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Almond farm profitability under agroecological management in south-eastern Spain: Accounting for externalities and opportunity costs

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ABSTRACT

Agroecological practices have been shown to control erosion, increase soil fertility, carbon stocks, pollination and biodiversity. As a consequence, these ecosystem services can contribute to a better farm economic resilience on the long-term; however, empirical evidence is scarce. In this study we aim to understand the economic performance of agroecological practices in almond orchards and the relevance of different economic and policy scenarios to incentivise the upscaling of agroecological practices. We investigated the development of the net present value (NPV) of several agroecological practices (no tillage (NT), green manure (GM) and compost (CM)) as compared to conventional tillage (CT), as well as the effect of internalising externalities through payments for soil carbon sequestration and by costs of erosion. Finally, we explored the effects of price premiums and public greening payments, on farm NPV. We found that all management regimes were profitable and that CM had a 17.2% higher NPV than CT, while both GM and NT had lower NPV than CT (69% for GM and 90.1% for NT). We found that despite NT and GM have higher soil organic carbon stocks, these provided a negligible additional income via carbon markets. CT had the highest externality costs of erosion but still its NPV was higher than NT and GM, despite the strong reductions in costs of erosion in NT and GM conferred by vegetation covers. We found that a price premium of 45% was necessary to make NT's economic performance comparable to that of CT, while a 27% price premium would be needed to make GM comparable to CT. Compensation through public greening payments would be in the order of €644 $ha^{-1}\ y^{-1}$ for NT and €387 $ha^{-1}\ y^{-1}$ for GM to have a similar NPV as CT. Our results suggest a trade-off between income from yield and costs from unaccounted externalities. We also find that private and public policy incentives could reverse this outcome, but requiring a large investment. Of the analysed agroecological practices, compost application appears the most promising to be scaled-up to improve both economic and environmental performance, and further research is needed to determine the outcomes of a combination of compost and vegetation covers.

1. Introduction

Agroecological management holds the premise to maintain yields while providing additional ecological benefits (FAO, 2018). Natural ecosystem-inspired agricultural management, i.e. agroecological management, uses practices such as no tillage, vegetation cover, application of organic soil amendments and others (Wezel et al., 2014) to balance agricultural productivity and ecological functionalities and improve the resilience to external bio-physical disturbances (e.g. erosion, droughts, plagues, etc.) (Altieri, 2002). Although it is expected that improved resilience to environmental degradation will result in higher farm-level economic stability (Darnhofer, 2014), agroecological management may also result in reduced yields of the main crop adding uncertainties to investment (Kremen et al., 2012). Up until now few studies have tried to empirically demonstrate the effect of agroecological management on the farm's economic performance, including all costs, benefits and externalities, which makes the adoption of agroecological practices a financially uncertain transition for farmers, thus hampering its large-scale implementation (Rodriguez et al., 2009; Schoonhoven and Runhaar, 2018). Therefore, we need a better understanding of how agroecological practices influence the long-term financial development of farms, and which financial barriers might need to be overtaken, to be

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able to accelerate the implementation of environmentally friendly agricultural practices.

Agroecology is an holistic agricultural movement that integrates both ecological and social concepts to design resilient food systems (FAO, 2018). Related to the specific land management, it aims to improve internal ecological processes that optimise the functionality and resilience of the farm system (Aguilera et al., 2020). A wide range of agroecological practices are used to apply these principles. For the Mediterranean area, the principles of minimum soil conservation, permanent soil coverage and organic soil amendment have been identified to be crucial to stimulate ecological functions (Aguilera et al., 2020; Wezel et al., 2014). Agroecological practices in Mediterranean orchards, such as cover crops, organic soil amendment and no tillage, benefit ecological processes such as erosion control, soil fertility, pollination, pest control, carbon sequestration and biodiversity maintenance (Almagro et al., 2016; De Leijster et al., 2019; Durán Zuazo et al., 2008; Gómez et al., 2017; Ramos et al., 2011). Yet these practices are rarely implemented and conventional tillage without application of organic amendments is still the most widespread practice (García-Ruiz, 2010; Meerkerk et al., 2008). In eastern Andalusia (south-eastern Spain) more than 50% of the almond farms are certified organic (Junta de Andalucía, 2016). Organic certificates, however, do not include criteria on orchard floor management, and therefore the mainstream floor management of these organic orchards is conventional tillage, which involves a tillage frequency of 3 to 5 times a year withholding natural vegetation to grow and therefore causing biophysical land degradation (Zdruli, 2014). Agroecological practices are until now voluntary practices, as there is no certification body or policies that require to apply them. In a recent study, we demonstrated that, compared to conventional tillage management, agroecological management in Mediterranean almond plantations has the potential to improve the provisioning of ecosystem services by 17–24%, namely nutrient cycling, carbon stock, habitat provisioning, pest control, pollination and food provisioning (De Leijster et al., 2019). Other studies report comparable results, for example, it has been shown that vegetation covers in almond crops improve pollinator activity (Norfolk et al., 2016; Saunders et al., 2013), and soil organic carbon by 56–67% (Ramos et al., 2010) and reduce soil erosion by 51–95% (Durán Zuazo and Rodríguez Pleguezuelo, 2008; Martínez-Mena et al., 2019).

Although that the environmental benefits of agroecological practices are well established, the economic impacts are less well studied. The effects of agroecological management on farm's economic performance metrics, such as management and investment costs, labour, and long-term profitability is barely known, as economic assessments tend to be limited to crop yields disregarding management costs and externalities (Bommarco et al., 2013). Examples of such studies on agroecological management and crop yields in Mediterranean treecrops reported trade-offs between understory vegetation covers and crop productivity (De Leijster et al., 2019; Martin-Gorriz et al., 2020; Martínez-Mena et al., 2013). Another study showed that the implementation of no-tillage with natural understory vegetation in a Spanish almond plantation reduced yield by 63% compared to conventional tillage management (Martin-Gorriz et al., 2020). Crop yield, however, is not a comprehensive indicator of farm economic benefits, as operational costs, investment costs, market price and subsidies also have a significant influence on farm profitability (Jezeer et al., 2018, 2017; Sgroi et al., 2015). Therefore, long-term profitability metrics that consider all the costs and income generated during the project life-time such as, Net Present Value (NPV), Internal Rate on Return (IRR) and Discounted Payback Time (DPBT) are more appropriate economic metrics. For example in Italian lemon orchards, organic management resulted in lower yields than conventional management, but still provided higher NPV because of lower management costs and higher market price (Testa et al., 2015). Similar results were found for Italian olive orchards (Sgroi et al., 2015) and for coffee and cocoa (Jezeer et al., 2017). These are examples of organic and tropical agroforestry management, and to our knowledge there is no research that assesses the economic performance of agroecological management in Mediterranean woody crops. Yet, there is another reason why long-term consideration is needed for financial assessments. Economic settings are not static as market prices and costs of, e.g., labour and materials fluctuate. Therefore, it is important to incorporate these annual fluctuations in costs and revenues in order to project whether years with negative financial metrics are expected to occur more regularly.

