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RESEARCH ARTICLE

Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops

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Abstract Agriculture is a major driver of climate change, particularly when all indirect emission sources are accounted for. Mitigation options targeted on one process are often proposed, ignoring their secondary effects on the overall greenhouse gas balance. Integrative methodologies such as life cycle assessment (LCA) are often applied without adjusting emission factors to specific site characteristics. Here, we used LCA to calculate the global warming potential of 38 pairs of organic and conventional herbaceous cropping systems and products in Spain. Crop products included rainfed cereals and pulses, rice, open-air vegetables, and greenhouse vegetables. We used data from farmer interviews and published conversion factors. Our results show that the emission balances were dominated by fossil fuel use rather than by direct field emissions. Organic management reduced crop emissions by 36–65 %, with the exception of rice showing an increase of 8 % due to methane generation. Product-based emissions of organic crops were also lower by 30 % on average, except for rice.

Keywords Life cycle assessment · Greenhouse gas emission · Mediterranean · Organic management · Carbon sequestration · Nitrous oxide · Coproduct allocation

1 Introduction

Agriculture is a major source of greenhouse gases and is also indirectly responsible for a large share of the greenhouse gases emitted in deforestation and other land use changes. Arable agriculture produces direct and indirect nitrous oxide (N_2O) emissions from nitrogen (N) application to soils, methane (CH_4) from rice paddies, carbon dioxide (CO_2) from direct fossil energy use, and N_2O and CH_4 from open biomass burning. Further emissions occur due to fossil energy use in the production of agricultural inputs, particularly N fertilizers. Last, the other major link between agriculture and climate change is soil carbon (C) balance. Historical C losses from agricultural soils have contributed to the increase in both the global greenhouse gas budget and the vulnerability of agriculture to climate change (Lal et al. 2011), but they could be reversed by adequate agricultural practices.

Most mitigation practices can be applied in conventional and organic systems, but broad differences between both management types can be identified. Organic farming aims to reduce the environmental impact of agriculture by avoiding the use of synthetic compounds such as fertilizers and pesticides and by promoting practices such as crop diversification and organic fertilizers. Organic farmers thus prevent fossil energy emission associated to the industrial production of many inputs and promote soil C accumulation. Enhanced soil organic carbon (SOC) under organic management is supported by extensive experimental data in Mediterranean cropping systems (Aguilera et al. 2013a). In spite of this, lower yields could offset reductions in greenhouse gas emissions when quantified on product basis (Nemecek et al. 2011; Venkat 2012). Spain is the country with the largest surface under organic farming in the European Union (EU-25), with 1.65 Mha or 6.5 % of total agricultural area (MAGRAMA 2011). The climate in Spain is mostly Mediterranean, with wet, mild winters and hot, dry summers. Herbaceous systems in Spain produce the majority of the local protein and high-value crops for export to nearby regions such as off-season vegetables. Rainfed cereals and legumes are cultivated in vast areas across the country with relatively low yields and low management intensities, occupying 5.36 Mha, or 83 % of grain cultivated area, and producing 65 % of the grain (MAGRAMA 2011). Vegetables

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represent one of the major agricultural commodities produced in Spain, with 44 % of local production being exported according to FAOSTAT (FAO 2014). They are mostly cultivated under irrigation, and greenhouse systems represent 18 % of the area, with yields usually doubling those of open-air horticulture (MAGRAMA 2011).

A number of papers studying greenhouse gases emissions in Mediterranean herbaceous systems have been published (e.g., Biswas et al. 2008; Venkat 2012; Theurl et al. 2013), although there is still a lack of information on some specific systems, such as rice paddies, and particularly of comprehensive comparisons between organic and conventional management. On the other hand, most agricultural life cycle assessment (LCA) studies employ Tier 1 IPCC N_2O emission factors and/or do not account for C sequestration, despite soil processes represent a large share of the carbon footprint of agricultural systems and are associated to very high uncertainty (IPCC 2006). All this may result in inaccurate estimations of total global warming potential, as shown by different studies under Mediterranean conditions (Biswas et al. 2008; Venkat 2012). Another common gap in LCAs of crop products is the study of the effects of the alternative destinies of coproducts such as cereal straw, particularly of their use as animal feed, energy production, and soil application for carbon sequestration. This is a very relevant issue in a context of increasing interest for straw energy production (e.g., Cherubini and Ulgiati 2010; Nguyen et al. 2013).

Given the lack of precision of IPCC Tier 1 factors under Mediterranean climate and the difficulty of implementing intensive field measurements, there is a need to develop simple models able to estimate soil greenhouse gases emissions balances from management information in these areas. We had previously synthesized the current scientific information on climate-specific N_2O emission factors and C sequestration responses to management practices under Mediterranean conditions in two meta-analyses (respectively, Aguilera et al. 2013a, b). In the present work, we combined information from those reviews with data on agricultural management obtained from interviews, conversion factors from LCA databases and the literature and IPCC emission factors to compare for the first time the full greenhouse gas emissions balance, or carbon footprint, of a representative sample of Spanish herbaceous crops under conventional and organic management. We calculated the balances according to LCA procedures, with the following objectives:

1. Determine the influence of organic management on area-based and product-based greenhouse gas balance of a range of herbaceous crops representing organic production in Spain
2. Identify critical processes in the carbon footprint of organic and conventional Mediterranean cropping systems and crop products
3. Analyze the effect of N_2O emission factor choice and coproduct consideration (allocation and system expansion) in the estimation of the carbon footprint of the main product
4. Identify critical options for improving the carbon footprint of organic and conventional Mediterranean cropping systems and crop products

2 Materials and methods

2.1 Data collection

Information on management and production features was obtained from personal interviews to a representative sample composed of 38 pairs of organic and conventional farmers in Spain (Alonso and Guzmán 2010). The database was composed by 18 crop species, grouped by five crop types: *rainfed cereals*, including barley (four pairs of interviews), wheat (three) and oats (one); *rainfed legumes*, including peas (four), fava beans (one), and vetch (one); *rice* (three pairs); *horticultural open air* (Fig. 1), including asparagus (one), lettuce (two), melon (two), celery (one), cauliflower (one), potato (one), broccoli (one), onions (two), and beans (two); and *horticultural greenhouse*, including cherry tomato (one), tomato (four), lettuce (one), pepper (one), and beans (one).

