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Sustainability and long-term nutrients flows in conventional and low-input globe artichoke cropping systems

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ABSTRACT

Globe artichoke cultivation causes high nitrogen (N) balance surpluses. The planning and cropping of sustainable systems (with no mineral fertilizer supply) can contribute to the reduction of the nutrients surplus.

The research hypothesis was that artichoke conventional system may be shifted to a sustainable one, by means of building-fertility crops use and rotation.

In the present work three different management systems, conventional (continuous monoculture with chemical fertilizers use), alternative monoculture (continuous monoculture with introduction of a short-cycle legume catch-crop and without chemical fertilizers supply) and biannual rotation (globe artichoke in a biannual rotation with cauliflower without chemical fertilizers supply and with cover-crop use) were compared over a ten years period. Soil initial and final conditions were monitored. Nitrogen, P, and K gross balances, for each growing season, were calculated and, also, soil respiration over the last two growing seasons were monitored.

Results show that soil total N content was significantly higher in alternative monoculture and biannual rotation than conventional systems. Planning a biannual rotation and introducing a legume cover-crop species were more beneficial for a well-balanced N budget with respect to conventional (N surplus), and alternative monoculture (N deficit). The mean seasonal CO_2 emissions increased significantly with residues return. Overall, globe artichoke traditional systems may highly benefit of rotation with another crop (e.g. cauliflower). The results, also, suggest that introducing legume species as catch- and cover-crops is the most promising approach to foster sustainability.

PREFACE

Globe artichoke [*Cynara cardunculus* L. var. *scolymus* (L.) Fiori] is a perennial diploid outcrossing *Asteraceae* species, *Tubuliflorae* subfamily, *Cynareae* tribe, originating from the Mediterranean region (Rottemberg and Zohary 2005; Sonnante et al. 2007).

The edible parts of the plant are large immature inflorescences, capitula or heads, either marketed as a fresh product or processed by canning or freezing (Basnizki 1985; Bianco 1990).

Since ancient time, globe artichoke has been, also, used in traditional medicine for its recognized therapeutic effects such as hepatoprotective, anticarcinogenic, antioxidative, antibacterial, urinative, anticholesterol, glycaemia reduction (Rondanelli et al. 2011; Fantini et al. 2011) linked principally to the high content of polyphenolic compounds, which include mono- and di-caffeoylquinic acids and flavonoids (Pandino et al. 2012, 2013; Negro et al. 2012).

In the last years, other possible applications of globe artichoke, alternative to the traditional ones, were envisaged. Different types of products can be harvested and utilized to obtain: (i) oil from seeds (Cocco et al. 2014); (ii) inulin from roots (Raccuia and Melilli, 2004, 2010); (iii) energy from biomass (Ledda et al. 2013); (iv) fiber as potential reinforcement in polymer composites (Fiore et al. 2011); (v) green forage for ruminant feeding (Fateh et al. 2009); and (vi) natural rennet for traditional cheese making (Llorente et al. 2004). Globe artichoke can also be used as crop for metal-accumulation (Hernández Allica et al. 2008).

In the world, globe artichoke is grown on approximately 130.000 ha (FAO data, 2013). Italy is the leading artichoke producer worldwide (50.0 out of 133.0 kha cultivated in the World and a mean annual production of about 480 kt of heads), followed by Spain (16.0 kha and 200 kt) and France (9.5 kha and 45 kt; FAOSTAT 2015). The remaining production comes from North-Africa (Egypt and Morocco, with 7.7 and 4.1 kha, respectively), Asia (mainly in China, 10.0 kha), North-America (especially California) and South-America (Peru, Chile and Argentina, with 7.7, 5.0 and 4.7 kha, respectively) (FAO data, 2013).

In Italy, the crop is mainly present in irrigated farmland of southern regions (Apulia, Sicily, Sardinia) through the cultivation of ancient, vegetatively propagated genotypes (e.g. 'Spinoso Sardo', 'Violet de Provence') which, despite their relatively low yields, are able to ensure high economic gains, most of all thanks to their marked earliness and long productive cycle (from October–November to April; Sgroi et al 2015).

In Sardinia, the most commonly grown traditional varieties is the spiny early type 'Spinoso sardo', of which, on the basis of the different pedo-climatic conditions of the growing areas, were identified three populations (Portis et al. 2004, 2005). Due to the high range of genetic variation found in cultivated populations, Lanteri et al. (2004) suggested that the term 'varietal type' instead of 'variety' would be more appropriate in order to define the accessions of germplasm at present in cultivation. More recently, other genotypes have started to make an impact in Sardinia, notably 'Tema 2000', a very early, productive cultivar, which produces medium-sized, purple capitula; the non-spiny types 'Violetto di Provenza' (early flowering) and 'Romanesco' (late); and the F1 hybrid 'Madrigal'.

Tilman et al. (2002) defined 'sustainable agriculture' as practices that meet current and future societal needs for food and fibre, for ecosystem services, and for healthy lives, and that do so by maximizing the net benefit to society when all costs and benefits of the practices are considered.

Sustainability implies both high yields that can be maintained, and agricultural practices that have acceptable environmental impacts. The main environmental impacts of agriculture come from the conversion of natural ecosystems to agriculture, from agricultural nutrients that pollute aquatic and terrestrial habitats and groundwater, and from pesticides, especially bioaccumulating or persistent organic agricultural pollutants.

Agricultural nutrients enter other ecosystems through leaching, volatilization and the waste streams of livestock and humans. Pesticides can also harm human health, as can pathogens, including antibiotic-resistant pathogens associated with certain animal production practices (Tilman et al. 2002).

Vegetable residues often have a high nitrogen (N) content and thus can release large amounts of N through mineralization (Chaves et al. 2006), potentially ranging from 20–80% of the N a few weeks after their incorporation into the soil (De Neve and Hofman 1996, 1998). This represents a potential source of available N for the following crop.

In globe artichoke, head production may vary depending on varietal type, plant density, and length of the crop cycle, but, in any case, it represents a small part of the total biomass production (~80-85% of the total plant, Llorach et al. 2002) that, at the end of each growing season, is usually grazed or burned (Ledda et al. 2013; De Menna et al. 2016). Conversely, according to several authors, the incorporation of crop residues, such as cereal straw, is an important measure to maintain or increase soil organic matter levels under cropland (Lugato et al., 2014; Shahbaz et al. 2017). In Italy, the globe artichoke crop, since the beginning of the twentieth century, is widely grown in continuous monoculture heavily relying on chemical inputs use such as synthetic fertilizers and pesticides (Calabrese et al 2010; Lenzi et al. 2015). Crop rotations that include soil-conserving crops are not widely used, thus same cultural practices are applied year after year. Lenzi et al. (2015) and Piras (2012) stated that at the end of growing seasons globe artichoke mobilized 104.4 kg N ha^{-1} in plant residues, that contained also 50 kg P ha^{-1}, and 156.8 kg K ha^{-1}.

