Carbon emissions and economic assessment of farm operations under different tillage practices in organic rainfed almond orchards in semiarid Mediterranean conditions

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ABSTRACT

Sustainable land management practices, such as reduced tillage or crop diversification, are potentially efficient measures to fight against soil degradation and desertification. The decision to approve these practices must be justified by both integrated environmental and economic assessment studies. In this work, we analysed the carbon emissions associated to farm operations and economic profitability for two organic rainfed almond (*Prunus dulcis* Mill.) farms under semiarid conditions. In the analysis, we considered the following soil management strategies: conventional tillage (CT); reduced tillage (RT); reduced tillage plus green manure (RTG); and no tillage (NT). A cradle-to-farm gate life cycle assessment (LCA) was applied based on long-term data from two farms. The results obtained showed that the NT strategy provided, as expected, the lowest greenhouse gas (GHG) emissions but that its yield was also the lowest, which negatively affects its economic viability even with the consideration of subsidies. The RT strategy reduced GHG emissions and improved the ratio of profit/GHG emissions, whilst the RTG strategy increased GHG emissions and reduced the ratio of profit/GHG emissions as a consequence of using seeds. In conclusion, it has been demonstrated that some level of reduced tillage leads to environmental and economic benefits with respect to conventional tillage in organic rainfed almond orchards under semiarid conditions.

1. Introduction

Almond is the major rainfed woody crop in Spain, covering 686,576 ha; i.e. 85% of the rainfed woody surface area. It is mostly concentrated in Mediterranean areas such as the Region of Murcia, where it accounts for 98% of the rainfed woody surface area (ESYRCE, 2018).

It has been traditionally considered as a marginal crop, and as such, has been located on poor lands where other crops cannot be established. In the Region of Murcia, almond rainfed orchards have been characterised by low density plantations (200 trees/ha); weed control by frequent tillage, which also favours the water reposition in the soil profile; and limitation of the tree size by pruning (Ramos et al., 2009; Martínez-Mena et al., 2013). However, conventional tillage also involves negative aspects such as high-water losses by direct soil evaporation, destruction of the soil structure, high organic matter and nutrient losses and high erosion rates (Gómez et al., 2009; Martínez-

Mena et al., 2008). Accordingly, rainfed almond orchards usually have low yields (about 350–400 kg of almond kernel per hectare; Arquero, 2013).

In this context, the application of sustainable management practices such as reduced tillage or the introduction of green manure has attracted increased interest. According to UNEP-UNDP-UNCCD (2008), such practices are basic tools to combat desertification, soil degradation and reduction of the structural stability, the organic carbon content and the microbial activity.

The benefits associated to reduced tillage are a reduction in soil erosion, leaching and runoff of agricultural chemicals and carbon emissions; the improvement of soil structure; and the increase in soil organic carbon sequestration (Aguilera et al., 2013; Alvaro-Fuentes et al., 2009; Arah et al., 1991; Aulakh et al., 1984; Holland, 2004; Towery, 1998; Uri et al., 1998). Despite these positive on-site effects on the ecosystem services due to the implementation of sustainable management practices in almond agriculture areas, the off-site effects of

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those practices on other ecosystem services have also been highlighted. These latter effects include soil erosion control, water availability and flood regulation at catchment scale (Bekhout and de Vente, 2019).

However, few studies have assessed the effect of energy consumption and carbon emissions associated to farm operations, and most that have done so focused mainly on the effects of conservation tillage in herbaceous crops (Clements et al., 1995; Guardia et al., 2016; West and Marland, 2002; Zaher et al., 2013).

Concerning the economic evaluation of rainfed almond orchards, herbaceous crop agro-systems with reduced tillage are more profitable in moderate and high rainfall zones but are less profitable in low rainfall zones (Zaher et al., 2013). Even though several studies have shown that energy and production cost savings may be achieved through reduced tillage systems compared with conventional tillage (Hernández et al., 1995; Holland, 2004), many producers in some European countries are reluctant to adopt such a practice as it may have contrasting consequences for crop yields, depending on the annual climatic conditions (Van den Putte et al., 2010). In this context, the common agricultural policy has put various instruments into place to promote a sustainable use of soil, including rural development programmes and greening measures (EC, 2019). Organic agriculture is one such practice included in the rural development programmes. Exceptionally, organic agriculture of almond orchards is becoming a common practice in southeast Spain, incentivised by agricultural subsidies and promoted by the low economic benefits of rainfed almond production (MAGRAMA, 2015). Indeed, around 63% of the almond production in the Region of Murcia is under organic agriculture (CAERM (Consejo de Agricultura Ecológica de Murcia), 2019). However, organic agriculture is not always accompanied by other conservation management practices such as reduced tillage intensity, or the use of cover crops including leguminous species (Almagro et al., 2016). It is therefore necessary to make widespread the environmental and economic benefits of sustainable management practices to achieve environmentally sustainable organic almond production.