The production of agricultural commodities often results in environmental externalities that are not integrated in the market process (Bommarco et al., 2013). In the Mediterranean woody crop sector, decrease in soil organic carbon content and accelerated erosion rates are considered externalities with the strongest effect on land degradation (Montanaro et al., 2017). The magnitude of the externalities is management specific; as mentioned before, conventional tillage management results in higher erosion rates and lower soil organic carbon content than agroecological management (Cucci et al., 2016; Durán Zuazo and Rodríguez Pleguezuelo, 2008). Alternative practices might result in lower externalities; however, they may also be less profitable than the conventional approach. When this is the case, the difference in economic net benefits, referred to as opportunity costs (European Commission, 2014), can serve as a metric to evaluate conventional and alternative practices. To overcome these opportunity costs and facilitate the adoption of improved agricultural practices by farmers, practice-based financial compensation can be provided (Kurkalova et al., 2004; Luo et al., 2014). Price premiums (e.g. coupled to certification schemes) and green subsidies (e.g. European Union's Common Agricultural Policy greening payment) are two examples of widespread incentive mechanisms aiming to internalise opportunity costs (Wiesmeth, 2012), yet to be applied to agroecological management in woody crops in Mediterranean regions.

In this study we aim to compare the economic performance of agroecological management with that of conventional tillage management and explore the relevance of different economic and policy options. First, we determine the long-term economic performance of three agroecological practices (no-tillage, green manure and compost) and compare it to conventional management in European Mediterranean almond orchards. We develop a stochastic model of economic performance to project the net present value (NPV), internal rate of return (IRR) and discounted payback time (DPBT) of the farms over 30 years. We use input data obtained from 3 yearlong field experiments in almond orchards in the South East of Spain. Second, we apply the economic model to compare economic performance of agroecological with conventional management when 1) externality costs are internalised through payments for erosion control and carbon sequestration services, and 2) opportunity costs are compensated for by private or public incentive-based policy systems. Through our results, we expect to gain a better understanding of the economic performance of agroecological and conventional management, and be able to identify the most suitable policy instruments to overcome financial barriers for agroecological management adoption, a needed step to accelerate the transition towards environmentally friendly agricultural landscapes.

2. Method

2.1. Study site and field experiments

This study was conducted in the eastern part of Andalusia, south-eastern Spain. Rainfed almond cultivation is rapidly expanding in this area, having increased by 18% between 2014 and 2017 (Junta de Andalucía, 2016). This expansion can be attributed to market opportunities and high prices, due to the failure in almond production in California (USA), which produces more than 90% of worlds' almonds (FAOSTAT, 2019). This makes rainfed almond cultivation currently one of the most abundant agricultural land-covers in the high plains of the provinces Granada and Almería. Almond farms in this region are typically located at elevations between 700 and 1300 m. This region is characterised by low annual precipitation of 300–400 mm and extreme differences in temperature with a maximum average of 31–39 °C in summer and a minimum average of 0–4 °C in winter (Cruz Pardo et al., 2010). The soils of the experimental sites (see section 2.1.1.) can be classified as Calcic Cambisols, Eutric Cambisols, and Calcic Regosols and had loam and sandy loam textures (De Leijster et al., 2019).

2.2. Agroecological experiments, yields and farmer surveys

2.2.1. Agroecological experiments

From 2016 to 2018 we conducted field experiments with four treatments on five experimental sites, located on private rainfed almond farms. On each farm, the treatments were implemented in randomly assigned locations similar in slope, crop variety and visual soil conditions; each treatment containing a minimum of sixteen trees (for specific farm characteristics see Supplementary materials Table S1). The conventional tillage (CT) treatments were harrowed 2–3 times a year at 20–30 cm depth, using a chisel plough to remove the understory. The no-tillage (NT) treatments were not harrowed and not mowed, which allowed wild plant species to grow. The green manure (GM) treatments were sown with a legume–cereal mixture (common vetch, bitter vetch, barley; 50–50-20 kg ha^{-1}) and then harrowed to incorporate the seeds in the soil. The compost (CM) treatments were fertilised with compost (fermented sheep manure and straw; type bokashi) applied manually near the almond trees at an approximate quantity of 6 m^3 ha^{-1} and incorporated in the soil by harrowing. In addition, the CM treatments were harrowed 1–2 times to remove weeds. Organic pest control was only reactively applied, but no impactful pest or plague outbreaks emerged in the experimental sites. All treatments were certified organic. Detailed information about the treatments can be found in the supplementary materials Table S2.

2.2.2. Harvest measurements

In each treatment of each experimental site we measured production during the harvest season, August–September, in 2016, 2017 and 2018. Per treatment 16 trees were harvested in groups of four, thus obtaining four replicates per farm. Almond fruits were hulled and shelled to obtain almond yield expressed as kernel weight per tree. Detailed methodology is described in De Leijster et al. (2019) and production data are given in supplementary material Fig. S1–2 and Table S3.

2.2.3. Survey

In the winter of 2015–2016 we conducted a survey among the same five farmers who owned the farms wherein the field experiments were conducted and an additional ten farmers who applied conventional tillage to get a better estimation of general farm expenses (pest control, harvest, pruning, etc.) and incomes (subsidies, prices and farm-gate yields) (total $n = 15$). The aim of the survey was to characterise management practices and to obtain data on investment and operational costs, self-reported yield, farm-gate price, and other in-farm sources of income besides almond cultivation. The data was collected using semi-structured interviews that followed a pre-designed questionnaire. We collected data on (i) farm characteristics (farm area, crop age, crop density and almond variety), (ii) management characteristics (tillage frequency, pruning frequency, fertiliser type and quantity, pest treatment type and quantity, ground cover management), (iii) investment costs (on-site crop design, first time soil preparation and purchase and planting of trees), (iv) operational costs (tillage, soil amendment, ground cover management, pruning, pest control, machinery maintenance, diesel), (v) labour, and (vi) income (self-reported almond yield, farm gate almond price and subsidies).

Table 1
Overview of the economic performance indicators.

Indicators of economic performance	Data source
Gross revenue	
Almond yield (kg ha^{-1} y^{-1})	Experiments[a], Surveys[b]
Almond price (€ kg^{-1})	Expert communication[c], FAOSTAT[d]
Subsidy (€ ha^{-1} y^{-1})	Surveys
Costs	
Operational costs (€ ha^{-1} y^{-1})	Surveys
Indirect costs (€ ha^{-1} y^{-1})	Literature + Survey
Capital costs (€ ha^{-1})	Literature
Investment costs (€ ha^{-1} y^{-1})	Surveys
Net revenue	
Gross revenue – Costs (€ ha^{-1} y^{-1})	Calculation
Economic performance metrics	
NPV (€ ha^{-1})	Stochastic cash flow model
IRR (%)	Stochastic cash flow model
DPBT (y)	Stochastic cash flow model

[a] See section 2.1.1.
[b] Surveys are described in section 2.1.2, and Table 2.
[c] See section 3.2.2 *gross revenue*.
[d] See section 3.2.2. *gross revenue*.