In the literature, fertilization recommendations range from 225– 300 kg N ha^{-1} (Calabrese et al. 2010) depending on the crop cycle, varietal type and growth conditions.

In this research the conventional artichoke system, despite the traditional one, was designed with crop residues incorporation at the end of the growing cycle (instead of animal grazing or field burning).

We therefore supposed that by applying moderate rates of nitrogen fertilizer, the globe artichoke crop would take up nitrogen derived from mineralized residues.

Multiple cropping systems using crop rotations or intercropping (two or more crops grown simultaneously) may improve pest control (Koockeki et al 2009) and increase nutrient- and water-use efficiency (Reckling et al 2015; 2016).

Cover crops have been promoted as a means of maximising the efficient use of available nitrogen in subsequent crops in agricultural systems, decreasing the risk of environmental problems associated with the nitrate contamination of surface and groundwater whilst potentially increasing profitability by reducing the need for nitrogen fertiliser (Mancinelli et al. 2013). Legume cover crops can fix nitrogen, some of which is available for subsequent crops. However, the full benefit of cover crops depends on the synchronisation of cover crop nitrogen mineralisation and the nitrogen demands of the subsequent crop (Yadav et al. 2000). Living mulches can be used to recycle nutrients and to fix nitrogen, but often compete too strongly with the main crop, decreasing crop growth and yield. Cover crop also increase the size and activity of soil microbial communities (Tejada et al. 2008).

By using soil management practices such as the application of cover crops, rotations, main-crop residues incorporation, it may be possible to develop a cropping system that will use inherent soil fertility via enhanced nutrient cycling by the resident soil biological community (Leskovar et al. 2013; Palermo et al. 2013; Montemurro et al. 2013; Negro et al. 2016). However, it is unclear how sustainable these practices are from a practical viewpoint.

Despite some contributions dealing with globe artichoke response to mineral fertilization (e.g. Ierna et al. 2012; Rincón et al. 2007), to our knowledge only few attempts (e.g. Lenzi et al. 2015) have been focused to date on planning an innovative cropping system based on the systematic use of legume species as catch- or cover crop and with use of rotation with e.g. another horticultural crop; which, instead, may represent a more useful framework toward a sustainable cropping approach for this species.

There exists a variety of tools used to evaluate the effects of land management practices on soil health. Therefore, our approach was to investigate alternative systems in relation to soil properties, soil respiration and with a primary focus on the status and dynamics of N, P, and K nutrients. Soil properties were characterized by accounting for initial and final conditions by analyzing soil organic matter content, total N, assimilable phosphorus, exchangeable potassium and cation exchange capacity. Soil respiration was characterized by a systematic monitoring carried out over the last two growing seasons and on a weekly basis. Nitrogen, P, and K status was assessed by mean of the nutrients gross balance calculation.

1. Introduction

Soil, is an important component of agro-ecosystems that provides ecosystems services such as net primary production, climate regulation, soil degradation control, nutrient conservation and soil organic matter turnover (Birgè et al. 2016).

Literature suggests that conventional agriculture alters soil quality (Henneron et al. 2015 and the references therein). Specifically it causes soil erosion and degradation, agrochemical pollution, nitrate leaching and groundwater pollution (Panagos et al. 2016; Poudel et al. 2002). In addition, as reported by several authors conventional farming systems cause soil organic matter depletion (Lal and Kimble 1997; Herzog and Konrad 1992; Pimentel et al. 2005) whose formation and decomposition contributes to maintain the agro-ecosystems productivity and soil quality (Araujo et al. 2008).

Conversely, sustainable agriculture is based on resource use efficiency that integrate soil management, water and biological resources (Giller et al. 2009). This agricultural management minimizes impacts due to conventional systems and preserves the soil resilience in a long run (Gomiero et al. 2011). Sacco et al. (2015) and Valboa et al. (2015) underlined through long-term studies the relevance of the practices used to enhance soil fertility (e.g. conservation tillage, crop rotations, catch-crops and cover-crops based on legumes use, manure soil application and crop residues incorporation). Ciaccia et al. (2015) showed that the nitrogen fixing crops introduction within cropping system planning fostered soil organic matter formation, when residues are ploughed into the soil. Furthermore, Mazzoncini et al. (2011) found that cover-crop introduction improved soil organic carbon and as a consequence reduced greenhouse emissions. Cropping system including legume cover-crop also showed positive impacts on preventing nitrogen leaching or denitrification, improving nutrients availability for main crops (Sànchez de Cima et al. 2015).

In absence of fertilizer, crop residues incorporation into the soil is crucial to improve and maintain soil productivity (Frasier et al. 2016). This agricultural practice increases soil organic matter and soil organic carbon sequestration as well as improve soil moisture retentions (Choudhury et al. 2014; Lehtinen et al. 2014; Li et al. 2013). In addition, fresh crop residues incorporation characterized by a low carbon-to-nitrogen ratio stimulates soil respiration, microorganisms growth and triggers a rapids mineralization nutrients specifically nitrogen and phosphorus (Turmel et al. 2015).

Globe artichoke (*Cynara cardunculus* var. *scolymus* L.) produces aboveground residual biomass that could have potential value in terms of nutrients if incorporated in same Mediterranean cropping systems (Ledda et al. 2013). Release of nutrients and their availability for crops is affected by bio-chemical composition of crop residues (e.g. cellulose and lignin concentration, soluble organic carbon concentration and carbon-to-nitrogen ratio) and environmental factors such as soil temperature and moisture (Nguyen et al. 2016). Studies conducted by several authors showed that *Cynara* spp. biomass (i.e. leaves and stems) have a high macro-elements concentration and a good availability in terms of iron and calcium (Monti et al. 2008; Pandino et al. 2010, 2011; Romani et al. 2006). In this context, annual incorporation of *Cynara* ssp. crop residues and introduction cover-crop of legumes, subsequently incorporated in the same Mediterranean cropping systems, may represent a win-win strategy for maintain soil fertility and nutrients supply for crop rotation in the long-term. Indeed, returning to soil fresh crop residues of both crops fosters rapid mineralization of labile compounds. On the contrary, recalcitrant materials stabilize and maintain soil organic matter through the humification process (Duong et al. 2009; Ferrari et al. 2011). To assess performance and environmental sustainability in long-term of alternative management practices it may be used an agri-environmental indicator, developed by OECD (2007a, b): gross nutrient balance. This indicator provides interesting information on flux of nutrients added into the soil and removed by crops in order to understand dynamics macro-nutrients and prevent pollution by nitrogen and phosphate mainly in horticultural sector that has higher environmental impacts (Bassanino et al. 2011; Caredda et al. 1997; Ingrao et al. 2015). To better understand the interactions between organic matter dynamics and nutrients availability is useful to monitor soil respiration in order to evaluated the effects that use of alternative soil management practices have on mineralization-humification process in Mediterranean cropping systems (Almagro et al. 2009).