The main goal of this study is to carry out an integrated environmental (focused on the CO₂ emissions) and economic assessment of farm operations under different tillage practices in organic rainfed almond orchards under semiarid Mediterranean conditions.

2. Materials and methods

2.1. Sites description

Two organic rainfed almond (*Prunus dulcis* Mill.) orchards located in the northwest (Cehegín, 38°3'15"N, 1°46'12"W; 633 m a.s.l., hereafter "Farm A") and centre (Zarzadilla de Totana, 37°51'59"N, 1°43'11"W; 839 m a.s.l., hereafter "Farm B") of the Region of Murcia, in south-eastern Spain, were selected for the carbon emission analysis and economic assessment (Fig. 1). This study was carried out at two 14-year-old commercial almond orchards, cv Ferranges in farm A and cv Desmayo in farm B. The trees were spaced at 7 m × 7 m for both farms. Both sites were located on relatively shallow soils (average soil depth about 30 and 45 cm at farms A and B, respectively) with moderate southeast-facing slopes of around 7% (farm A) and east-facing slopes ranging from 5% to 15% (farm B). Further information on the experimental plots is available in Almagro et al. (2016, 2017) and Martínez-Mena et al. (2013).

2.2. Strategies and input data

The studied strategies were based on four different soil tillage approaches: (i) conventional tillage (CT; designed as the control strategy), (ii) reduced tillage (RT), reduced tillage combined with green manure (RTG), and no-tillage (NT). Tables 1 and 2 show, for each scenario, the farm operations considered in farms A and B, respectively.

In farm A, these conservation practices were carried out for ten

consecutive years, between 2009 and 2018; whereas in farm B, they were conducted for seven consecutive years, between 2009 and 2015. No fertilisers or pesticides (organic almonds) were applied during the study period. As systems inputs, almond kernel yield and pruned woody biomass were collected annually (Table 3). Differences in yield between plots were mainly attributed to significant differences in: (1) tree size: although in both farms the trees had the same age, the average value of trunk perimeter in farm B was about two thirds lower than that in farm A (13.6 ± 0.02 cm vs 50.07 ± 5.56 cm); (2) different almond varieties; (3) annual rainfall: during the trial period the average annual rainfall in farm B (261.3 ± 111.4 mm) was lower than in farm A (340.11 ± 30.9 mm, SIAM, 2019); and (4) the slope of the land: it was much higher in farm B than in farm A, which leads to significantly greater losses of nutrients by erosion in the former (Martínez-Mena et al., 2019a).

2.3. System boundaries

The system boundaries are presented in Fig. 2. A cradle-to-gate approach was used. The system boundaries included all processes that took place in the field, from soil management to harvesting. The following four main field operations were considered for both experimental fields (Tables 1 and 2):

i) Soil management: tillage was performed mechanically with tractors and their respective implements (a disc harrow in farm A and a field cultivator in farm B) to control weeds. In the CT strategy, which is the most common soil management practice among farmers in this area, mechanical soil management was applied three times a year following important rainfall events. In the RT strategy, tillage operations were reduced to twice a year (autumn/spring). In the RTG strategy, tillage operations were also reduced to twice a year (in early autumn to bury the seeds applied manually and in May/June to bury the green manure residues) (Tables 1 and 2). The green manure consisted of a mix of common vetch (*Vicia sativa* L.) and common oat (*Avena sativa* L.) planted at a rate of 150 kg seeds/ha in a proportion of 3:1. In the NT strategy, the weeds are cut in May and left on the soil surface.

ii) Pruning and pick-up of pruned biomass: this was carried out manually with pruning shears, and the pruned woody biomass was collected using a tractor and a pick-up device, to be burned.

iii) Almond harvest: this was carried out using a tractor with a trunk shaker incorporated. This task was performed by external dealers (services) in both farms, using a high-powered tractor not available on the farms.

iv) Transport in-shell almonds (field to farm gate): harvested almonds were transported, on average, a one-way distance of 5 km in a farm trailer.