2.2 LCA scope

An attributional LCA was performed based on the “cradle-to-farm gate” perspective, which considers all inputs and processes for the plant production as well as all the necessary upstream processes. In particular, the following processes were included within system boundaries: manufacturing and maintenance of machinery, fuel production and combustion, greenhouse infrastructure, fertilizer manufacturing, pesticide production, soil N_2O emissions, indirect N_2O emissions, N_2O and CH_4 emissions from open biomass burning, CH_4 emissions from rice paddies, and soil C balance. The temporal boundaries were adjusted to 100 years, and all emissions were converted to CO_2 equivalents using IPCC (2006) coefficients. Emissions associated to manure production were excluded from system boundaries, considering that they belong to the animal production systems (Nemecek et al. 2011; Venkat 2012).

Both 1 ha of cultivated land and 1 kg of marketed product were chosen as functional units. Some of the studied cropping systems produced coproducts in addition to the main marketable product, specifically legumes and cereals. These coproducts can be either unused (burned, landfilled), reused (incorporated to the soil), or extracted as additional products for feed or energy valorization (the latter not widespread now). As cereal and legume straw are mainly used for animal production as feed and bedding material, this coproduct was included in the impact assessment through economic allocation. IPCC (2006) Tier 1 methodology was used for the calculation the change in CH_4 emissions resulting from the substitution of cereal grains by straw. Vegetable residues were considered as waste products, and no emissions were allocated to them.

2.3 Carbon footprint method

2.3.1 Emissions from the production of inputs

Data on machinery, fuel and electricity consumption, and greenhouse infrastructure material requirements were estimated as described by Alonso and Guzmán (2010). According to this procedure, the resource consumption of machinery and implements is attributable to four factors: production of raw materials, manufacture, repair and maintenance, and fuel consumption. In this work, we included minor changes in the calculation of fuel consumption. In particular, a load ratio of 75:45 % was taken for light duties (atomizing, spraying, bar rolling, and hydraulic sweeper). Emissions associated to the production of most inputs from the technosphere, such as machinery, pesticides, and some fertilizers were modeled using databases contained in SimaPro 7.2 software (PRé Consultants 2010), including ecoinvent 2.0 (ecoinvent Centre 2007) and LCA Food DK (Nielsen et al. 2003) with preference given to ecoinvent 2.0 database. Pesticides were differentiated by compound, family or broad type depending on information availability. Specific Spanish emission factors (Lago et al. 2013) were used for major NPK fertilizers, including ammonium nitrate, ammonium sulfate, ammonium nitrosulfate, urea, N in compound fertilizers, K_2O, and P_2O_5. Vermicompost emissions were calculated by scaling compost emissions from ecoinvent by the relative N content. Likewise, the N-scaled ecoinvent emission value for dried poultry manure was taken for all granulated organic fertilizers. N contents of the organic fertilizers were 2.2, 0.7, 0.6, and 1.1 % for vermicompost, sheep manure, cow manure, and chicken manure. Fertilizers were assumed to be transported to the farm by lorry of >16 t from distances of 300 km (synthetic fertilizers) and 30 km (organic fertilizers).

Electricity used in irrigation was assumed to come from the 2004 Spanish grid, as modeled in ecoinvent database, and to be half medium voltage and half low voltage. Emission values associated to irrigation infrastructure in the farm were taken from Lal (2004), distinguishing surface irrigation with and without recirculation system, sprinkler, and trickle irrigation systems.

Emissions associated to seed production were estimated using the grain emission factors obtained in the present study. This approach implies a self-reference in emission factor calculations, which was solved by iteration of the function until the result stabilized. One emission factor for conventional management and another for organic management were derived for seeds of rainfed cereals, rainfed legumes, and rice. In the case of organic management, some of the seed was not of organic origin. This proportion of conventional seed in organic systems was taken into account using Andalusian data from RAS (2006). Andalusia is the largest organic producing region in Spain, representing about half of the certified organic area in the country (MAGRAMA 2011). In order to make the results easier to visualize, all the seed was assumed to be bought in the marked, despite self-production is quite extended in organic farms (RAS 2006). This choice did not influence the results (data not shown). The impacts of vegetable seedling production were estimated based on peat consumption, assuming that the carbon content in peat was 55 kg m^{-3} (Hall 2006); that the peat volume used per seedling was 6–40 cm^3, depending on crop species; and that all peat carbon was ultimately released to the atmosphere.

2.3.2 Production and destinies of crop residues

Residual biomass production quantities (straw and other crop residues) were estimated using yield information obtained from the interviews, and residue indexes were taken from Guzmán et al. (2014). The only information on residue management available in the interviews referred to the cases in which it was mulched and incorporated to the soil. In the remaining cases, burning rates of 1.2 % for cereal straw, 20 % for legume straw (fava beans and dry peas), 20 % for vegetables, and 50 % for potatoes were obtained from the National Spanish Emission Inventory (MARM 2010).