According to our knowledge the scientific literature does not reported field experiment similar to one analyzed in this study, namely based on fertility building crops use and biannual rotation in a long-term perspective. For this reason this work might be considered a good starting point in order to replicate the experiment also concerning other horticultural crops in similar Mediterranean-type pedo-climatic conditions. Furthermore, the introduction of a legume crop (catch- or cover-crop) in artichoke cropping system might be an added value with respect the agricultural management optimization since it enables to minimize nutrient inputs use.

In this study, by combining information on yearly basis nutrients fluxes, we evaluated the long-term sustainability of each management system. The specific objectives were: 1) To calculate nutrients field gross balances for each studied management type; 2) To study soil respiration in order to support the outcomes of nutrients balance with additional information on soil organic matter dynamic.

2. Materials and methods

2.1 Experimental site

The experimental device was established in 2006 at the experimental station 'Mauro Deidda' near Sassari, Italy (41° 19′ N, 8° 39′ E, elevation 81 m asl) (Fig. 1) and it is still ongoing.

The study aims to assess the agronomic, environmental and qualitative performances of globe artichoke alternative cropping systems with respect to a representative conventional one (characterized by monoculture, absence of organic amendment, and high yields) in the long-term period.

Before the trial setup, the site was under rainfed cereals conventional management.

The climate is attenuated thermo-Mediterranean (Emberger et al. 1962), with a mean annual temperature of 17.1 °C and a mean annual rainfall of 550 mm.

The soil is classified as a sandy-clay loam, Eutric Leptosols overlaid on limestone, with 49.9 % sand, 20.8 % silt and 29.3 % clay in the plough layer (0–25 cm), field capacity 30.6 % w/w, wilting point 22.1 % w/w, organic carbon 1.89 %, carbon-to-nitrogen ratio 12, pH 7.91, electric conductivity 0.22 mS cm^{-1}, cation exchange capacity 29.2 meq 100 g^{-1}, Ca^{2+} 24.7 meq 100 g^{-1}.

2.2 Management systems and experimental design

Three cropping systems were studied: a conventional system (CONV), an alternative monoculture system (ALMO), and a biannual rotation-based system (BIRO). Their management differed mainly in pest management, fertilisation (type and amount), use of fertility-building crops (catch-crop and cover-crop), and rotation (Fig. 1 and Table 1).

The three cropping systems were arranged in a completely randomised block design with three replicates. Blocks and plots were situated approximately 3 m apart in order to avoid as much as possible interaction effects and cross-contaminations among the differently managed systems.

Conventional (CONV)

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
	Artichoke												Artichoke	

Alternative monoculture (ALMO)

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
	Artichoke										French bean		Artichoke	

Biannual rotation (BIRO)

Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
	Artichoke													
								Pea						
					Cauliflower								Artichoke	
								Pea						

Figure 1 Temporal and spatial crops management scheme for each studied treatment.

Each year, starting from 2006 onwards, after soil preparation by ploughing (25 cm depth) and tilling, a total of 0.4 ha were planted within the first decade of August with 15-cm-long semi-dormant offshoots of ‘Spinoso Sardo’ artichoke. The distance between plants within a row was 70 cm, achieving an overall density of 9524 plants per ha.

The CONV was yearly managed in continuous monoculture and with incorporation of dried plants residues into the soil by harrowing up to 20 cm depth at the end of crop cycle (first half of July). Application rates of N, P, and K as mineral fertilizers followed the regional recommendations (LAORE, 2016 and Table 1). Pests and diseases control was performed according to regional farm service agency recommendations guide (LAORE, 2016). Weed control was achieved by mechanical means.

The ALMO and BIRO systems were conducted with no synthetic pesticides and fertilizers use.

Table 1 The principal agronomic operations in experimental field. CONV = conventional system, ALMO = alternative monoculture, BIRO = biannual rotation system (artichoke – cauliflower).

Agricultural practice	**Date of application**	**All growing seasons**	**Management system**
Seed bed preparation	Mid-July	Harrowing	All treatments
Fertilization	At planting	Urea 46 N Triple superphosphate 138 P_2O_5 Potassium sulphate 150 K_2O	CONV
		Chicken manure 3.7 N, 3.6 organic N, 3 P_2O_5	All treatments (only in 2013-14)
	During crop growth	Urea 46 N	CONV
Irrigation	August to November	Drip irrigation system	All treatments
Planting	August (artichoke)	First decade	All treatments
	November (cauliflower)	First decade	BIRO
	February (cover-crop)	Mid-February	BIRO
	May (catch-crop)	Beginning of May	ALMO
Harvesting	December - March (artichoke)	On a weekly basis	All treatments
	January - March (cauliflower)		BIRO
	May - June (catch-crop)		ALMO
Weeding	During crop growth	Mechanical weeding	CONV
Residues management	April	Artichoke broadcast incorporated	ALMO
		Pea (cover-crop) broadcast incorporated Artichoke broadcast incorporated Cauliflower broadcast incorporated	BIRO
	July	Artichoke broadcast incorporated	CONV
		French bean (catch-crop)broadcast incorporated	ALMO

In ALMO system, artichoke growing cycle was early interrupted at the end of marketable harvest period (beginning of April) and its fresh residues were chopped and ploughed. A short-cycle legume catch-crop (*Phaseolus vulgaris* L. cv Rex, Olter Seeds SpA, Italy) was introduced both for additional incomes and for N supply. Indeed, the French bean was ended at the first legume stages, when plants produced the first pods (end of flowering). Also, fresh residues from this last crop were returned to soil by harrowing before artichoke new growing season started.