In short, for all these field operations, the manufactured machinery used for the orchards, the diesel fuel used by the tractors, and the production of seeds for sowing in the RTG strategy were considered.

The assessment did not include: (i) the nursery stage of almond trees, mainly due to the lack of reliable data regarding this phase; (ii) the disposal of material or waste; (iii) the manufacture and construction of a shed for farm machinery storage and a plot fence; and (iv) the soil and biomass carbon sequestration rate in rainfed almond orchards.

2.4. Functional units

In this study, two functional units (FU) were used; i.e. (a) 1 hectare (ha) of almond orchard, and (b) 1 kilogram (kg) of raw brown-skin almond (almond kernel). We selected these two because of the substantial variations in the environmental footprint when comparing crops per unit of area and per product unit (Tuomisto et al., 2012).

2.5. Calculation of greenhouse gas emissions

Greenhouse gas (GHG) emissions were estimated following the IPCC

Fig. 1. Location of the study areas and the different soil management practices implemented: **A** Conventional Tillage (CT); **B** No Tillage (NT); **C** Reduced Tillage plus Green Manure (RTG); and **D** Reduced Tillage (RT). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

2013 v 1.03 (time frame of 100 years) methodology from the Intergovernmental Panel on Climate Change (IPCC, 2006) by quantifying the total GHG emissions directly or indirectly caused by, or accumulated during, the cultivation of 1 ha of almond orchards. GHG emissions were reported in units of carbon dioxide equivalent ($\text{CO}_2 \text{ eq}$) based on the most recent IPCC factors (Myhre et al., 2013). The life cycle impact analysis was performed using the commercial Simapro 8.5.2 (Pre Consultants, 2019) software, by taking into account the phases of classification and characterisation defined by the standards of ISO 14040–14044 series (ISO, 2006).

The following four inputs were considered in order to calculate the GHG emissions:

i) Manufacture of agricultural machinery: farm machinery releases GHG emissions through its manufacturing and by burning fossil fuels during field operations. The LCA inventories for the manufacture of agricultural machinery are specific to the various types of machinery (tractors, tillage implements or other implements). The amount of machinery (AM) used for a specific agricultural operation was calculated by multiplying the mass (MA) of that machinery by the operation time (OT) and dividing the result by the lifetime of the machinery (LT) (Nemecek et al., 2000):

$$\text{AM (kg/FU)} = \text{MA (kg)} \times \text{OT (h/FU)} / \text{LT (h)} [\text{Eq.1}]$$

where FU (see Section 2.4) is the functional unit of the LCA. The lifetime of the machinery considered for these case studies was a Spanish average for each type of machinery (Márquez, 2004). The machinery used in farms A and B for each tillage strategy are shown in Tables 1 and 2.

ii) Production, transportation and combustion of diesel fuel: the diesel consumption used by the agricultural machinery was estimated for each field operation according to Márquez (2004), who presented diesel consumption of specific machinery for woody crops. The inventories for the extraction and transportation of crude oil, its transformation into diesel, its distribution, and diesel exhaust emissions were taken from the Ecoinvent database v 3.5.

iii) Seed production: the emissions involved in seed production were taken from the Ecoinvent database v.3.5. according to common vetch (*Vicia sativa* L.) and common oat (*Avena sativa* L.) at the proportion of 3:1.

2.6. Carbon footprint calculation

The carbon footprint (CF) expresses the total GHGs emitted by direct or indirect effects by a product. In this study, the CO_2 emissions per kg of almond kernel produced ($\text{kg CO}_2 \text{ eq/kg}$ almond kernel) were calculated as the ratio between the total GHG emissions ($\text{kg CO}_2 \text{ eq/ha}$) and the yield (kg almond kernel/ha).

Since the functional unit used to express CF is a mass unit, it was important to document the mass yields (kg/ha) of almond kernel used (Table 3).

2.7. Economic assessment

An economic analysis, based on the inventoried data presented in Tables 1 and 2, was also performed to compare the profitability of the two dryland areas; farms A and B. Data were converted into economic information, inputting the prices presented in Table 4. Detailed hourly cost calculations of field operations can be found in the Supplementary material (Table 1S). The economic valuations were obtained from interviews to several agricultural stakeholders, extension service and market operators. The economic result was calculated as the difference between the total output (TO) and the operational costs (OC). TO was the revenue from sales of almond kernel valued according to the official prices published by the Government of the Region of Murcia (CARM, 2019); i.e. a price for organic almonds kernel cv Ferragnes 7.92 ± 1.4 €/kg, and cv. Desmayo 8.47 ± 1.51 €/kg calculated as the average of all the origin prices between 2012–2018 (CARM, 2019). The price of organic almonds was around 2 €/kg higher than conventional almonds. In addition, organic producers benefit from agri-environment subsidies.