2.3. Model description and assumptions

We used a stochastic cash flow model to simulate the economic performance of four management practices (CT, NT, GM and CM) for almond cultivation. Stochastic models allow for random variation over time in one or more input variables, for example yields, costs and market prices, making them an efficient tool to more realistically project farm cash flows (Richardson and Mapp, 1976). Stochastic models incorporate random variation using e.g. a Monte Carlo approach, requiring input values (averages) and information about the variance (standard deviations) that needs to be incorporated, and are increasingly used to project cash flows of farms and to compare the profitability of multiple management practices (Gobbi, 2000; Lalani et al., 2017; Yates et al., 2007). We used the stochastic cash flow model to project net present value (NPV), internal rate of return (IRR) and discounted payback time (DPBT), based on information from a combination of sources (Table 1). The model was implemented in Microsoft Office 365 Excel 32-bit (version 1902).

2.3.1. Revenue of rainfed almond orchards

2.3.1.1. Gross revenue. Input data on yield was obtained from the experimental field sites (see section 2.1.2). Revenue from almond production for the agroecological treatments was calculated as the relative production, i.e., the production compared to conventional tillage production, based on the experimental data (supplementary materials: Fig. S1–2, Table S3). To do so, we divided the average production per treatment on each farm by the production of conventional tillage on that farm to obtain the relative production per farm. Then we averaged the relative production values of all the farms per treatment. This average relative production value was then multiplied by the average self-reported production per hectare in 2013, 2014, 2015 obtained from the surveys (350 kg ha^{-1} shelled almond, $n = 13$), and the same was done for the standard deviations of the measured yields. We assumed, based on communications with almond farmers, that almond trees got productive starting from year 5, were on full production in year 9 until year 25, after which they were gradually getting less productive (supplementary materials Table S4.). The assumed income from subsidies for organic almond production was based on the surveys and did not differ between treatments (average of €229.50 ha^{-1}, $n = 7$). Market price was assumed to be €6.50 per kg organic shelled almond, which was what farmers in this region received in 2018 (pers. comm. Frank Ohlenschlaeger, employee almond trader ‘Almendrehesa’; Llonja de Reus, 2019), and a standard deviation of 20% (or €1.30) was assumed based on the fluctuations in almond market

Table 2
Assumed values for costs of rainfed almond production in south-eastern Spain, based on surveys of 2016. *Variable per treatment; treatment specific costs are given in the text.

	Unit	Assumed value	Survey n	External source	Analysis
Operational costs					
Tillage	€ ha^{-1} freq^{-1}	€ 104.27	8		Variable per T*
Compost application	€ ha^{-1}	€ 119.50	6		Only CM
Seeding ground cover	€ ha^{-1}	€ 76.34	4		Only GM
Mowing ground cover	€ ha^{-1}	€ 140.05	1		Only NT
Pruning	€ ha^{-1}	€ 151.10	6		All
Pest control	€ ha^{-1}	€ 64.10	7		All
Harvest	€ ha^{-1}	€ 257.10	8		All
Machinery maintenance	€ ha^{-1}	€ 59.30	3		All
Indirect costs					
Certificate	€ ha^{-1}	€ 26.52	2		All
Other*	€ ha^{-1}	€ 144.18		MAPA, 2018	All
Capital costs					
Land costs	€ ha-1	€ 104.14		MAPA, 2018	All
Depreciation	€ ha-1	€ 120.55		MAPA, 2018	All
Investment costs in year 0					
Design	€ ha-1	€ 205.50	1		All
Purchase trees	€ ha-1	€ 563.88	3		All
Planting the trees	€ ha-1	€ 101.67	2		All
Soil preparation	€ ha-1	€ 95.75	3		All
Compost application	€ ha-1	€ 105.80	6		Only CM

price in Spain between 2012 and 2018 (FAOSTAT, 2019).

2.3.1.2. Costs. The assumed values for operational costs and investment costs were based on the survey results (Section 2.1.3.). Table 2 provides an overview of the indicators, the number of responders that contributed to the data and the average costs per hectare. We assumed the most frequently applied cropping density of 156 almond trees per hectare, which corresponds to a planting distance of 8 by 8 m. Farmers rarely recorded costs in financial reports and therefore we only included those costs that farmers did record in notebooks, where they kept notes of, those that they paid recently, or where they were sure of for another reason. None of the interviewed farmers documented the administrative and capital costs of the farm, such as insurances, social security, taxes, land costs and deprivation costs, and therefore these costs were taken from a report based on financial surveys undertaken by the Spanish Ministry of Agriculture, Fisheries and Food in 2015 (MAPA, 2018). These financial surveys were conducted in the autonomous community of Murcia, which is directly bordering eastern Andalusia, where our study is conducted. The almond sector of Murcia is comparable to that of Andalusia as the majority of the almonds of both provinces is produced on the high plains, with comparable biophysical conditions and similar current and historic land management activities. Moreover, the operational costs found in this study are in the order of magnitude as found in other Spanish almond studies (García et al., 2004; MAPA, 2018), and were validated with a local extension service company ('Crisara', Chirivel, Spain).

The costs of each of the activities in operational costs include resources, labour and diesel (diesel not for pruning and pest control). Tillage costs were multiplied by 3 for CT, by 0 for NT, by 2 for GM and by 3 for CM, to represent the frequency of tillage per year. Diesel costs (€1.00/L) were allocated to tasks that used machinery based on time that machinery was used, resulting in total €120.90 for CT, €92.25 for NT, €106.91 for GM and €134.89 for CM, which are included in the operational costs. Labour costs varied between treatments according to labour hours per management activity and its relative price per hour, as labour for some activities was more expensive (€30 h^{-1} for harrowing tractor driver and €50 h^{-1} for harvesting tractor driver) than for others (€15 h^{-1} for pruning and €9 h^{-1} for pest control, seeding and applying compost). This resulted in total labour costs of €386.50 for CT, €272.50 for NT, €334.25 for GM and €396.00 for CM, which are included in the operational costs of each activity.

2.3.1.3. Net revenue. Net revenue was calculated by subtracting the sum of the operational costs, indirect costs and capital costs from the gross revenues for a normal operational year.

2.3.2. Long-term profitability metrics

The cash flow model allows to calculate NPV, IRR and DPBT over the full life time of an almond plantation. These economic metrics are widely used to assess and compare management practices, including comparison between environmentally friendly practices with conventional management (Lalani et al., 2017; Sgroi et al., 2015; Stillitano et al., 2016; Torres et al., 2016). We assumed an almond plantation project horizon of 30 years, as it is reported that almond plantations' life-time in this region exceeds 30 years (Sanz and Marco, 2018), and this time horizon is considered adequate for long-term economic analysis of agricultural projects (Sgroi et al., 2015). The economic metrics NPV, IRR and DPBT were calculated using 1000 Monte Carlo iterations (Di Trapani et al., 2014).

Net Present Value (NPV) takes all costs and benefits generated during the entire project life time into account and assumes that costs and revenues generated in the beginning of the project are valued more, therefore it uses a discount factor to correct for the time discrepancy. NPV is calculated as the cumulated yearly present value (FAO, 1991):

$$NPV = \sum_{n-1}^{n} CF_n (1 + r)^{-n} - IC \tag{1}$$

where CF_n represents the annual cash flow in period n (year 1–30) and is calculated as the revenues minus the operational costs for that given year, r is the discount rate, and IC the investment cost of the project. The baseline discount rate was set to 5%, which is realistic for Mediterranean tree-crop plantations (Sgroi et al., 2015; Torres et al., 2016), and advised by the European Commission (European Commission, 2014).