2.3.3 Direct field emissions

N_2O emissions were estimated based on N inputs in the form of organic and synthetic fertilizers and agricultural residues. N content in the residues was obtained from López et al. (2005) (grain crops) and Rahn and Lillywhite (2002) (vegetables). Following IPCC (2006) guidelines, N released from soils with diminishing soil organic C stocks was also accounted as an input for N_2O emission estimation, assuming a C/N ratio in soil organic matter of 10:1. Direct N_2O emissions were calculated using specific Mediterranean factors adjusted to irrigation type (Aguilera et al. 2013a): 0.08, 0.66, and 1.01 % of applied N emitted as N_2O-N for rainfed, drip irrigation, and high-water irrigation systems, respectively. These factors are the means of all published information compiled by Aguilera et al. (2013a). IPCC (2006) emission factor of 0.3 % was assumed for rice systems. In cereal and vegetable systems, Mediterranean factors were compared through a sensitivity analysis with IPCC factor of 1 %. The influence of applying a reduction of 20 % in the emission factor of solid organic fertilizers was also studied in the sensitivity analysis, as N_2O emissions associated to organic fertilizers could be lower than those of synthetic ones under Mediterranean conditions (Aguilera et al. 2013a). Indirect emissions were estimated using IPCC (2006) Tier 1 methodology, obtaining a N_2O indirect emission factor of 0.4 % N_2O-N per kilogram of N applied for synthetic fertilizers and 0.5 % for organic ones. Emissions of N_2O and CH_4 from biomass burning were calculated following IPCC (2006) Tier 1 methodology.

CH_4 emissions from rice cultivation were estimated following IPCC (2006) Tier 1 guidelines, considering continuous flooding during cultivation and a non-flooding period of <180 days previous to cultivation, and accounting for the amounts of rice straw (applied long before cultivation), weeds, and manure applied to the soil.

2.3.4 Carbon sequestration

In Aguilera et al. (Accepted), we developed a simple model for the calculation sequestration rates based on specific information from Mediterranean cropping systems. Soil C was assumed to be in equilibrium in conventional systems with no organic inputs and conventional tillage, and carbon inputs influenced the balance according to experimental values, which were modified to account for a 100-year time horizon. In this work, we adjusted the model to the particularities of herbaceous crops, taking into account the effect of tillage in herbaceous systems, the presence of N inputs in any form, and the presence of C inputs in the form of straw and weeds. C content of residues was obtained from Rahn and Lillywhite (2002). We assumed that full tillage was the reference practice, with no associated changes in soil carbon, while no tillage was associated to a net sequestration of 0.15 Mg C per hectare per year. This value is the average effect between no tillage and full tillage in the cases with similar C inputs in the meta-analysis by Aguilera et al. (2013b). Using the same source, the absence of some kind of N input in herbaceous systems was associated to a net emission of 0.48 Mg C per hectare. We considered that 8.5 % of straw C was incorporated into the soil at a 100-year time horizon using data from other studies under Mediterranean conditions (Alvaro-Fuentes and Paustian 2011; Kong et al. 2005). Organic farms usually produce more weed biomass than conventional ones (Guzmán et al. 2014). This difference was considered as an additional C input to organic systems (Table 1).

2.4 Sensitivity analysis

We performed sensitivity analyses of the effects of using different N_2O emission factors in cereals and open-air vegetables and of applying different methods of allocation and system expansion for coproduct consideration in cereals (Fig. 1). Nitrous oxide scenarios are compared to *Base*, which represents base case sequestration using Mediterranean factors, and include a scenario based on IPCC Tier 1 methodology (*IPCC*) and another with a 20 % reduction in the emission factor of organic fertilizers (*Reduction*).

In a sensitivity analysis of cereal grain production, we compared economic allocation applied in the base case with different methods for coproduct consideration, including allocation and system expansion methods. Coproduct scenarios include the base case scenario (*Economic*); product allocation (*Product*), in which all emissions are allocated to the main product; dry matter allocation (*Dry matter*); and system expansion, in which coproduced straw is assumed to substitute cereal grain for cattle feeding. In *Expansion 1*, emissions from replaced grain production, calculated by the metabolizable energy content of each feedstock, are subtracted from product emissions. In *Expansion 2*, the change in enteric CH_4 emissions due to the increase in straw in ruminant diet is also considered, following IPCC (2006) methodology based on total energy intake and feed digestibility.

3 Results and discussion

3.1 The greenhouse gas profiles of the studied systems

The studied categories are composed by heterogeneous cases, including different crop types, study sites, and management characteristics. This is reflected in the high variability of yields and carbon footprints that can be observed in Tables 1 and 2. Therefore, the results presented herein must be taken with care. Nonetheless, certain clear trends can be identified between categories, and the pairwise selection of organic and conventional study cases reduces the influence of external factors on the estimated carbon footprints.

3.1.1 Rainfed grains

Because of the low N_2O emission factor in rainfed Mediterranean cropping systems, the role of this gas was very limited in rainfed cereals, while the production and use of industrial inputs account for a major share of the emission profile. These inputs were mainly composed of machinery and fuel in the case of organic management, with a higher contribution of fertilizers in the case of conventional management (Fig. 2a). Interestingly, average C sequestration was not higher

Table 1 Main characteristics of the life cycle inventory of the studied conventional (Con) and organic (Org) groups of herbaceous crops in Spain