Table 1
Farm operations and main farming inputs used in farm A.

Field operation	Power (kW) and mass (kg) of tractor	Farm implements (characteristics)	Tillage strategy			
			CT	RT	RTG	NT
1. Soil management: - Harrowing	73; 5,100	Disc harrow (2.75 m wide, 963 kg mass, 15 cm deep)	2.1 h/ha, 20.5 L diesel/ha	1.4 h/ha, 13.8 L diesel/ha	0.7 h/ha, 6.9 L diesel/ha	NA
- Sowing	73; 5,100	Manual sowing, Disc harrow (2.75 m wide, 963 kg mass, 15 cm deep)	NA	NA	0.7 h/ha, 6.9 L diesel/ha, 150 kg seeds/ha	NA
- Mowing	73; 5,100	Disc mower (3.40 m wide, 830 kg mass)	NA	NA	NA	0.6 h/ha, 5.8 L diesel/ha
2. Pruning and management of residues	73; 5,100	Pruning shears, Pick-up device (480 kg mass)	51 h/ha pruning, 0.5 h/ha pick-up, 3.7 L diesel/ha			
3. Mechanical harvested	137; 5,350	Trunk shaker (1,290 kg mass)	1.5 h/ha, 9.0 L diesel/ha			
4. Transport of yield	73; 5,100	Farm trailer (1,200 kg mass)	0.3 h, 5 km of distance, 2.2 L diesel/ha			

NA: not applicable.

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

Table 2
Farm operations and main farming inputs used in farm B.

Field operation	Power (kW) and mass (kg) of tractor	Farm implements (characteristics)	Tillage strategy			
			CT	RT	RTG	NT
1. Soil management: - Harrowing	55; 2,791	Field cultivator (3 m wide, 600 kg mass, 20 cm deep)	1.9 h/ha, 15.6 L diesel/ha	1.3 h/ha, 10.4 L diesel/ha	0.6 h/ha, 5.2 L diesel/ha	NA
- Sowing	55; 2,791	Manual sowing, Field cultivator (3 m wide, 600 kg mass, 20 cm deep)	NA	NA	0.6 h/ha, 5.2 L diesel/ha, 150 kg seeds/ha	NA
2. Pruning and management of residues	55; 2,791	Pruning shears Pick-up device (325 kg mass)	34 h/ha pruning, 0.5 h/ha pick-up, 2.7 L diesel/ha			NA
3. Mechanical harvested	137; 5,350	Trunk shaker (1,290 kg mass)	1.5 h/ha, 9.0 L diesel/ha			NA
4. Transport of yield	55; 2,791	Farm trailer (1,000 kg mass)	0.3 h, 5 km of distance, 1.6 L diesel/ha			NA

NA: not applicable.

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

Table 3
Almond yield (kg kernel/ha/year) and pruned biomass by tillage strategy at the two farms.

Item	Place	Tillage strategy			
		CT	RT	RTG	NT
Yield (kg kernel/ha-year)	Farm A ¹	321 ± 165 b ³	311 ± 178 b	269 ± 160 b	87 ± 66 a
	Farm B ²	40 ± 37 a	61 ± 77 a	31 ± 34 a	*
Pruned biomass (Mg/ha-year)	Farm A	2.10 ± 2.56 a ⁴	3.60 ± 4.59 a	1.87 ± 2.14 a	0.60 ± 0.20 a
	Farm B	0.71 ± 0.41 ⁴			

*: In farm B, no tillage strategy was carried out.

1: average of 10-year period (2009–2018).

2: average of 7-year period (2009–2015).

3: Martínez-Mena et al. (2019b) (Farm A) and personal communication (Farm B).

4: calculated following Velázquez-Martí et al. (2011).

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

In each farm, production systems with different letters had significant differences according to Fisher (LSD) at 95.0%.

Fig. 2. Field operations considered within the system boundaries for the tillage strategies analysed.

The European Union recognises the role of organic farming as an asset for both the land and for consumers. Under the common agricultural policy for the period 2014–2020, organic farmers can benefit from several support measures. Organic almond producers in the Region of Murcia receive a grant of 240 €/ha-year from the European Union devoted to organic agriculture maintenance (BORM, 2015).