Internal Rate of Return (IRR) is the discount rate at which discounted cash inflows equal discounted cash outflows, meaning the discount rate at which NPV equals zero. IRR is an indicator of investment decisions, as an IRR lower than or around the reference discount rate (in our case 5%) suggests that the investment is risking to provide insufficient returns. Unlike NPV, IRR does not depend on a chosen discount rate, allowing for different outcomes. IRR was calculated as (Di Trapani et al., 2014; FAO, 1991):

$$NPV = \sum_{n-1}^{n} CF_n(1 + IRR)^{-n} - IC = 0 \tag{2}$$

Discounted Payback Time (DPBT) is the point in time (n) when the discounted returns match the initial investments and at which the project becomes profitable, in other words the year wherein the cumulated present value equals zero. DPBT ignores cash flows that are produced afterwards and therefore excludes information of the overall project investment. DPBT was numerically solved as (FAO, 1991):

$$\sum_{n_0}^{DPBT} CF_n(1 + r)^{-n} - IC = 0 \tag{3}$$

The input variables to calculate these economic performance metrics are described in detail in the next section.

2.3.3. Variance of input variables and sensitivity analysis

The input values for the parameters yield, market price and maintenance costs were randomly varied for each iteration of the model based on the respective standard deviation. To do so, we used the Excel function NORM.INV(RAND()). The standard deviation for yield was estimated from the field experiments (CT st.dev = 73.32 kg ha^{-1}, NT st.dev = 120.6 kg ha^{-1}, GM st.dev = 135.5 kg ha^{-1}, CM st.dev = 150.8 kg ha^{-1}). The standard deviation of market price was estimated based on the Spanish almond market price fluctuation (FAOSTAT, 2019) between 2012 and 2017 (for all treatments we assumed st.dev = €1.30). The standard deviation of maintenance costs was assumed to be 10% of the maintenance costs of the specific treatment.

We executed a sensitivity analysis for discount rate by modelling four alternative discount rate scenarios besides the baseline discount scenario of 5%. We simulated NPV, IRR and DPBT in the stochastic model at discount rates 25% lower (r = 3.75%), 15% lower (r = 4.25%), 15% higher (r = 5.75%) and 25% higher (r = 6.25%).

2.4. Data analysis: Compensating opportunity costs and internalising costs

We explored incentive-based policy options to compensate for the opportunity costs by price premiums and public greening payments, and to internalise environmental externality costs through payment for environmental services. In the following, adjustments that were applied to the economic model to simulate the incentive-based policy options are discussed.

2.4.1. Public and private policy incentives to compensate for opportunity costs

We simulated the effects of public and private policy incentives on the NPV values of the treatments. First, for private incentives we assessed the amount of price premium, above regular market price, that would be required in order to compensate for opportunity costs. Therefore, value for market price was varied in the stochastic model in order to reconstruct a range of possible outcomes. These outcomes were used on a linear regression (using R-studio version 1.2.5019, package ‘lme4’) between price premium value and NPV, which was then used to find the breakeven point with conventional tillage. Price premiums were expressed in € ha^{-1} y^{-1} by multiplying the value that was added to the market price by the treatment-specific production per ha and to the number of productive years divided by the full life time of the project, 30 years.

Second, for public incentives we calculated the additional public greening payment that would be necessary to compensate for opportunity costs. Therefore, we added additional income from a hypothetical greening payment that can be made available by governments to promote sustainable practices, which is for example also given by European Union's Common Agricultural Policy (CAP) to promote other types of green measures in agricultural landscapes (Pillar 2; Matthews, 2013). This income source was also varied to construct a linear regression between public greening payment and the treatments NPV. Finally, we combined price premiums and public greening payments to explore mutual effects on the NPV. For all these analyses the discount rate was kept constant at 5%.

2.4.2. Payments for environmental services (PES)

We explored the financial compensation for the environmental externalities related to soil carbon stocks and soil erosion, as these are considered externalities with the strongest effect on biophysical land degradation in the region (Montanaro et al., 2017). First, we evaluated compensation for stored organic carbon in the soil through valuing treatment specific soil carbon stocks using the voluntary carbon market price and the EU Emissions Trading System carbon price (EU-ETS; Zhang and Wei, 2010). Additionally, we calculated the externality costs of erosion by valuing the treatment-specific on-site and off-site costs of soil loss due to water erosion. For this part of the study CM was not included in the analyses due to absence of information on its long-term effects on SOC and soil erosion.

The value of soil organic carbon stocks (SOC) is given as the value for the net carbon gain that is generated over the full life time of the project (30 years). We assumed that the SOC stocks would increase with 46% for NT and with 34% for GM compared to CT, which is reported by Cucci et al. (2016) after a 35 yearlong experiment in an Italian almond plantation with similar treatments. No comparable long-term study was found for compost application, so this was not considered for this part of the analysis. We assumed a baseline SOC level of 8.4 tC ha^{-1} for the reference situation, CT, as reported in De Leijster et al. (2019). The value per ton carbon on the voluntary carbon market was assumed to be €5.54 ($5.1; European Central Bank Currency Converter, 14-08-2019), which is reported by the Ecosystem Marketplace as the average voluntary market carbon price for carbon stored in forestry and land-use projects (Hamrick and Gallant, 2017). With an increase of 46% in SOC, the soil organic carbon stock of NT has an added value of €21.41 ha^{-1} over 35 years and that of GM with an increase of 34% in soil organic carbon an added value of €15.82 ha^{-1}. This corresponds to an annual income of €0.61 for NT and €0.45 for GM, when the stored carbon is traded on the voluntary carbon market. The carbon value of the EU-ETS is higher and was assumed to be €20, which was the average price in 2019 (Marcu et al., 2019) and corresponded to an annual income of €2.21 ha^{-1} y^{-1} for NT and €1.63 ha^{-1} y^{-1} for GM.

The externality costs for erosion were calculated based on average European costs of erosion, as calculated by the EU (Görlach et al., 2004). The latter study reports average on-site private costs of €9.83 ha^{-1} y^{-1} (based on €7.56 ha^{-1} y^{-1} in 2003 with correction for inflation between 2003 and 2019), which included projected yield losses as a result of reduced nutrient balance, organic matter content and plant rooting depth in the farms' soil. Additionally, the study reports average off-site social costs of €111.52 ha^{-1} y^{-1} (based on 85.92 ha^{-1} y^{-1} in 2003 with inflation correction), which include siltation of dams and canals and costs of sedimentation. Combined, these costs add up to €121.35 ha^{-1} y^{-1} for CT. In the supplementary material Table S5 we show the results of a literature review that demonstrates that NT and GM reduce erosion by 71.4% and 73.1%, respectively. Therefore, we attributed erosion costs of €34.71 to NT and €32.64 to GM. For all analyses the discount rate was kept constant at 5%.