	Rainfed cereals		Rainfed legumes		Rice		Open-air vegetables		Greenhouse vegetables	
	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org
Number of interviews	8	8	6	6	3	3	13	13	8	8
Inputs										
Drip irrigation (%)	0	0	0	0	0	0	54	54	100	100
Surface irrigation (%)	0	0	0	0	100	100	38	38	0	0
Water use (m^3)	0	0	0	0	11,500	11,500	3677	3677	3613	3613
Electricity (kWh)	0	0	0	0	3634	3634	1162	1162	1141	1141
Seeds (kg)	183	173	182	192	215	235	0	0	0	0
Seedlings (1000 units)	0.00	0.00	0.00	0.00	0.00	0.00	42.55	40.70	31.90	32.22
Machinery use (h)	8	6	6	5	12	10	27	20	35	36
Fuel consumption (l)	135	109	108	93	211	194	269	219	298	281
Mulching plastic (kg)	0	0	0	0	0	0	35	11	185	168
Mineral nitrogen (kg N)	73	0	13	0	152	0	104	0	264	0
Mineral phosphorus (kg P_2O_5)	38	0	21	0	19	0	54	0	190	0
Mineral potassium (kg K_2O)	34	0	23	0	19	0	141	3	292	0
Manure (Mg)	0.00	1.43	0.00	0.72	0.00	7.67	5.08	18.08	7.00	13.75
Slurry (Mg)	3.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Other organic fertilizers (kg)	0	0	0	0	0	0	1	6	63	1103
Total carbon inputs (kg)	108	577	407	532	2233	3171	690	3182	1546	2736
Total nitrogen inputs (kg)	87	17	61	50	177	90	162	167	393	155
Synthetic pesticides (kg active matter)	0.43	0.00	0.91	0.00	7.14	0.00	5.46	0.00	52.36	0.00
Sulfur (kg)	1.56	0.00	0.00	0.00	0.00	0.00	2.31	0.23	3.00	42.78
Copper (kg)	0.00	0.00	0.00	0.00	0.33	0.00	3.02	0.20	3.45	2.15
Natural pesticides (kg)	0.00	0.00	0.00	0.00	0.23	0.31	0.00	3.95	0.00	29.44
Steel (kg)	0	0	0	0	0	0	0	0	411	411
Greenhouse cover plastic (kg)	0	0	0	0	0	0	0	0	1208	1208
Concrete (kg)	0	0	0	0	0	0	0	0	7290	7290
Production										
Yield (Mg fresh matter, mean)	2.95	1.95	2.32	1.32	7.50	5.17	23.37	17.48	66.23	47.96
Yield (Mg fresh matter, standard deviation)	1.57	0.62	0.92	0.65	0.50	0.76	16.31	14.67	29.71	17.42
Yield (Mg dry matter, mean)	2.54	1.68	1.99	1.13	6.48	4.46	2.48	1.93	3.66	2.75
Weeds (Mg dry matter)	0.39	0.67	0.39	0.67	0.30	0.64	0.00	2.00	0.00	2.00
Residue yield (Mg dry matter)	3.26	2.15	3.23	1.81	8.19	5.64	3.08	2.32	9.55	7.28
Residue destiny										
Open burning (Mg)	0.04	0.02	0.45	0.21	2.73	0.00	1.11	0.30	1.35	1.27
Soil incorporation (Mg)	0.19	0.73	0.99	0.76	5.46	5.64	0.65	1.16	2.81	0.93
Coproduct (Mg)	3.03	1.40	1.79	0.83	0.00	0.00	0.00	0.00	0.00	0.00
Allocation to coproduct (%)	13	9	8	8	0	0	0	0	0	0
Soil emissions										
Direct nitrous oxide (kg N_2O)	0.11	0.02	0.03	0.02	0.84	0.42	1.84	1.98	4.03	1.56
Indirect nitrous oxide (kg N_2O)	0.57	0.14	0.18	0.12	1.15	0.71	1.07	1.27	2.64	1.18
Methane (kg CH_4)	0.10	0.05	1.21	0.56	347.60	440.60	3.00	0.81	3.64	3.43
Carbon (kg C)	−60	−55	−69	−100	−381	−633	−180	−740	−352	−654

Data refer to 1 ha per year unless otherwise stated

under organic than under conventional management, despite greater average C inputs, mainly in the form of crop residues. This could happen because there was one organic case with no organic inputs, and subsequently with a high C loss from the soil, according to our model. The net area-based global warming potential was 1024 kg CO_2e per hectare of

Fig. 1 Organic open-air vegetable cultivation in South Spain

conventional cereal, in comparison with 361 kg per hectare of organic cereal (Table 2), with an average decrease of 65 % for organic products. The change was reduced to −42 % on a product basis due to lower yields under organic management, with emission values of 318 and 185 g CO2e per kilogram of conventional and organic product, respectively. The production of fertilizers was the main factor responsible for the differences observed, while C sequestration was similar between both types of management on an area basis. Our results for conventional grain production are in the lower range of global estimations by Nemecek et al. (2012) and in accordance with studies under Mediterranean climate such as that of Biswas et al. (2008).

Legumes are usually cultivated in rotation with cereals, and their management is similar to theirs in very aspects, particularly machinery use (Table 1). The low use of synthetic inputs under conventional legume management makes it relatively similar to organic legume management in terms of the composition and net value of the greenhouse gas emission balance (Fig. 2), with a modest change of −16 % in CO_2e emissions per kilogram under organic management. Emission values per kilogram of conventional and organic legumes, of 233 and 195 g CO_2e, respectively, are 60–80 % lower than those of different legumes reported in ecoinvent for different European sites (Nemecek et al. 2007). These low emission values support the extended use of legumes in Mediterranean arable crop rotations, adding to their key role as N-fixers and protein suppliers.

3.1.2 Rice

Rice emissions are dominated by methane, with a significant contribution of irrigation (Fig. 2a). The relative performance of organic management in rice systems was the poorest among all crop types considered, mainly due to high methane emissions and low yields. Area-based global warming potential was 9 % higher, but the differences were more marked on a product basis, with an average increase of 60 % (1658 and 2650 g CO_2e per kilogram of conventional and organic rice, respectively). Increased methane emissions in organic systems were associated to the incorporation of rice straw and manures. As shown in other studies, C sequestration promoted by these inputs could not overcome the increase in methane emissions in terms of global warming potential (Wang et al. 2012). Straw and manure have a high content of easily decomposable C, which is associated to methane emissions in rice paddies and therefore to a high scaling factor according to IPCC (2006) methodology. Conventional rice emissions are in the lower range of the global estimations reported by Nemecek et al. (2012), while organic rice emissions are in the upper range.