Machinery costs, manpower and seeds (in the RTG strategy) were calculated as follows: machinery costs were calculated according to Miserque et al. (1997) and Márquez (2004). The following variables were used (Table 4 and Table 1S of the supplementary material): (a) purchase price for tractors and implements; (b) depreciation estimated by working life (years) and annual usage (h); (c) interest rate, 5% of

purchase price; (d) taxes, insurance and housing, 2% of purchase price; (e) cumulative repair and maintenance costs estimated by working time; (f) diesel consumption for farm operation (L/h) and diesel price of 1 €/L; and (g) manpower 9.92 €/h for trained workers (drivers and pruner workers) and 8.72 €/h for labourers.

3. Results

3.1. Greenhouse gas emissions

Different results were obtained for the same strategy in each farm. Overall, the GHG emissions in farm A were higher than those in farm B (Table 5). This was mainly due to the lower power and mass of the tractors and implements in farm B; using smaller tractors means lower fuel consumption and GHG emissions. Total GHG emissions in CT were 134 and 106 kg CO_{2eq}/ha in farms A and B, respectively (Table 5). GHG emissions in the RT strategy were lower than in CT (19% in both farms). The main cause of these reductions was the reduction of one tillage labour per year (Tables 1 and 2). As expected, the NT strategy, with zero tillage, showed the lowest GHG emissions with reductions of 33% in farm A. Note that in farm B, the NT strategy was not implemented. In contrast, the highest GHG emissions were observed in the RTG strategy, despite the reduction of tillage. In this latter strategy, GHG emissions increased 41% in farm A and 57% in farm B compared to CT (Table 5). This was due to the seed production processes that were used as green manure in the RTG strategy and emitted 80 kg CO_{2 eq} per 150 kg seeds; the figure corresponds to 25 (oat) and 55 (vetch) kg CO_{2 eq}.

The emissions from the production, transportation and combustion of diesel ranged, irrespective of the experimental farm, between 42% in the RTG strategies to about 76% in the CT, RT and NT strategies and were the main component of the total GHG emissions (Table 5). Within these emissions, soil management showed the highest GHG emissions. It should be noted that mowing is the labour used in the NT strategy to control weeds, which represents 28.1%. Mechanical harvesting was the second cause of GHG emissions. In farm A, mechanical harvesting

Table 4
Cost of field operations and inputs by farm.

Farm	Tractor	Tillage implement	Manual sowing	Disc mower	Manual pruning	Pick-up device	Trunk shaker	Farm trailer
Farm A								
- Machinery (€/h)	21.28 ^a	19.78 ^b		13.96		13.07	60	15.95
- Labour (€/h)	9.92		8.72		9.92			
- Seeds (€/kg)			0.5					
Farm B								
- Machinery (€/h)	18.44 ^c	16.93 ^d				11.25	60	14.12
- Labour (€/h)	9.92		8.72		9.92			
- Seeds (€/kg)			0.5					

a: tractor 73 kW, b: disc harrow, c: tractor 55 kW, d: field cultivator.

Table 5
GHG emissions (kg CO₂ eq/ha) associated with inputs for tillage strategy at the farms.

Input / field operation	Farm A. Tillage strategy				Farm B. Tillage strategy		
	CT	RT	RTG	NT	CT	RT	RTG
1. Emissions from production, transportation and combustion of diesel	105 (78.7)	84 (76.6)	84 (44.3)	69 (76.3)	84 (79.1)	66 (76.3)	66 (39.6)
- Soil management	62 (46.1)	40 (36.6)	40 (21.2)	25 (28.1)	47 (44.7)	29 (33.9)	29 (16.0)
- Pruning and management of residues	11 (8.1)	11 (9.9)	11 (5.8)	11 (12.1)	7 (6.9)	7 (8.5)	7 (3.9)
- Mechanical harvester	25 (19.0)	25 (23.3)	25 (13.5)	25 (28.0)	25 (24.1)	25 (29.7)	25 (13.7)
- Transport of yield	7 (5.4)	7 (6.7)	7 (3.9)	7 (8.1)	4 (3.4)	4 (4.2)	4 (2.0)
2. Emissions from manufacture of agricultural machinery	29 (21.3)	25 (23.5)	25 (13.5)	21 (23.7)	22 (20.9)	20 (23.7)	20 (12.2)
- Soil management	9 (6.2)	6 (5.2)	6 (3.0)	1 (1.1)	5 (4.4)	3 (3.6)	3 (0.6)
- Pruning and management of residues	2 (2.1)	2 (1.9)	2 (1.1)	2 (2.3)	1 (1.0)	1 (1.2)	1 (4.9)
- Mechanical harvester	8 (6.0)	8 (7.3)	8 (4.3)	8 (9.0)	8 (7.7)	8 (9.5)	8 (4.9)
- Transport of yield	10 (7.5)	10 (9.1)	10 (5.3)	10 (11.3)	8 (7.7)	8 (9.5)	8 (4.9)
3. Emissions of seed production	NA	NA	80 (42.2)	NA	NA	NA	80 (48.2)
Total emissions (1 + 2 + 3)	134	109	189	90	106	86	166

