, identifying such situations is also valuable as an indicator to redirect future research. Another limitation of our approach is that it could not capture the value of a high amount of basic research that does not focus on GHG emissions directly but characterizes the biogeochemical processes responsible for GHG emissions. Similarly, research conducted under other bioclimatic conditions constitutes the basis for understanding and interpreting the observed GHG emission patterns, and they are not included in the present analysis.

The outcomes of this study can support the design of more effective research GHG quantification and mitigation strategies that aim to fulfill the objectives of the Paris Agreement (UN, 2015). This is particularly relevant today, when climate change mitigation in agriculture and food systems is gaining momentum in many international and national policy frameworks, such as the EU "Farm to Fork" strategy (European Commission, 2020) recently promoted by the EU Commission to decrease environmental impacts associated with food systems. Most such policy strategies promote research aiming to achieve C neutrality at the farm level by reducing GHG emissions and promoting C sequestration and storage. Closing existing knowledge gaps is the key to increasing the effectiveness of such ambitious actions and for providing scientific evidence that can be used as the basis of effective strategies devoted to achieving overall C neutrality in all climate areas.

Our study is the first to assess agriculture-related GHG in a biome on a global scale. We compared research efforts with the magnitude of the main components of agroecosystem GHG budget and identified the underrepresentation of livestock production systems as a research focus with respect to climate change mitigation in the Mediterranean biome. These aspects need to be further addressed to provide a more accurate insight into the C footprint of livestock systems, which are considered responsible for more than 50% of current GHG emissions from agri-food systems and which should, therefore, be the core focus of many present and future mitigation actions (Aguilera et al., 2020b; IPCC, 2019b; Poore and Nemecek, 2018; Willett et al., 2019). Finally, our results facilitate in placing the C sequestration potential of agricultural soils in context (Smith et al., 2020), through its comparison with GHG emission levels, and evaluation of whether it can be used to achieve C neutrality in agriculture through offsetting emissions. This can facilitate the evaluation of the potential effectiveness of numerous global climate change mitigation initiatives in which C sequestration is central, such as the "4 per 1000" initiative (Soussana et al., 2019), the Global Research Alliance for GHG mitigation in Agriculture (https://globalresearchalliance.org) (Shafer et al., 2011; Yeluripati et al., 2015), and the initiative for Coordination of International Research Cooperation on Soil Carbon Sequestration in Agriculture (CIRCASA, https://www.circasa-project.eu) (Smith et al., 2019).

5. Conclusions

The results of the present study facilitate the identification of emission hotspots and research gaps in Mediterranean agriculture. By combining GHG budget quantification and the bibliometric analyses of research publications into a novel indicator, "research intensity," we could identify the systems and processes that require greater research effort. In addition, our analysis reveals the need for the refinement of carbon footprint estimation methods in life cycle assessments of Mediterranean agricultural products, which should pay attention to the increasing body of knowledge that indicates the need to apply Mediterranean-specific emission factors and to include relevant processes, such as soil C sequestration.

We generally observed an underrepresentation of livestock systems in research efforts, which is in contrast with the large share of emissions that can be attributed to livestock production. A more detailed analysis reveals key knowledge gaps for many types of crops and livestock species, many geographical areas, many specific components of the GHG emission balances and for organic and extensive management. Such a discrepancy between research effort and the weight of each component of the agricultural GHG budget can influence the effectiveness of research and institutional efforts to address climate change mitigation. Therefore, the results of our analysis could facilitate more effective research through the redirection of research efforts to systems and processes with large emission shares, and low research effort. This is particularly relevant in the current international context, in which numerous policy actions are being directed at climate change mitigation in agriculture and food production systems.

CRediT authorship contribution statement

Eduardo Aguilera: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing - original draft. **Carolina Reyes-Palomo:** Methodology, Investigation, Data curation, Writing - review & editing. **Cipriano Díaz-Gaona:** Conceptualization, Methodology, Resources, Writing - review & editing. **Alberto Sanz-Cobena:** Methodology, Investigation, Resources, Writing - review & editing. **Pete Smith:** Methodology, Writing - review & editing. **Raquel García-Laureano:** Investigation, Data curation. **Vicente Rodríguez-Estévez:** Resources, Supervision, Project administration, Writing - review & editing, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2021.102319.

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