3. Results

3.1. Costs and benefits

In the field experiment we found differences in almond yield between treatments (supplementary materials. Fig. S1–2). We found that

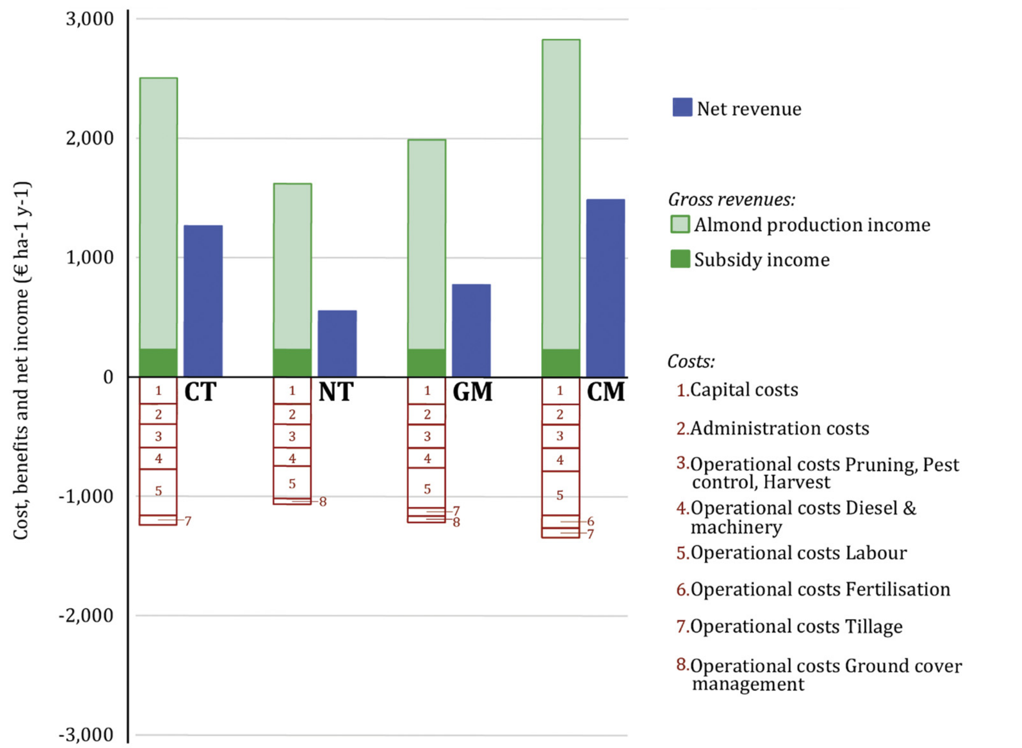

Fig. 1. Treatment specific costs, benefits and net revenue of an average operational year of almond production. Treatments include: conventional tillage (CT), no tillage (NT), green manure (GM), compost (CM). Green coloured bars indicate gross revenues, red bars with numbers costs and blue bars net revenues. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

CM produced the highest yields with an average of 1.47 kg per tree, followed by an average almond yield (kg tree^{-1}) of 1.12 for CT, 0.77 for GM and 0.67 NT, which resulted in the relative production values of 1 for CT, 0.6 for NT, 0.63 for GM and 1.20 for CM. Consequently, the gross revenue generated from almond production followed the same order (Fig. 1), with —compared to CT— 13.0% higher gross revenue from CM and 35.3% and 20.5% lower gross revenue from NT and GM. In 2017 the lowest production was measured in our site, due to a combination of exceptionally cold temperatures in Spring causing frost and the alternate bearing behaviour of almond trees (supplementary materials. Fig. S1).

Table 2 and Fig. 1 show farm-level costs, benefits and net revenues per hectare. The response rates (n) per cost category were low, with an average of 5.1 out of 15 respondents for the operational costs.

NT had 20.5% lower operational costs than CT, as no tillage resulted in lower operational, labour and diesel costs (Fig. 1). The operational costs of GM were comparable with CT (3.8% lower), and the operational costs of CM were 15.3% higher than CT as a consequence of additional costs for compost application. In an average operational year, CM generated the highest net revenue of €1349 ha^{-1} y^{-1}, followed by CT, then GM and then NT, with €1126, €636, €415 ha^{-1} y^{-1}, respectively (Fig. 1). The opportunity costs per operational year were €711 ha^{-1} y^{-1} for NT and €490 ha^{-1} y^{-1} for GM.

3.2. Long-term economic performance

On the long-term, the CM treatment was the most profitable as it provided a 17.2% higher NPV than CT. Although CM required larger investment costs (Fig. 2), the DPBT was similar to CT amounting to 11.7–11.9 years (Table 3). NT resulted in the lowest NPV, followed by GM, which were 90.1% and 69.0% lower than CT, respectively. The DPBT for these treatments was also 6.1–10.4 years longer (DPBT of 22 years for NT and 18 years for GM). In terms of IRR the treatments followed the same order (Table 3). The sensitivity analysis showed that there was no interaction effect between management regimes and discount rates, and that NPV values were positive for each discount rate scenario, indicating that all treatments were profitable in the given settings (supplementary materials Table S6).

3.3. Policy options

3.3.1. Compensating opportunity costs: Public and private policy incentives

We modelled the effects of implementing a public greening payment for agroecological management on the NPV of different treatments. Without public payments, CM had higher a NPV than CT and additional public greening payments would increase this difference (Fig. 2.a). Because NPV of NT and GM were lower than CT, the breakeven point of public greening payments was respectively €321.30 ha^{-1} y^{-1} and €430.27 ha^{-1} y^{-1} for GM and NT. Price premiums on almond sales were considered as a private incentive to compensate for opportunity costs (Fig. 2.b). GM required an almond price of €8.25 kg^{-1} (or €1.75 kg^{-1} premium) to compensate for the opportunity costs, which corresponds to an average of €386.95 ha^{-1} y^{-1}. NT required an almond price of €9.43 kg^{-1} (or €2.93 kg^{-1} premium), which corresponds to an average of €644.09 ha^{-1} y^{-1}. Hence, total compensation was higher for price premiums. Fig. 2.c shows how a combination of price premiums and public greening payments affects NPV.