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

The number in parentheses indicates a percentage of each crop total GHG emissions.

NA: not applicable.

ranged from 13.5% in RTG to 28.1% in NT. In farm B, it ranged from 13.7% in RTG to 29.7% in RT; 25 kg CO₂ eq/ha in both farms.

3.2. Carbon footprint

While analysing the carbon emissions per kg of almond kernel, farm A was four-fold lower than farm B (3.14 vs 0.63 CO₂ eq/kg almond kernel, on average; Table 6). The foremost cause for this difference was attributed to the low yield in farm B. On the other hand, analysing by tillage strategy, reduced tillage in farm A showed a slight effect on the CF; however, RTG and NT increased CF. The mainly reason for this result in the RTG strategy was the increase in GHG emissions due to the use of seeds; however, in NT it was the reduction of GHG emissions and also the yield; i.e. the substitution of tillage labour by mowing in the NT strategy which reduced the GHG emissions from 134 to 90 kg CO₂ eq/ha in farm A (reduction of 33%; Table 5) and the yield from 321 to 87 kg kernel/ha-year (reduction of 73%). Consequently, the kg CO₂ eq/kg almond kernel reached 1.03 in the NT strategy. This supposes an increase of 148% with respect to the CT strategy. In farm B, despite following the same methodology, the results are somewhat distorted by the high variability in yield among the strategies (Table 3).

3.3. Economic assessment

Table 7 shows the operational costs, revenues, and profits for farms A and B considering the different experimental treatments.

In both farms, the RT and NT (not analysed in farm B) strategies reduced the operational costs by 4% and 10%, respectively. On the contrary, the RTG strategy, which considered seed acquisition and the manual sowing, increased the cost by 7%–10% compared to the CT treatment, in farms A and B, respectively.

In farm A, the highest revenue was observed in the CT treatment

Table 6
Carbon footprint (kg CO₂ eq/kg almond kernel) by tillage strategy and farm.

Place	Tillage strategy			
	CT	RT	RTG	NT
Farm A ¹	0.42	0.35	0.70	1.03
Farm B ²	2.65	1.41	5.35	*

*: In farm B, no tillage strategy was carried out.

1: average of 10-year period (2009–2018).

2: average of 7-year period (2009–2015).

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

(2,781.17 €/ha), whereas the lowest was obtained in the NT treatment (854.95 €/ha). In this latter case, if the subsidy to organic farming is not considered, it even led to a negative profit of -30.69 €/ha. Considering the economic and environmental analysis together, RT was the best strategy with the highest ratio of profit/GHG emissions (18.78 €/kgCO₂ eq).

In farm B, the highest revenue was observed in the RT strategy due to the higher yield compared to the CT treatment. In that farm, if the subsidy to organic farming is not considered, it even led to negative profits in the CT (-187.62 €/ha) and in RTG (-321.99 €/ha) strategies. Considering the economic and environmental analysis together, RT was again the best strategy with the highest ratio of profit/GHG emissions (3.04 €/kgCO₂ eq). Comparing between farms, the RT strategy in farm A reported a six-fold higher ratio of profit/GHG emissions than in farm B.

4. Discussion

The GHG emissions estimated in this work were much lower than the emissions given by other authors in almond crops. For example, in the USA, GHG emissions ranged from 3,200 to 6,842 kgCO₂ eq/ha (Marvinney et al., 2015; Venkat, 2012) and in Spain GHG emissions ranged from 1,269 (organic) to 1,531 (no organic) kgCO₂ eq/ha (Aguilera et al., 2015). The main cause for those high GHG emissions, as compared to our study, was the heavy use of pesticides, irrigation and above all fertilisers in the case of non-organic farms. In fact, N fertiliser production and application was the dominant cause of GHG emissions in all the studies in conventional farms; i.e. 31% (Venkat, 2012) to 40% (Aguilera et al., 2015) share of GHG emissions. However, in organic farms, diesel was the main contributor to GHG emissions (63% in the case of Aguilera et al., 2015). In our study, those emissions from diesel amounted to around 80% of the GHG emissions, because tillage was the only field operation in the CT strategy (Table 5).