The BIRO was based on a two-year rotation with cauliflower (*Brassica oleracea* L. var *botrytis* Clause Italia SpA, Italy). Both species were investigated on two adjacent plots, so all the phases of the crop sequences were present in field every year. A legume cover-crop (*Pisum sativum* L. Attika; Limagrain Verneuil Holding, France) was undersown in artichoke in February. At the end of each growing season (April), artichoke, cauliflower, and pea fresh residues were incorporated into the soil (Fig. 1 and Table 1). Three to four weeks after incorporation, the beds in all plots were rotary tillered for the next cauliflower or artichoke production cycle.

For all the cropping systems, in 2013-2014, a chicken manure addition contributed to supply 107, 141 and 146 kg of N, P and K ha^{-1} $year^{-1}$, respectively. Crop management in the three systems is summarized in Table 1.

2.3 Soil sampling and analysis

Soil was sampled in 2006, to assess soil initial conditions, and in 2016, at the end of the last crop cycle. In each plot, four composite soil samples were collected from 0–20 cm and 20-40 cm depth, 4 cm Ø. Each sample point was separated of at least 20 m from each other and was located at least 10 m away from the field margins in order to avoid edge effect. Soil samples were then sieved (10 mm) and used for chemical, and physical analyses. After air drying and sieving (2 mm), total organic carbon and total nitrogen contents were measured by dry combustion using an elemental analyzer LECO 628 (628 Series, LECO Corp., St Joseph, MI, USA). Soil pH was measured in a soil suspension with demineralized water (1:2.5 w/w) (Table 2).

2.4 Gross nutrients balance calculation

The field gross nutrients balances were evaluated following the criteria proposed by OECD (2007a, b) and Andrist-Rangel et al. (2007) for the calculation of the surface input/output balances of N, P, and K, respectively.

Concerning N balance, fertilizers, N fixed in the soil, and atmospheric deposition of N compounds were included as inputs, while marketed crops (e.g. artichoke and cauliflower heads, and French bean pods) were included as outputs (OECD, 2007). In the case of P and K balances, fixed elements by symbionts were omitted.

The amounts (kg ha^{-1}) of N, P and K applied to the crops by fertilizers were recorded yearly for each management system. Concentrations of N, P and K declared by the manufacturers were used for the mineral fertilizer, whereas poultry was sampled and analyzed in occasion of the single spreading event.

Annual atmospheric deposition rates of N, and P were derived from Markaki et al. (2010). The mean flow rates for 2001 and 2002 reported by Markaki et al. (2010) for the whole region were taken for the entire lasting of experiment. According to Andrist-Rangel et al. (2007), K depositions were not included in the calculation since it was estimated the they are very small (Morselli et al. 2008; Nastos et al. 2007).

The proportion of N derived from the atmosphere (%Ndfa) in each plant organ was calculated according to the 15N isotopic dilution method (Warembourg, 1993). Finally, the amount of N fixed (kg ha^{-1}) was calculated by multiplying French bean and pea N yield (kg N ha^{-1}) by %Ndfa.

Artichoke, cauliflower and French bean marketable production data were determined, each growing season, by picking artichoke and cauliflower heads and French bean pods, at weekly intervals on each plot and throughout the harvest period. The average yield per plant was multiplied by crop density for absolute yield (kg ha^{-1}) estimation. Productions were expressed as oven-dried matter (DM). At each sampling, the collected plants material was dried at 72 °C for 96 h, and was grounded to pass through a 1-mm sieve and then N, P and K were determined. Total N concentration in the samples was measured by dry combustion in an elemental analyzer LECO 628 (628 Series, LECO Corp., St Joseph, MI, USA). Phosphorus was determined by the colorimetric method with molybdo-vanadate reagent (AOAC Method 965.17, 1995). Potassium was determined by atomic absorption spectrometry (PerkinElmer AAnalyst 200, Norwalk, CT, USA) according to the AOAC Method 968.08 (1995). Nitrogen, P and K output per ha of heads and pods yield were calculated multiplying their own element content by the aerial biomass value (dry weight basis).

2.5 Soil respiration monitoring

In October 2014, two PVC collars (20 cm high, 40 cm diameter) were placed in the center of each plot. The collars were inserted into the soil to 2 cm depth and all the native litter inside the collars was removed. Soil CO_2 efflux measurements were carried out on a weekly basis over 12 months. A portable infrared gas analyser (IRGA) EGM-4 (PP Systems, Hertfordshire, UK) was connected through a closed chamber SRC1 (PP Systems, Hertfordshire, UK) to the internal collar of each plot. The rate of soil CO_2 efflux was obtained by the software of the PP system, which fitted a quadratic equation to the increase of CO_2 concentration in the chamber recorded every 124 s. The measurement was repeated 3 times for each collar, with the chamber being displaced and repositioned on the collar at each repetition. The mean value of the 3 repeated measurements was taken as a reading for each collar. The soil temperature and moisture at 10 cm depth was measured for each plot at the time of efflux measurement. Efflux measurements from all collars were conducted on the same day at each sampling occasion.

2.6 Statistical analysis

The effect of management systems on soil properties were analyzed using the SAS MIXED procedure (SAS v. 9.3 SAS Institute, Cary, NC) with blocks as random effects. When needed means were compared by the Tukey–Kramer test ($P<0.05$).

Gross nutrients balances data were subjected to analysis of variance using the MIXED procedure. Statistical analyses were performed using a linear mixed model with years, management systems, and their interactions as fixed effects, and blocks and interactions with blocks as random effects. The homogeneity of variance was tested and in the case of heterogeneous variances the model was fitted for partitioned variances (Littell et al., 2011). The degrees of freedom were determined based on the Kenward–Roger method. Least squares means were calculated and mean comparisons were conducted using the Tukey–Kramer test ($P<0.05$) within the SAS procedure MIXED.

For soil respiration, measured multiple times per year, sampling dates were treated as a repeated measure. The Pearson correlation coefficients between soil respiration and soil temperature and moisture were determined using the SAS correlation procedure.

3. Results and discussion

3.1 Long-term trends in soil quality and nutrients

Since the soil properties were consistent across the ten years between artichoke and cauliflower plots in the biannual rotation (BIRO), only average data are reported herein.