3.1.3 Vegetables

Irrigation in Mediterranean vegetable cropping systems implies high energy consumption and associated emissions for water pumping and infrastructure building (Table 1), but also allows for higher response to, and thus higher use of fertilizers and pesticides, whose importance in the greenhouse gases emissions balance grows at the expense of machinery emissions (Fig. 2a). The observed decrease in emissions per hectare in organic vegetable cropping systems (−59 % change on average) was due to lower emissions associated to fuel use, fertilizer and pesticide production, and a nearly threefold increase in C sequestration (Table 2). When studied per kilogram of product, organic emissions were still lower in 12 out of the 13 cases studied, with an average change of −32 % (238 and 161 g CO_2e per kilogram of conventional and organic product, respectively). The reduction occurred despite increased N_2O emissions per hectare due to higher indirect N_2O emission factor for organic fertilizers. This could happen because fertilizer intensification in the studied organic systems promotes soil C sequestration through the increase in C inputs and maintains low emission levels in the production of fertilizers, as it mainly employs organic waste materials. The observed global warming potential for conventional systems agrees with assessments performed in many other conditions (González et al. 2011; Nemecek et al. 2012) including a study under Mediterranean climate in California (Venkat 2012). Therefore, differences with other climates seem to be less marked for irrigated Mediterranean systems than for rainfed ones.

Emissions in greenhouse cropping systems were dominated by greenhouse infrastructure (41 and 59 % of emissions in conventional and organic systems, as average), as was also observed in the energy balance of the same crops (Alonso and Guzmán 2010). Emissions in greenhouse cropping systems were relatively high per hectare and low per kilogram of product in both types of management, due to input intensification and high yields. We observed that the average differences in the net global warming potential between organic and

Table 2 Global warming potential of organic and conventional Spanish herbaceous cropping systems for a 100-year time horizon expressed as kilograms of CO_2e per hectare per year and as grams of CO_2e per kilogram of product

	Rainfed cereals		Rainfed legumes		Rice		Open-air vegetables		Greenhouse vegetables	
	Con	Org	Con	Org	Con	Org	Con	Org	Con	Org
Area-based emissions (kg CO_2e ha^{-1})										
Machinery production	28	22	21	19	45	42	52	43	64	56
Fuel production	58	47	47	40	91	84	116	95	129	122
Fuel use	364	294	290	251	569	523	725	591	804	758
Fertilizer production	410	5	183	3	521	29	792	73	2364	216
Direct nitrous oxide	33	6	10	6	249	126	547	591	1202	465
Indirect nitrous oxide	170	41	54	35	344	210	318	378	787	352
Pesticides	3	0	9	0	81	3	58	12	362	91
Irrigation infrastructure	0	0	0	0	90	90	206	206	311	311
Irrigation energy	0	0	0	0	2018	2018	645	645	634	634
Methane	2	1	30	14	8690	11,015	75	20	91	86
Greenhouse	0	0	0	0	0	0	0	0	5157	5157
Nursery	65	46	42	44	343	501	146	135	164	166
Carbon	−110	−102	−127	−184	−699	−1160	−330	−1399	−645	−1199
Total (mean)	1024	361	568	232	12,401	13,481	3448	1418	11,841	7592
Total (standard deviation)	432	394	287	157	1751	208	1633	557	5216	1150
Product-based emissions (g CO_2e kg^{-1})										
Machinery production	10	11	9	15	6	8	4	5	1	1
Fuel production	22	24	21	32	12	17	9	12	2	3
Fuel use	137	152	131	202	76	103	55	77	14	17
Fertilizer production	117	2	63	3	70	6	46	7	34	5
Direct nitrous oxide	10	3	4	4	33	26	31	47	19	10
Indirect nitrous oxide	54	19	22	25	46	43	23	37	12	8
Pesticides	1	0	3	0	11	1	3	1	5	2
Irrigation infrastructure	0	0	0	0	12	18	23	31	7	8
Irrigation energy	0	0	0	0	270	396	58	73	10	13
Methane	1	0	11	11	1161	2164	7	2	2	2
Greenhouse	0	0	0	0	0	0	0	0	109	126
Nursery	21	21	19	35	47	91	5	8	3	4
Carbon	−58	−50	−54	−135	−93	−228	−34	−144	−12	−27
Total (mean)	315	183	233	195	1660	2644	238	161	215	178
Total (standard deviation)	88	219	94	125	258	415	196	176	113	66
Coproduct	50	27	21	23	0	0	0	0	0	0

conventional management were relatively small (−17 % on a product basis), which can be attributed to the high burden of greenhouse infrastructure and water consumption in these systems. The average emission values of 215 and 178 g CO_2e per kilogram of conventional and organic vegetables, respectively, confirm the relatively low carbon footprint of vegetable production in Mediterranean greenhouses obtained in other studies, as compared to vegetables cultivated in heated, glass built greenhouses in colder regions (Theurl et al. 2013; González et al. 2011). We found no previous data reporting emissions of organic vegetables cultivated in Mediterranean greenhouses.

Quality differences should be taken into account when comparing organic and conventional vegetables, as higher dry matter content of organic products (Lester and Saftner 2011) may partially offset lower yields.