3.3.2. Internalising environmental externalities

The belowground carbon stock of NT and GM had an economic value of €0.61 and €0.45 ha^{-1} y^{-1}, which is 0.02% and 0.01% of the total annual gross revenues. This potential additional income did not change NPV for both treatments (Table 4). The economic value using the carbon price of the EU Emission Trading System (EU-ETS) resulted in 1.40% and 1.06% additional annual revenue for NT and GM, respectively. The changes in NPV under the EU-ETS scenario were also

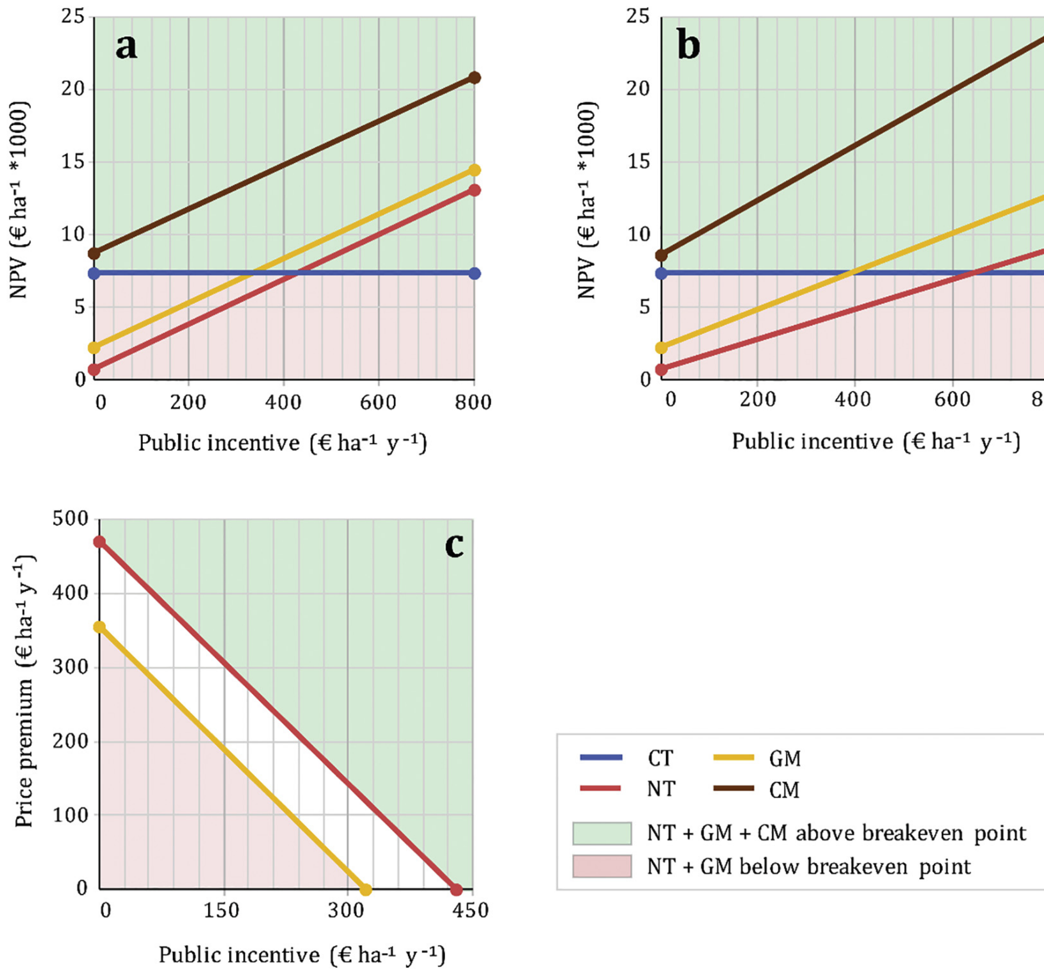

Fig. 2. Responses of net present value (NPV) to different management regimes, with variability in obtained price premiums (private incentives) and greening payments (public incentives). Management regimes are: in blue conventional tillage (CT), in red no tillage (NT), in yellow green manure (GM) and in brown compost (CM). **a)** The effect of public greening payment for agroecological management on the NPV of the management regimes. **b)** The effect of price premiums for agroecologically managed products on the NPV of the management regimes. Baseline almond price is €6.50, additional price premium is calculated on a hectare level by multiplying price premium with production per hectare, multiplied by number of productive years per 30 years. **c)** Combined effect of public greening payment and price premium on the NPV of NT and GM. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Net present value (NPV), Internal rate of return (IRR) and Discounted payback time (DPBT) for the four treatments: conventional tillage (CT), no tillage (NT), green manure (GM) and compost (CM).

		CT		NT		GM		CM	
Output variable	Unit	Mean	SD	Mean	SD	Mean	SD	Mean	SD
NPV	€	7364	1388	732	807	2284	1294	8631	2942
IRR	%	13.5	1.5	6.3	1.4	8.2	1.8	13.7	2.7
DPBT	y	11.7	1.5	22.1	4.4	17.8	3.9	11.9	2.9

negligible.

The yearly externality costs of soil erosion were €121 for CT, €35 for NT and €33 for GM. Although the erosion costs were lowest for NT, the NPV was reduced the most, namely, 73%, while the NPV of CT was reduced by 26% and that of GM by 20%.

4. Discussion

To our knowledge this is the first study that investigated the economic costs, benefits and profitability of agroecological management in Mediterranean tree-crops including externalities and the effect of public and private compensation schemes. By applying a stochastic model and using empirical input data, we were able to incorporate management-specific annual variance in yields, market prices and operational costs. We demonstrated that each of the investigated agroecological practices were profitable, but net revenues differed considerably among treatments. Compost (CM) application improved economic performance (NPV) by 17.2% compared to conventional tillage (CT) practice (Table 2). Both CM and CT had the fastest payback time (DPBT) of 11–12 years after starting a new almond farm. Agroecological practices aiming to maintain vegetation cover, no-tillage (NT) and green manure (GM), resulted in 90.1% and 69.0% lower NPV levels respectively, which can be explained by lower yields (supplementary materials Fig. S1–2). This study showed that relatively small differences in yields can result in large effects on the long-term economic performance. The opportunity costs related to NT and GM can be compensated for by price premiums or public greening payments, but cannot —under the current conditions— fully be compensated by payments for soil organic carbon storage or by internalising externality costs of soil erosion.

Although not all farmers recorded their expenses, therefore we only included costs farmers were certain of. The operational costs estimated in this study are similar to those reported in other studies on Spanish almonds (MAPA, 2018; Martin-Gorriz et al., 2020). For example, Martin-Gorriz et al. (2020) found that almonds managed with

Table 4
Net present value for the management regimes under payments for environmental services scenarios. The management regimes include: conventional tillage (CT), no-tillage (NT), green manure (GM) and compost (CM). The scenarios include: voluntary carbon market (VCM), where the soil organic carbon stocks of NT and GM are valued with the VCM price (€5.54); EU Emission Trading System (EU-ETS), where the soil organic carbon stocks of NT and GM are valued using the VCM price (€20); Erosion, where the external costs of erosion are included; EU-ETS + Erosion, which combines the latter two scenarios. *The first three and the last two scenarios have the same input variables, but outcomes differ due to the random variation that is inherent to the model. **NPV of NT was lower in the VCM scenario compared to baseline, which is explained by random variation that is inherent to the model.

Unit	PES scenario	CT*		NT		GM		CM	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
NPV ($€ ha^{-1}$)	Baseline	7364	1388	732	807	2284	1294	8631	2942
	VCM	7384	1420	724**	841	2307	1344		
	EU-ETS	7333	1411	759	774	2344	1259		
	Erosion	5447	1400	195	775	1836	1254		
	EU-ETS + Erosion	5454	1410	245	803	1844	1315		

conventional tillage in Murcia (Spain) had operational costs of €710 ha^{-1} y^{-1}, while we found €844 ha^{-1} y^{-1}.