Table 2 Comparison among initial (2006) and final (2016) soil conditions for conventional (CONV), alternative monoculture (ALMO), and biannual rotation (BIRO) systems. Values within a column are not significantly different from each other if marked with the same letter as determined by Student-Newman-Keuls test (P<0.05).

	pH	SOM[a]	Total N[b]	P_2O_5[c]	K^+ [d]	CEC[e]
Cropping systems						
Initial soil conditions	7.95	33.35 a	1.77 a	87.50 a	0.56 ab	29.36 a
CONV	7.93	35.13 a	1.51 b	89.38 a	0.47 b	27.06 b
ALMO	7.91	34.13 a	1.60 ab	60.50 b	0.87 a	29.12 a
BIRO	7.91	26.00 b	1.68 ab	49.13 c	0.92 a	29.67 a
Test Student-Newman-Keuls						
Blocks	ns	ns	ns	ns	ns	ns
Treatments	ns	***	*	***	*	**
Block x Treatment	ns	ns	ns	ns	ns	ns

[a] SOM, soil organic matter (g kg^{-1})
[b] Total N (g kg^{-1})
[c] P_2O_5, available phosphorus (mg kg^{-1})
[d] K^+, exchangeable potassium (meq 100 g^{-1})
[e] CEC, cation exchange capacity (meq 100 g^{-1})

In our trial, the two monoculture systems (CONV and ALMO) had a significant greater soil organic matter (Table 2) compared with biannual rotation system (BIRO). Organic matter is widely considered a sensitive indicator of changes in soil fertility in response to agricultural management (Trivedi et al. 2016). In our study, the alternative monoculture system was the only, alternative to conventional treatment, successful in accruing soil organic matter over time. Conversely, in biannual rotation structures, soil organic matter content was lower both than soil initial conditions and monoculture systems. A higher soil respiration peak and a slightly higher soil temperature (+ 1 °C), although without significant differences among the compared treatments, was shown (cfr with section 3.3) in biannual rotation system. As consequence, we may hypothesize that soil in this system was likely more prone to soil organic matter loss through increased microbial respiration and soil temperature. The biannual rotation system has comparable residues amount to conventional and alternative monoculture, but perhaps the low carbon-to-nitrogen ratio of pea (≤15 according to Murungu et al. 2011) leads to more rapid biomass decomposition and less storage as organic matter than in continuous artichoke and alternative monoculture. This hypothesis agrees with Russell (1973) who stated that peas biomass breaks down very quickly due to the plant's low carbon-to-nitrogen ratio, and may not improve soil organic matter over the long-term. At the end of the crop cycle, residue in CONV had a carbon-to-nitrogen ratio of 24 (Mahmoud and Abd EL-Kader 2012). Lower carbon-to-nitrogen ratio material has a faster initial decomposition rate, which may reduce storage as organic matter (Enríquez et al. 1993, Nicolardot et al. 2001), however, some models suggest that high-quality residue, easily incorporated into microbial biomass, may lead to more long-term soil organic matter storage (Cotrufo et al. 2013). Total N percentage was significantly lower in the conventional system. Here, we hypothesize that since to grow microbes need carbon for energy and nitrogen to build proteins, when an aboveground biomass with a high carbon-to-nitrogen ratio is incorporated, nitrogen is not available from the newly-added organic material, and microbes will take it from the soil by depriving growing plants of nitrogen. The highest values recorded on both alternative systems were probably the result of cover crops + artichoke aboveground biomass production that, when incorporated into soil, progressively mineralized and increased the available N content. Some authors, also, found that pea N concentration increased as pea flowers approached anthesis, and when the pea is ended, the total N amount in aboveground biomass is equivalent to standard inorganic fertilizer N application rates. Similarly, Ledgard (2001) and Tonitto et al. (2006) found that legumes can contribute up to 300 kg N ha^{-1}. Although much of this N comes from aboveground biomass, it has been reported that pea root biomass may comprise as much as 12% of aboveground biomass amounts (Puget and Drinkwater 2001; Sainju et al. 2005) and will decompose more slowly belowground. To maintain P availability to artichoke on calcareous soils, P fertilizer was applied on a regular basis in conventional system, avoiding the significant P decrease, with respect to initial soil conditions, that we observed in alternative monoculture and biannual rotation systems. Exchangeable potassium (Table 2) increased over the experimental period, reaching the highest value at the end of the experiment and for both the unfertilized systems. Moreover, the soil measurements were not consistent with the negative calculated K budgets. This phenomenon, already reported by Kautz et al (2013), can be explained as a consequence of the biocycling of subsoil K, characterised by the slow release of the available potassium sources. Significant differences in cation exchange capacity which were caused by management treatments can be seen in Table 2. Conventional treatment significantly decreased cation exchange capacity in soil samples when compared to initial conditions and to non-fertilized plots (Table 2). As the unfertilized treatments in our study did not receive any kind of mineral fertilizer during 10 years of investigation, the differences observed here may therefore be judged as conservative estimates of the effect of soil organic matter on cation exchange capacity.

3.2 Nutrients gross balances

Since there were significant interactions between treatments and years for all the analyzed nutrient balances, data were reanalyzed by years (Figs. 2-4). The annual N gross balances (and those for P and K) were rather consistent over years, and appeared positive for all the analyzed systems only in 2013-2014 growing season (Figs. 2-4). The conventional system had an average N surplus amounting to 198 kg N ha^{-1}. The alternative monoculture had negative N gross balances, and over the 10 years, the reductions were in the range between 55.9 and 65.9 kg ha^{-1} (Fig. 2). By contrast, the N gross balance of biannual rotation appeared to be positive.

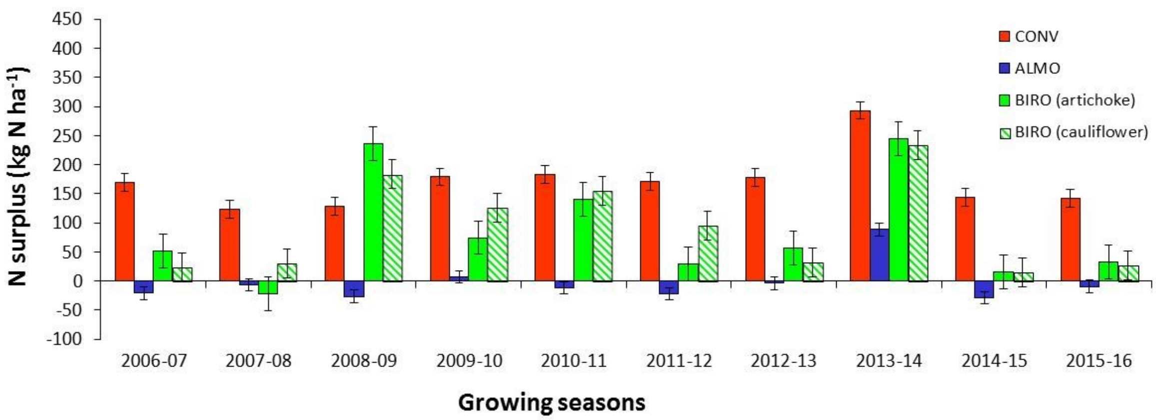

Figure 2 Gross N balance for conventional (red bars), alternative monoculture (blue bars), and biannual rotation (green bars for artichoke, and green/white bars for cauliflower) over the 10 years period. Error bars indicate standard error of the means.