3.2 Sensitivity analysis

3.2.1 Nitrous oxide emission factor

The results showed a high variability in the response to the choice of N_2O emission factor. The use of a reduced emission factor for organic fertilizers had an almost negligible effect on

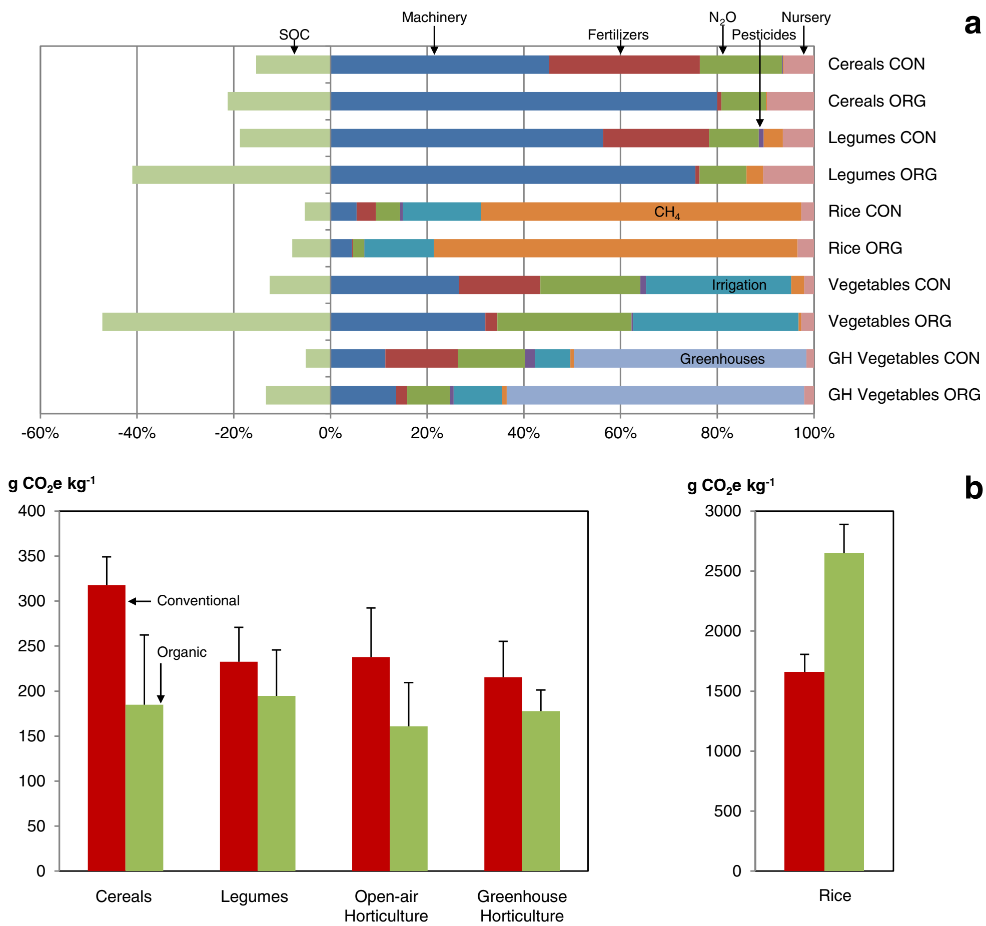

Fig. 2 Global warming potential (g CO_2e kg^{-1}) of the five types of crop products and the two types of management (Conventional (Con) and organic (Org)) studied, expressed as the breakdown of the main processes implicated and as the net balance resulting from subtracting carbon sequestration to total emissions (means with standard errors). The components of the emission balance comprise *Nursery*, including seed production in grain crops and plant nursery in vegetables; *CH_4*, methane from rice cultivation and biomass burning; *Pesticide* production; *N_2O*, including soil emissions, indirect emissions and biomass burning emissions of nitrous oxide; *Fertilizers* production and transport; *Machinery* production and use, including fuel production and use; and *SOC*, which accounts for the changes in soil organic carbon resulting from management practices

the global warming potential of the studied systems. By contrast, largest changes occurred when IPCC factor was used in conventional cereals, which increased net emissions by 33 %, as compared to only 18 % in organic cereals (Fig. 3a). N_2O emission in cereals were actually highly affected by the emission factor due to the large difference between Mediterranean rainfed factor and IPCC factor (one order of magnitude lower for Mediterranean), but in organic systems, the relative contribution of nitrous oxide to the total carbon footprint was small due to low rates of fertilizer application (Fig. 2a). In vegetables, the net effect of the change of N_2O emission factor was much lower (Fig. 3b) because the Mediterranean factors for irrigated systems used in the base case were very similar to the IPCC factor (they were equal in the case of high-water irrigation and 30 % lower for drip irrigation). Our results show that the use of climate-specific emission factors instead of IPCC Tier 1 factors for the estimation of N_2O emissions in LCA of Mediterranean cropping systems leads to substantial differences in the net global warming potential, especially under rainfed conditions. These results agree with the LCA of rainfed cereal systems in Mediterranean-climate Western Australia performed by Biswas et al. (2008).