4.1. Management regimes and yields

Our findings show that NT and GM produced lower yields than CT (reduction in yields of NT and GM of 16% and 11% on average (supplementary materials Fig. S1–2)), and CM produced higher yields than CT. Giller et al. (2009) suggest that NT requires a minimum transition period of 10 years, after which it will be able to produce similar yields as CT. In the current study we used yield data obtained from short-term (3 year) field experiments to make long-term financial projections. According to Giller et al. (2009) yield levels can change over larger time spans after implementation of new management, therefore our short-term experiment may have missed these developments. However, previous studies in Mediterranean European almond plantations showed contrasting results to what Giller et al. (2009) suggest, as they found over a longer time scale (10–12 years) larger yield gaps for NT (−63% and − 28%) compared to our short-term study (De Giorgio and Lamascese, 2005; Martin-Gorriz et al., 2020; Martínez-Mena et al., 2013). One of these studies, an agroecological almond experiment in the same Spanish study region as ours observed declining yields for NT in the first 7 years after implementation followed by stabilization of yields until the 10th year, at a level of 85% lower than CT (Martínez-Mena et al. unpubl., pers. comm.). This indicates that the production in the NT treatment of our experiment could decrease further in the following years, increasing the opportunity costs. The lower yields in the GM treatment are, however, not in line with earlier findings that reported no significant yield differences compared to CT (De Giorgio and Lamascese, 2005; Martin-Gorriz et al., 2020). Apparently, when NT is applied it results in a trade-off between farm profitability and ecosystem services provisioning, since we demonstrated earlier that NT management increased ecosystem service supply (e.g. nutrient cycling, understory plant diversity and understory carbon stock) compared to CT (De Leijster et al., 2019). The implementation of CM, on the other hand, rehabilitated nutrient cycling and carbon stock, and also provided higher economic returns than CT. Therefore, CM provides a bundle of ecosystem services and can be implemented without external financial support. Nevertheless, the positive effect of CM on biodiversity and erosion control is limited compared to vegetation covers (De Leijster et al., 2019; Maetens et al., 2012a). Therefore, applying CM without vegetation covers may not fully prevent land degradation (Bai et al., 2008).

In this study, the vegetation covers in the NT treatment covered the experimental plot entirely and for GM a 1.5 m strip from the almond trunks was kept bare while the remainder of land was sowed (approximately 5 m wide). Another study on vegetation cover management in peach orchards in North Carolina (USA) demonstrated that there was a negative correlation between the proportion of soil that was covered by vegetation and peach tree productivity, with higher production at less vegetation cover (Fisk et al., 2015). There might be similarities between the responses of almonds and those of peaches to vegetation cover. The NT treatment in the current study was not mowed and not grazed, and therefore spontaneous vegetation was left to grow without limitation, potentially leading to more competition for resources such as water and nutrients. In a seven year study on Portuguese rainfed olive orchards it was shown that mowing, compared to tillage, did not reduce olive yields (Simoes et al., 2014). Therefore, we suggest that further research is needed to unravel the environmental and economic benefits of other understory management practices. These may include, narrow vegetation strips in the middle of alleys, alternate alleys with vegetation covers and bare soil, mowing or grazing. Moreover, combining multiple agroecological practices, such as application of soil organic amendments and vegetation covers, may be an effective approach to improve ecosystem services without compromising on yields (Montanaro et al., 2010). In our study, CM management resulted in higher yields than CT while CM, GM and NT all improved different ecosystem services compared to CT (De Leijster et al., 2019). A combination of CM with vegetation covers may combine a wide range of environmental benefits and economic benefits, but additional empirical research is needed.

In De Leijster et al. (2019) we demonstrated an interaction between management regimes and farms, concerning the yields. Farm based local differences in response to treatments may be explained by the farms' characteristics. For example, on one of the farms GM improved yields compared to CT and on one other farm CM reduced yields compared to CT, which were opposite to what was found in other farms. In the current study, using the stochastic economic model, we used averages yield values and corresponding standard deviations in order to simulate an 'average' farm in the study region. However, because of the farm variability we would caution against extrapolating to all farms, as each farm will respond differently depending on soil type (Zingore et al., 2007), micro climatic conditions (Maetens et al., 2012b), presence of ecosystem service providing organisms (Luck et al., 2014), life history of the farm (Zingore et al., 2007), uncontrolled management differences of farmers, etc. According to the Food and Agriculture Organisation (FAO) the adaptive capacity is an important aspect of agroecology, and therefore producers should learn from, and adapt to the local conditions such as climate, knowledge, traditions and all other social and biophysical aspects that influence the agroecosystem in order to develop a management regime that is resilient (FAO, 2018). Nevertheless, our results provide insights in the response of an average farm in this region, and enables investigating market incentives that may alter the economic benefits of each management regime.

4.2. Public and private incentives

According to Tilman et al. (2002), both public and private incentives can play a crucial role in the transition towards sustainable agricultural management. In this study we found that both public greening payment and price premiums can compensate for opportunity costs in Spanish almond plantations. Public greening payments of €321.30 ha^{-1} y^{-1} for GM, and €430.27 ha^{-1} y^{-1} for NT would be required to reach the breakeven point with CT income. To put this in perspective, the EU CAP allocates 30% of the total budget to greening measures (environmentally friendly practices other than agroecological practices) (Pillar 1; Matthews, 2013). The public greening payment that is required in the current study would be 5–7 times the current CAP's greening payment, when standardized to hectare level, suggesting that much higher compensations are required than currently given in the European society. A previous study analysed whether the 30% CAP greening payment would be sufficient to compensate for the costs of greening measures in Italian arable farms in mountainous, hilly and flat regions (Vanni et al., 2013). They concluded that the greening payment was sufficient to compensate for greening investments for the majority of the farmers in the mountainous region, but not for more than 75% of the farmers in the hilly and flat regions, since they experienced net losses of up to €303 ha^{-1}, which is similar to the finance gap in our study.

Our study showed that opportunity costs of NT and GM can be compensated by paying 45% and 27% higher market prices, respectively, which equals to €386.95 ha^{-1} y^{-} for GM and €644.09 ha^{-1} $y^{-1}$for NT. This is 5 to7 times the current price premiums received by some pioneer almond farmers of the farmers' cooperation 'Almendrehesa' that sells organically produced almonds (5–7% premium; personal communication from Almendrehesa staff). We also found that more compensation should be given via price premiums than via public greening payments to match the breakeven point of CT's NPV. The compensation through price premiums was given in the years that the farm is productive, which was later in the project and therefore the cash flows had lower net revenues early in the project life time. The values obtained early in a project weigh more because of the discount approach that is characteristic for NPV and therefore the amount needed to compensate for the opportunity costs through price premiums was higher. Also, price premiums were more effective when yield was higher and hectare-based compensation was more effective when costs were lower, but these effects resulted in negligible differences between treatments in our case study. Sgroi et al. (2015) demonstrated that Italian organic olives had higher long-term profitability, despite having 26% lower yields than conventional olive orchards, which is a larger yield gap than found in our study. These Italian organic olive farmers received 70% more subsidies and a 21% higher price than the conventional olive farmers in that region, but also had 13% lower operational costs. According to our model, a 21% price premium combined with an 70% additional public greening payment would also make GM more profitable than CT, but this would not yet make NT more profitable (Fig. 2.c). Thus, opportunity costs can be compensated with public greening payments and price premiums, but these incentives would need to be higher than what is currently practiced.