The pattern of the P and K budgets was similar (Figs. 3-4), and significantly differed between conventionally and alternatively managed systems.

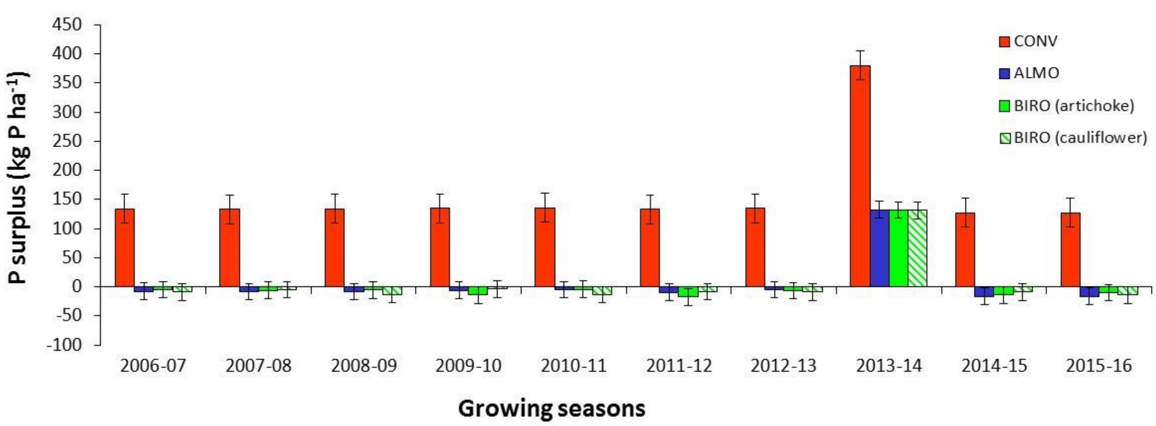

Figure 3 Gross P balance for conventional (red bars), alternative monoculture (blue bars), and biannual rotation (green bars for artichoke, and green/white bars for cauliflower) over the 10 years period. Error bars indicate standard error of the means.

Alternative monoculture and biannual rotation systems had calculated P and K deficits, whereas the conventional one appeared to accumulate both P and K. Despite the negative K balance, our results highlighted that the K exchangeable concentration increased significantly in the soil, during the long-term experiment (for ALMO and BIRO systems). This phenomenon, which has already been reported in other studies (Benbi and Biswas 1999; Askegaard and Eriksen 2002; Srivastava et al 2002), can be explained as a consequence of the biocycling of subsoil K, characterised by the slow release of the available potassium sources (Andersson et al. 2007). It is known that the K uptake by plants is highly dependent on the soil's capacity to deliver K to the root surface by mass flow and diffusion (Jungk and Claassen 1997; Jungk 2001; Liebersbach et al. 2004).

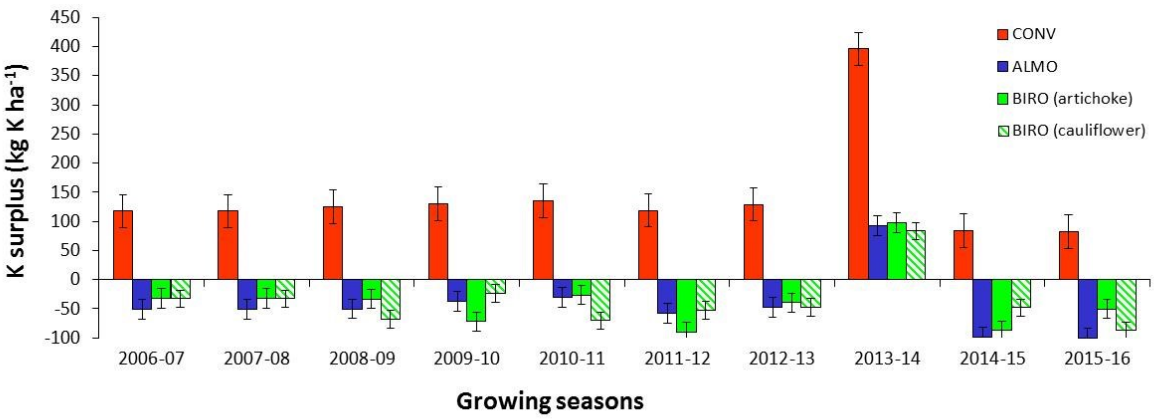

Figure 4 Gross K balance for conventional (red bars), alternative monoculture (blue bars), and biannual rotation (green bars for artichoke, and green/white bars for cauliflower) over the 10 years period. Error bars indicate standard error of the means.

Maintaining deficiency of nitrogen (solely alternative monoculture system), phosphorus and potassium (both alternative monoculture and biannual-based rotation) for a long time may lead to a reduction in soil fertility in this area. Conversely, in conventional system, fertilizers applied to the field in excess of plant needs may be loss by leaching. The main purpose of the work was to evaluate the influence of sustainable artichoke cultivation on the conservation of soil fertility, as well as the long-term performance of these cropping systems.

To the best of our knowledge, this paper is the first study to assess the effect of long-term artichoke new crop management on plant-soil system. Considering a period of several years, the calculated balances provide a useful index to assess the possible environmental effects of the adopted management strategies. In our study, between non-fertilized systems, a positive N balance (inputs > outputs) was observed in biannual based rotation, thus indicating appropriate fertilisation management. The positive N balance, here observed (14 kg ha^{-1} $year^{-1}$), was mainly due to the effect of crop residues (artichoke + cover crop or cauliflower + cover crop) which returned to the soil. We observed that, after 10 years of cultivation in biannual rotation, the residues retention maintained a high and rather stable agronomic productivity and the efficiency of N inputs, thus enhancing sustainability.