3.2.2 Coproduct consideration

The sensitivity test shown in Fig. 3c clearly indicates the relevance of the consideration of this coproduct in the greenhouse gas emission balance of cereal grains. The different methods compared address different research questions and lead to very different results. The results obtained using economic criteria for allocation (Economic), as in the base scenario, only slightly differed from those obtained allocating all emissions to the main product (Product), due to the low economic value of straw. When mass criteria were used (Dry matter), however, major changes in the estimated carbon footprint were observed, as the production of commercialized straw, in terms of dry matter, was similar to that of grain (Table 1). The largest effect of coproduct consideration was observed when the system was expanded. In Expansion 1 scenario, we subtracted the emissions associated to the production of the grains replaced by straw as animal feed. This resulted in the lowest global warming potential among the studied methodologies. Other studies have also shown that consequential LCAs usually yield lower global warming potential estimates than attributional LCAs (Thomassen et al. 2008). The observed reduction, however, was more than offset

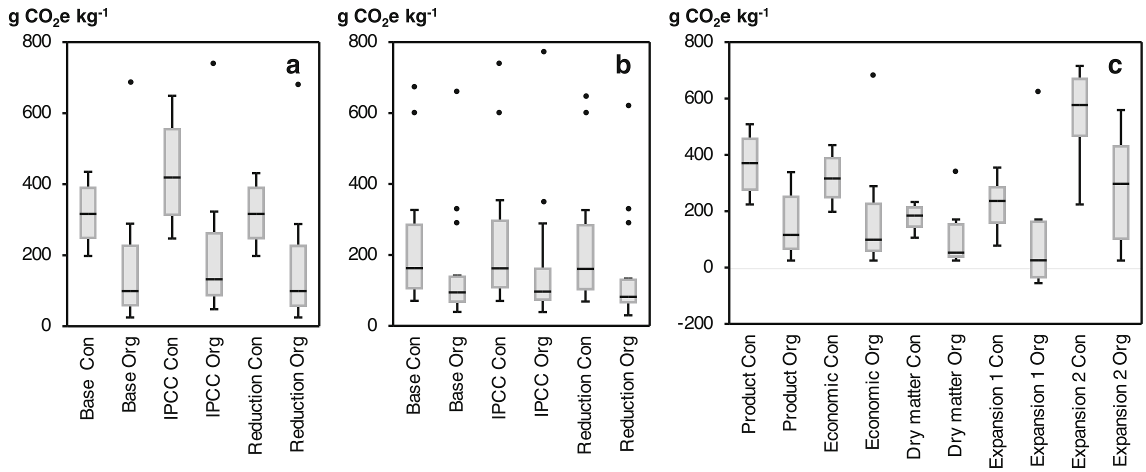

Fig. 3 Sensitivity analysis of the global warming potential (g CO_2e kg^{-1}) of conventional (Con) and organic (Org) management as affected by different estimations of nitrous oxide emissions in cereals (**a**) and open-air vegetables (**b**) and as affected by changes in coproduct consideration in cereals (**c**). Nitrous oxide scenarios are compared to *Base*, which represents base case sequestration using Mediterranean factors and include estimates using IPCC Tier 1 methodology (IPCC) and a 20 % reduction in the emission factor of organic fertilizers (Reduction). Coproduct scenarios include product allocation (Product), in which all emissions are allocated to the main product; economic allocation (Economic); dry matter allocation (Dry matter); and system expansion, in which coproduced straw is assumed to substitute cereal grain for cattle feeding. In Expansion 1, emissions from replaced grain production are subtracted from product emissions, and in Expansion 2, the change in enteric CH_4 emissions is also considered. Data are presented by medians (*lines*), 25–75 % percentiles (*boxes*), non-outlier ranges (*whiskers*), outliers (*dots*), and extremes (*asterisks*)

by increased enteric CH_4 emissions due to the use of a lower quality feed (Expansion 2). These results highlight the need for a full accounting of the effect of these destinies when studying the potential of straw for C sequestration or for other uses such as energy production. Our analysis suggests that complementing the attributional assessment of agricultural products with a consequential analysis would provide insights for understanding these trade-offs.

3.3 The potential for mitigation in herbaceous systems

As described in Sect. 3.1, most of the studied agricultural systems show relatively low emission levels, especially under organic management. The high variability observed, however, together with the limited extension of some climate-friendly practices, suggest that the potential for mitigation is still very large. A singular case is the high emission observed in organic rice production, whose reduction would probably benefit from the use of more stabilized organic inputs, such as compost, vermicompost, or digested slurries, as well as from the increase in yield performance and the reduction in flooding period and in non-renewable input use.

3.3.1 Reducing fossil fuel-based inputs

Fossil energy use dominated the greenhouse gas profiles of the studied systems. In rainfed systems, most emissions were produced by machinery and fuel use, plus fertilizer production in the case of conventional systems. In irrigated systems, the emission profile was diversified by water extraction and greenhouse infrastructure, which are also based on fossil fuels. Fossil fuel-based inputs can be reduced through efficiency gains and through substitution by self-produced renewable ones. The first strategy could make use of techniques such as drip irrigation and reduced tillage practices. The second would imply the use of renewable energy in irrigation, such as solar or wind energy, and the self-production of the fuel used in the farm. Drip irrigation clearly appears as a win-win strategy, saving water and the energy needed for its extraction, while potentially lowering N_2O emissions (Aguilera et al. 2013a). Our results show that the increased emissions due to drip irrigation infrastructure are clearly offset by the emission savings.

In mechanization-dominated rainfed systems, reduced tillage would promote C sequestration (Aguilera et al. 2013b) while saving fuel, cutting greenhouse gas emissions, and reducing the dependence on the increasingly scarce supply of oil derivatives. Tillage reduction often relies on chemical weed control, which may increase pesticide production emissions, but purely mechanical minimum tillage methods are also available. Fuel savings would also improve the feasibility of self-producing the fuel needed in the farm, as a smaller fraction of the product would be needed for producing the biofuel. Self-production of the fuel could increase the efficiency in the use of non-renewable energy while producing a protein-rich coproduct (Aguilera 2009).