Overall, the use of inputs in irrigated woody orchards is much higher than in rainfed woody orchards. For example, regarding GHG emissions related to machinery use (machinery and diesel consumption) in organic almonds production, Aguilera et al. (2015) reported seven-fold higher GHG emissions than in our study. It should be noted that in said study, machinery was also used for other field operations such as the application of pesticides. In another study, Garcia et al. (2004) reported four phytosanitary treatments per year in irrigated almond orchards.

Several ways to minimize the GHG emissions from diesel consumption which ought to be mentioned here have been identified:

(1) employ biodiesel from waste vegetable oil when possible. It should be noted that CO₂eq emissions from diesel are 74.3 gCO₂ eq/MJ

Table 7

Operational costs, revenues, and profits for farms A and B considering the different experimental treatments. It also presents the ratio profit/GHG emissions.

Field operation		Farm A. Tillage strategy				Farm B. Tillage strategy		
		CT	RT	RTG	NT	CT	RT	RTG
Operational cost (€/ha)		709.51	681.07	764.90	645.64	520.22	497.45	581.16
1.1. Soil management	Harrowing	85.01	56.57	28.34		68.32	45.55	22.77
	Harrowing			28.34				22.77
	Manual sowing			8.72				8.72
	Seeds			75.00				75.00
	Mowing				21.14			
1.2. Pruning and management of residues	Hand pruning	505.92	505.92	505.92	505.92	337.28	337.28	337.28
	Pick-up	17.41	17.41	17.41	17.41	14.85	14.85	14.85
1.3. Mechanical harvested	Trunk shaker	90	90	90	90	90	90	90
1.4. Transport of yield	Farm trailer	11.17	11.17	11.17	11.17	9.77	9.77	9.77
2. Revenue^a (€/ha)		2,781.17	2,728.61	2,421.61	854.95	572.60	758.34	499.17
2.1. Sale of almond		2,541.17	2,488.61	2,181.61	614.95	332.60	518.34	259.17
2.2. Subsidy to organic farming		240	240	240	240	240	240	240
3. Profit^a (€/ha)		2,071.66	2,047.54	1,656.71	209.31	52.38	260.89	-81.99
3.1. Without considering 2.2		1,831.66	1,807.54	1,416.71	-30.69	-187.62	20.89	-321.99
3.2. Considering 2.2		2,071.66	2,047.54	1,656.71	209.31	52.38	260.89	-81.99
4. Ratio Profit/GHG emissions (€/kgCO_{2eq})		15.46	18.78	8.77	3.31	0.49	3.04	-0.49

Tillage strategies: conventional tillage (CT), reduced tillage (RT), reduced tillage plus green manure (RTG) and no tillage (NT).

^a Revenue and profit have been shown considering the subsidy to organic farming.

(IPCC, 2006), whereas for biodiesel the figure is 14 gCO₂ eq/MJ (EPC (European Parliament and Council), 2009). As a result, this measure could cut the emissions by an average of between 56 (NT) and 77 (CT) kg CO₂ eq/ha using biodiesel from waste vegetable oil; this would mean a decrease of 19% in GHG emissions by hectare.

(2) proper sizing of agricultural machinery in farm has been proposed by several authors (Page et al., 2011; Sastre et al., 2014). In our study, the use of diesel and the associated emissions per hectare could be lowered in farm A by using a smaller low-powered tractor (using 55 kW instead of 73 kW); i.e. annual diesel consumption in farm A using 73 kW tractor was 35 (CT), 29 (RT or RTG) and 22 (NT) L/ha-year; however in farm B, using a 55 kW tractor it was 29 (CT) and 24 (RT or RTG) L/ha-year. Accordingly, tractor B saved around 17% of diesel fuel by this strategy. From an economic point of view, it is also appealing given that it could save around 27% of the operational cost by year.