The opposite was found in the alternative monoculture indicating that the relatively high production has been maintained at the cost of the soil organic N pool. The negative N budget of alternative monoculture suggested that the introduction of French bean as catch-crop after globe artichoke (main-crop) did not guarantee a balanced nutrients budget. The benefits of residue retention on agronomic productivity and sustainability are especially important in soils, like in the Mediterranean areas, which are prone to accelerate erosion, drought, high soil temperatures, crusting or surface sealing and hard-setting on drying (Lal 2009). For this reason, the evaluation of the chemical properties of rhizome and root residues in biannual rotation system and the relationship between these characteristics and carbon mineralization, could be interesting for future research.

3.3 Soil respiration response to cropping systems

Over a complete growing season soil respiration remained at the lowest values during winter, gradually increased from March, and reached a maximum in June-July, in a pattern similar to soil temperature (Figs. 5 and 6). The soil respiration values, throughout the study period, ranged from 0.04–0.85, 0.06–1.21, and 0.04–1.30 g CO_2 m^{-2} s^{-1} for conventional, alternative monoculture, and biannual rotation, respectively.

Typically, three peaks per year occurred, at the mid-April, beginning of June, and early July. The first peak was caused by rapid crop growth (overall French bean and pea cover-crop in alternative monoculture and biannual rotation, respectively), the second by the return of residues combined with soil tillage (artichoke residues for alternative monoculture and artichoke/cauliflower + pea residues for biannual rotation), and the last by French bean (alternative monoculture) and artichoke (conventional) residues incorporation. Both alternative cropping systems (alternative monoculture and biannual rotation) resulted in an overall higher soil respiration compared to the conventional system.

The maximum peaks of soil respiration in conventional were 0.60, and 0.85 g CO_2 m^{-2} s^{-1} for 2014-15 and 2015-16 growing seasons, respectively. Soil respiration from alternative monoculture with catch-crop was higher than the conventional, with maximum values ranging from 1.01 to 1.21 g CO_2 m^{-2} s^{-1} for 2014-15 and 2015-16 growing seasons, respectively, and it increased to 1.29, and 1.30 g CO_2 m^{-2} s^{-1} in biannual rotation during the corresponding periods. The soil respiration from systems with catch- and cover crops fluctuated more than the conventional (Figs. 5-6).

Soil moisture was not the key driving factor in affecting soil respiration, being poorly correlated with soil respiration in our study (data not shown).

Soil respiration showed a positive relationship with soil temperature. There were no differences in soil temperature among the three systems. Our study showed that the CO_2 emission increased, as the soil temperature increased, and this increase effect was more important for the biannual rotation system (y=0.0498x - 0.3348, where y is the soil respiration and x is the soil temperature; R_2= 0.72) than for the alternative monoculture and conventional systems (R_2= 0.68, and R_2= 0.67) (Figs. 5-6, and 7). Thus, in spite of the well supported relationship between the temporal variability of CO_2 emissions and their relationship with temperature and soil moisture levels (Gao et al 2013), we found a good and positive relationship only between soil respiration and soil temperature. This result was probably due to the fact that in this study soil temperature averaged 19.4 °C. Mancinelli et al (2010) found that the optimal conditions for soil respiration in a

Mediterranean environment were reached when soil temperature was around 17.2 °C. Consequently, the range of temperature from 7.8 to 22.1 °C might limit CO_2 emission from uncovered soil, but in soil with a cover crop treatment the respiration process may still increases as soil temperature increases. Moreover, the cover-crop absence could also have depleted soil biota as consequence of lower litter inputs and root exudates supply (Blanchart et al. 2006). Under these conditions, the stable and relatively dry conditions near the soil surface favors a low and constant soil respiration, most likely related to a reduced root growth and a slow metabolism (Bryla et al. 1997, Bouma and Bryla 2000; Bouma et al. 2001).

Concerning mineral fertilizers uses in a conventional system, Wardle (1995) and Bunemann et al. (2006) reported mainly indirect effect such as alterations of the plant community composition, litter quality, and soil abiotic conditions (Bardgett and McAlister 1999; Wardle et al. 2001). The low rates obtained in conventional system might be the result of our controlled field conditions (Dugas 1993; Lambers et al. 1996), including the absence of ground cover that minimizes the microbial contribution to soil respiration. In our study, the alternative systems have benefited of the legume catch- and cover crops effect induced by continuous French bean and pea cropping and whose residues have been incorporated into the soil.

Overall, our study suggests that, after 10 years, long-term alternative cropping associated with cover-crop use has greater enhancement potential for soil respiration than periodic legume catch-crop use and pesticide and mineral fertilizer use. Legume fresh residues incorporation also appears as a major factor explaining differential response of soil respiration to alternative versus conventional systems. The same pattern was already observed by Gao et al (2013) for the response of the soil respiration to agricultural intensification.