In our case study the mainstream reference management practice of the almond orchards, organic conventional tillage, already receives both higher subsidy and a price premium for omitting chemical input use compared to the less widespread, but still common, non-organic conventional tillage management (Ramos García et al., 2018). The production of almonds without chemical inputs is an accessible option in this region because chemical fertilisers are barely used and large-scale incidence of pests is not common. As a result of organic certification, farmer's income from subsidies increases from about €120 ha^{-1} to €230 ha^{-1}, and market value of shelled almond increases from around €5 kg^{-1} to €6.5 kg^{-1} (de Reus, 2019a, 2019b), which are increases of 92% in subsidy and 30% in price. Although strong financial benefits are currently provided, this management still results in strong negative effects on ecosystem services provisioning as long as it is combined with conventional tillage (De Leijster et al., 2019). Therefore, we suggest that organic certification schemes should incorporate criteria on organic amendments and farm floor management. Moreover, a better inclusion of agroecological concepts that relate to more complex dynamics (e.g. adaptive capacity of farmers and resilience) in agroecological studies is needed to improve their application and widen their use in, for example, certification schemes.

4.3. Payments for environmental services

Payment for carbon sequestration is often claimed to be an important incentive for farmers to apply soil rehabilitation practices (Lal et al., 2015). In the current study we found that carbon markets —under the current conditions— cannot provide compensation for the opportunity costs in almond plantations. The average voluntary carbon price was too low to make a noticeable difference in almond farmers' annual budgets (0.02–0.04% of total income) and also the fourfold EU-ETS carbon price was still too low to compensate for the opportunity costs (1.06–1.40% of total income). Antle and Stoorvogel (2009) described three case studies of payments for agricultural soil carbon sequestration in developing countries and also concluded that in each of these cases the additional payment was only partly compensating for the opportunity or implementation costs of the carbon mitigating practices applied by farmers. The authors concluded that, for their case studies, the carbon price was too low, and that prices of up to $200–300 tC^{-1} should be paid to fully compensate for the restoration practices. Moreover, the payment for carbon sequestration schemes, where farmers are paid per tonne carbon sequestered in the soil, are less effective in the Mediterranean region, as soil organic carbon content of Mediterranean soils changes relatively slowly and remains low compared to other biomes (Montanaro et al., 2012).

We also showed that erosion generated by CT managed almond plantations had an estimated cost of €121.35 ha^{-1} y^{-1}. These costs can be reduced significantly by the vegetation covers of NT and GM, as they reduced erosion by 71.4 and 73.1%, respectively (supplementary materials Table S5). Despite the fact that erosion was significantly reduced by NT and GM, soil erosion was not fully prevented and still led to additional cost. Due to the low income of NT, this management regime experienced the largest reduction in NPV. Internalising the costs of erosion in the farm's budget does not result in an improvement of the profitability of agroecological practices in this setting. The erosion costs in our study were higher than those reported in another study on Spanish almond plantations, where the authors estimated an average erosion cost of €27.16 ha^{-1} y^{-1} (Hein, 2007). However, Hein (2007) emphasised the on-site costs of nutrient loss and did not take into account the loss and replacement of soil and SOM, nor the restoration costs of off-site sedimentation. The erosion costs of Görlach et al. (2004), which we used in the current study, incorporated these additional costs. However, this study also has strong limitations as erosion costs were generalised for the entire European land surface and calculated per hectare without relating to quantity of lost soil. Therefore, more research is needed to estimate the costs of erosion per land use type and per quantity of lost soil. In another study, the erosion costs in Italian vineyards were estimated at €1575 ha^{-1} y^{-1} (Galati et al., 2015), which is much higher than the values we report. This can be explained by the 10-fold erosion rates in the Italian study compared to our study, making the costs per tonne lost soil comparable. Moreover, Galati et al. (2015) reported that agroecological management reduced erosion by 61% in Italian vineyards, which is comparable to what we found. Despite the significant reduction in erosion rates through implementing agroecological practices, long-term profitability did not improve when erosion costs were accounted for, as low levels of erosion persisted and still resulted in costs, consequently NT and GM were associated to lower NPV than CT (Table 4).

4.4. Limitations

In this study we estimated the economic performance of agroecological practices using a stochastic cash-flow model. The results of this study provide important insights in opportunity costs that can occur, and identifies strategies to overcome these opportunity costs by exploring market and public incentives and compensation schemes. This study, however, does not prove that each individual almond farm will economically respond similarly as we have shown. The relative economic performance of each of the included management regimes can locally be influenced by market infrastructure, labour costs, climatic conditions, soil types, presence or absence of service providing biodiversity, uncontrolled management activities, and many other biotic and abiotic factors. Therefore, we propose, based on the agroecology concept, that for each location adaptive capacity is needed to learn how the management of a farm can optimally use both the local economic conditions and stimulate the ecological processes. This will minimise opportunity costs.

In this study we economically valuated soil-based ecosystem service to demonstrate the potential of compensation schemes. The valuation of ecosystem services is, however, a contentious topic as it requires assumptions on value (monetary and non-monetary), as it is volatile to external factors, and as it is a difficult approach for non-material ecosystem services, if possible at all. However, it is important to do so in order to provide guidelines and reference points to be able to conduct first order evaluations of management decisions.

4.5. Recommendations

Based on our findings we make recommendations on how to overcome barriers that hamper large scale adoption of agroecological management. First, we suggest that organic certification schemes should incorporate additional criteria on farm soil and vegetation management. By doing so, organically produced almonds will lead to lower negative environmental impact, which will provide a stronger contrast between the environmental performance of conventionally versus organically produced almonds. Secondly, we call for more research on a wider range of vegetation cover practices. More knowledge is needed on how ecological and economic performance can be optimised by either varying in the distribution of tilled soil versus vegetation covered soil (e.g. full cover, narrow vegetation strips, alternating alleys, etc.), or by combining vegetation covers with organic amendments. Finally, it is necessary to reconsider whether the value that is attributed by society to the environment of agroecological landscapes is high enough to sustain agricultural production in the future. In some regions more financial compensation, either through public investment or through private investment, is needed than is currently paid in order to match the observed opportunity costs of some types of agroecological management.

5. Conclusion

In this study we demonstrated that, under current economic conditions, compost application provided the highest long-term profitability of almond farms in Mediterranean Europe, and together with conventional tillage had the shortest payback time. No tillage and green manure provided lower net economic benefits over the project life time than conventional tillage. The long-term profitability was best explained by the differences in yields, and not by differences in operational costs. Thus, compost can be implemented without external financial support, whereas for no tillage and green manure public or private policies are required. Under the current conditions, payments for carbon sequestration and internalising costs of erosion are not suitable options to compensate for the opportunity costs of implementing NT and GM. On the other hand, price premiums and public greening payments do provide the possibility to compensate for these opportunity costs. The required price premiums and public greening payments would however be 5–7 times the amount currently provided in agri-environmental schemes.

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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.

Appendix A. Supplemenatry data

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