(3) the reduction of the tillage frequency in farm, as tillage reduction or suppression implies a decrease in CO₂ emissions associated to farm operations, mainly driven by lower diesel consumption (Govaerts et al., 2009). In our study, the annual savings in diesel consumption using reduced-tillage strategies (RT and RTG) were 6.8 and 5.2 L/ha-year compared to CT, in farms A and B, respectively (Tables 1 and 2). Such reductions were equivalent to a reduction in CO₂ emissions of 22 and 18 kg CO₂ eq/ha-year, in farms A and B, respectively; In short, reducing one out of three tillages per year involved a reduction of 20% GHG emissions. We note that all our proposals detailed above can be compatible.

In terms of kg CO₂ eq/kg almond kernel, in farm A we found much lower values for CF than those estimated by other authors who displayed values from 0.95 to 3.77 kg CO₂ eq/kg almond kernel under irrigated almond orchards (Clune et al., 2017; Kendall et al., 2015; Marvinney et al., 2015; Nemecek et al., 2012). In those farms, intensive use of water, fertilisers and pesticides were given; this can explain the differences in CF with our farm where rainfed conditions and no fertilisation prevailed. Furthermore, the almond yield under irrigation is three- to four-fold higher than under rainfed almond orchards (Arquero et al., 2013; Calatrava et al., 2006).

On the other hand, the highest specific emission in farm B (3.1 kg CO₂ eq/kg almond kernel, on average) compared to farm A can be explained by the extremely low productivity in that farm (Table 3).

Overall, there were important differences in yield between the farms (Table 3). The yield in farm A was much higher than in farm B; eight-fold in CT, five-fold in RT and nine-fold in RTG. In farm A, significant

differences were found between NT (87 kg almond kernel/ha) and the rest of the tillage strategies (CT, RT and RTG with an average of 300 kg almond kernel/ha). In farm B, the statistical analysis showed no significant differences among the tillage strategies (CT, RT and RTG) with an average of 44 kg almond kernel/ha (Table 3). Differences in yield between farms were explained in section 2.2.

Concerning the economic profitability (Table 7), farm B showed a negative mean profit (without subsidy), similar to that reported as the average value in the Region of Murcia (MAGRAMA, 2015); and closely matching those obtained by Calatrava et al. (2006) who conditioned the profit of rainfed almond producers in this region to EU subsidies. This demonstrates the powerful role that subsidies play on the configuration of agricultural and semi-natural landscapes, as established by other studies (van Leeuwen et al., 2019), with a very important influence on the soil conditions and economic viability.

On the other hand, farm A showed a positive profit without EU subsidies in all strategies except in the NT strategy. The economic benefits associated to RT compared to CT were very low, reporting a 4% reduction in operational cost but 20% in GHG emissions. It should be noted that with reduced tillage in extensive crops this can reach up to 10% (FAO, 2019).

The highest GHG emissions by farmer operations in RTG and also the lower profitability compared to CT or even RT should be taken with caution, given that: i) in this approximation other associated ecosystem services in the category of regulating (erosion control, flood control, pollination) and provisioning (green water availability, increase of biodiversity), as investigated by Almagro et al. (2016) have not been taken into account; and ii) an improvement in crop yields under RTG compared to CT has been observed after seven years from its implementation (Martínez-Mena et al., 2019b), which is not reflected in the average value of the ten years considered in this study (in the case of farm A). In order to promote the adoption of sustainable agricultural practices such as reduced tillage by farmers, it should be necessary to emphasise the environmental (GHG emissions reductions) rather than the economic benefits associated to it, and this requires support from public administrations through different strategies.

5. Conclusions

This study has determined carbon emissions and economically evaluated two organic rainfed almond agro-ecosystems considering different farm operations, including several tillage practices under

semiarid Mediterranean conditions.

No tillage, as implemented in this study, provided the lowest GHG emissions, although this result must be taken with caution since yield was also significantly reduced and, even with subsidies, the strategy is very close to being economically unfeasible. The results hence suggest that some level of reduced tillage may provide certain environmental and economic benefits with respect to conventional tillage. Reducing one tillage pass per year; *i.e.* from three times to twice, has considerably reduced the GHG emissions and improved the ratio of profit/GHG emissions. However, reduced tillage combined with green manure has increased the GHG emissions from farm operations and reduced the ratio of profit/GHG emissions as a consequence of using seeds.

In short, under the conditions of this study and for the tested environmental and economic indicators, reduced tillage without green manure is the best strategy for almond producers and the sustainability of land. Nevertheless RTG could be become more positive in case other ecosystem services, in particular carbon sequestration, were considered.

Longer-term studies that integrate and quantify all the environmental benefits of these sustainable management practices would be necessary in order to obtain a more complete picture of their feasibility.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.scienta.2019.108978>.

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