3.3.2 Maximizing total yield

Lower yields in organic systems were responsible for decreased carbon footprint reductions under organic farming when studied on a product basis instead of on an area basis. Increasing yields thus appears as a priority for the improvement of the environmental profile of organic cropping systems. Yield improvement would require solving problems associated to the management of pests, diseases, weeds, and nutrients. On the other hand, proposals for changes in management practices have to consider their full impacts. For example, weeds also contribute to the reduction of the net global warming potential by promoting carbon sequestration, as well as to pest control by the provision of habitats for biological control agents. Furthermore, in forage-oriented systems such as cereal and legume fields, the production of weeds may represent an additional forage output that could increase total forage yield when compared with weed-free monocultures (Gholamhoseini et al. 2013). Therefore, deriving weed management recommendations in relation with climate change mitigation is not straightforward and should take into account the multiple functions of weeds in cropping systems. A similar problem appears with the valorization of straw as an additional product. The direct utilization of straw for electricity or thermal energy production is gaining increasing interest (Nguyen et al. 2013), but our analysis suggests that the extraction of straw for energetic purposes should always consider the effect on other uses such as animal feeding and the needed straw to be retained for maintaining or increasing SOC balance. Hence, the revision of yield metrics to consider the multifunctionality of the primary production of cropping systems would contribute to a more accurate quantification of their yield-related environmental burdens, helping to reduce the land cost of sustainability (Guzmán et al. 2011). From this view, techniques that simultaneously address multiple functions seem the most interesting.

3.3.3 Increasing carbon sequestration

Our data suggest that enhancing C sequestration leads to climate change mitigation in Mediterranean systems, which usually show low N_2O emissions and a high soil C response to organic inputs. On the other hand, our estimation of carbon sequestration is based on a 100-year time horizon. Higher carbon sequestration rates, and thus a higher influence of carbon sequestration in the overall balance, would be occurring at a shorter time frames (i.e., 20 years), as shown in a sensitivity analysis of the carbon footprint of Spanish fruit tree orchards (Aguilera et al., Accepted).

Maximizing organic matter inputs both in organic and conventional systems is a way to achieve carbon sequestration that could help improving yields in the former, while reducing the need for synthetic fertilizers and their associated emissions in the latter. However, a number of factors limit endogenous-based C sequestration in herbaceous systems. A major structural limit is space availability for cultivating cover crops, as it would usually mean cultivating less commercial crops in the rotations. The majority of the potential for expanding cover crops relies in crop rotations including a year of fallow and in summer irrigated crops in which the soil is now left bare in the winter.

Another limitation to the increase in organic inputs for soil C sequestration is the alternative use of straws as animal feed. In a country such as Spain, highly dependent on feed imports (Lassaletta et al. 2014), straw may be playing an important role preventing the use of imported grains. Our calculations show that this replacement would have a larger effect on the carbon footprint of crop products than its application to soil. At the same time, increasing soil organic matter levels in Mediterranean soils may be key for adapting to climate change, due to its positive effect on soil physical properties (Aguilera et al. 2013b). This trade-off suggests that there is a need to ensure that the majority of the C removed with straw returns to the soil in some form. The transformation of plant biomass in ruminant bodies implies a release of C as CO_2 and CH_4, but could also contribute to stabilization of the C remaining in the manure, potentially resulting in similar soil retention of the original C with manures than with raw plant biomass (Thomsen et al. 2013). Accordingly, some studies have shown that grazing cereal stubble may not have detrimental effects on C stocks, at least under semi-arid conditions (Quiroga et al. 2009). In spite of this potential, however, the comparison of the global warming potential of these alternative uses of straw would also require considering CH_4 and N_2O emissions produced by animal raising and the potential of dietary changes for the reduction of the demand of meat.

4 Conclusions

Our analysis of the greenhouse gas emission profile of 38 pairs of conventional and organic herbaceous cropping systems in Spain shows that energy-related emissions are the main contributors to the net global warming potential of most of the studied systems, followed by C sequestration. The other soil emissions usually represent a minor role, especially in rainfed systems, which are dominated by fuel emissions. Relatively low N_2O emissions under Mediterranean conditions, due to low N application rates and low N_2O emission factors as compared to global IPCC (2006), are partially responsible for this. These data suggest that management recommendations for climate change mitigation should be based on comprehensive approaches to the quantification of agricultural greenhouse gases, including upstream life cycle processes and climate-specific calculations of direct field emissions and carbon sequestration.

Despite a high variability, we observed a general trend for lower greenhouse gases emissions under organic management, with the significant exception of rice, which represents a clear outlier in our analysis. Higher methane emissions under organic farming point at the convenience of using more stabilized organic inputs in organic rice systems. In the other systems, emission savings under organic farming were due to lower input use or higher C sequestration, or to the combination of both processes, and they were not fully offset by lower yields.

Our results show for the first time that Mediterranean conditions favor intensification in the application of organic matter inputs for climate change mitigation in rainfed and drip-irrigated systems, because the higher C sequestration and yields achieved are not accompanied by very high increases in N_2O emissions. On the contrary, this effect is jeopardized by high fossil energy consumption in surface-irrigated systems and greenhouse systems. More research is needed to verify if similar patterns are found in other semi-arid climates. The dominance of non-renewable energy emissions in the global warming potential of the studied crop products suggests that strategies aiming to reduce resource consumption would successfully contribute to climate change mitigation. For instance, drip irrigation increases yield and residual biomass with low water use and N_2O emissions. Non-renewable fuels could be substituted by self-produced ones, and irrigation water could be extracted with solar or wind energy.

Finally, our results underline the importance of the current and potential multifunctionality of coproducts in the greenhouse gases emissions balance of crop products. For example, the use of herbaceous residues and weeds as animal feed, ensuring that the manure is appropriately applied to the soil, could produce extra food with minor effects on soil C balance but also promotes CH_4 emissions. Thus, this practice seems to be more resource efficient but may increase net greenhouse gases emissions as compared to directly incorporating those residues into the soil. In any case, the role of straw and weeds as ruminant feed needs to be taken into account in the assessment of alternative uses such as C sequestration or energy provision.

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