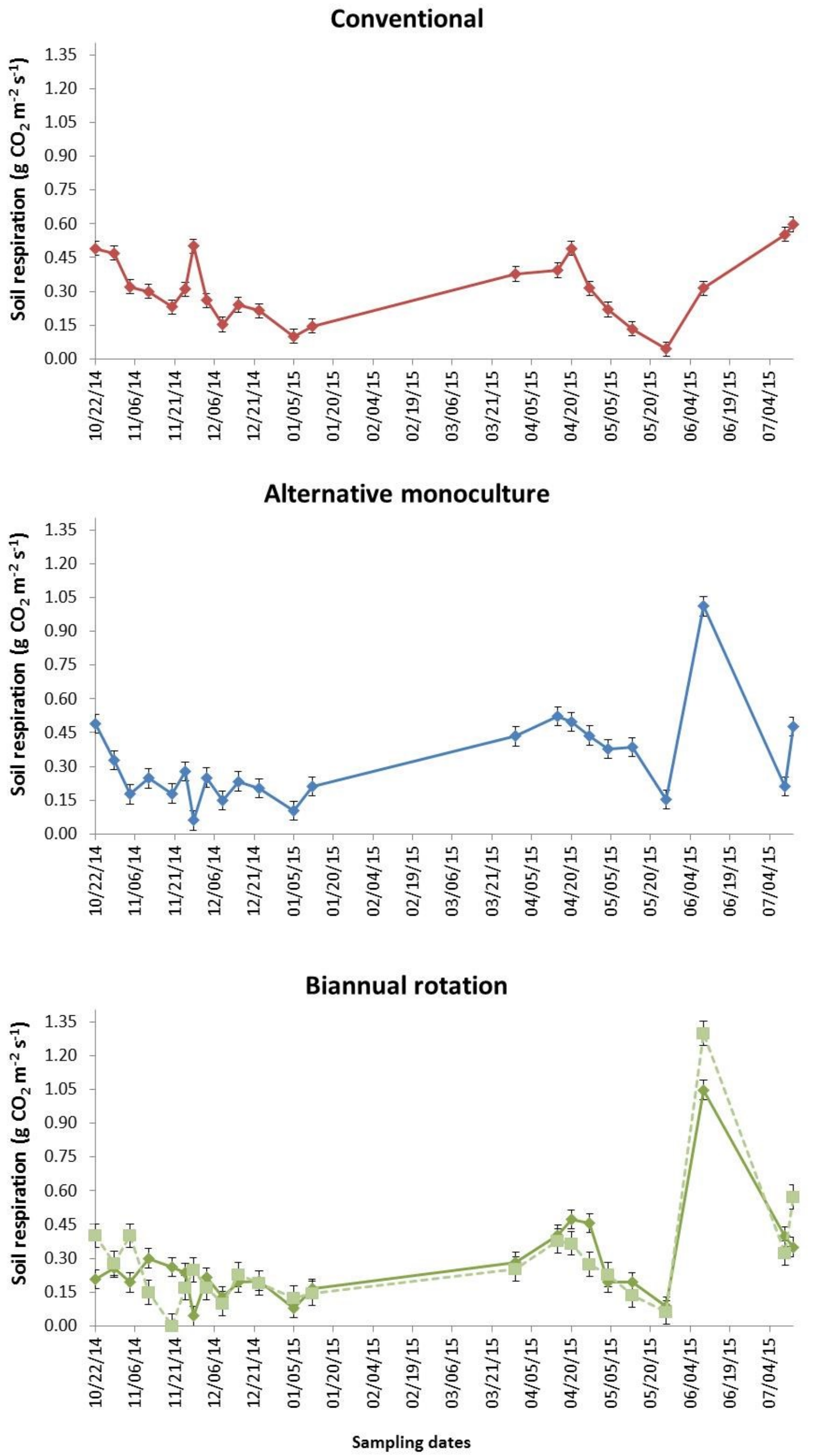

Figure 5 Seasonal course of soil CO_2 emission rates during the 2014-15 growing season. In biannual rotation: artichoke (—) and cauliflower (----). Error bars indicate standard error of the mean (n = 12 plots per treatment and season).

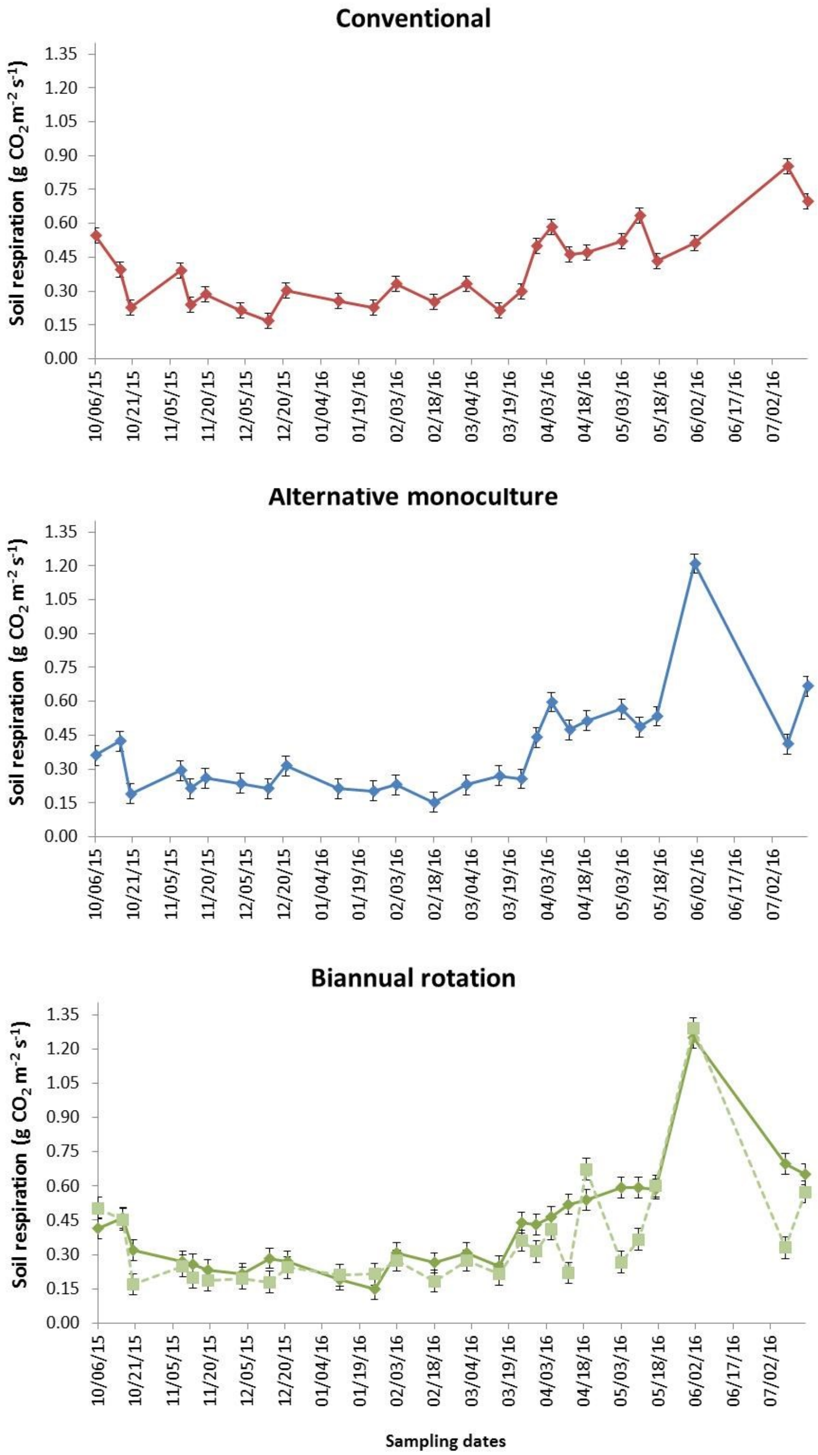

Figure 6 Seasonal course of soil CO2 emission rates during the 2015-16 growing season. In biannual rotation: artichoke (—) and cauliflower (----). Error bars indicate standard error of the mean (n = 12 plots per treatment and season).

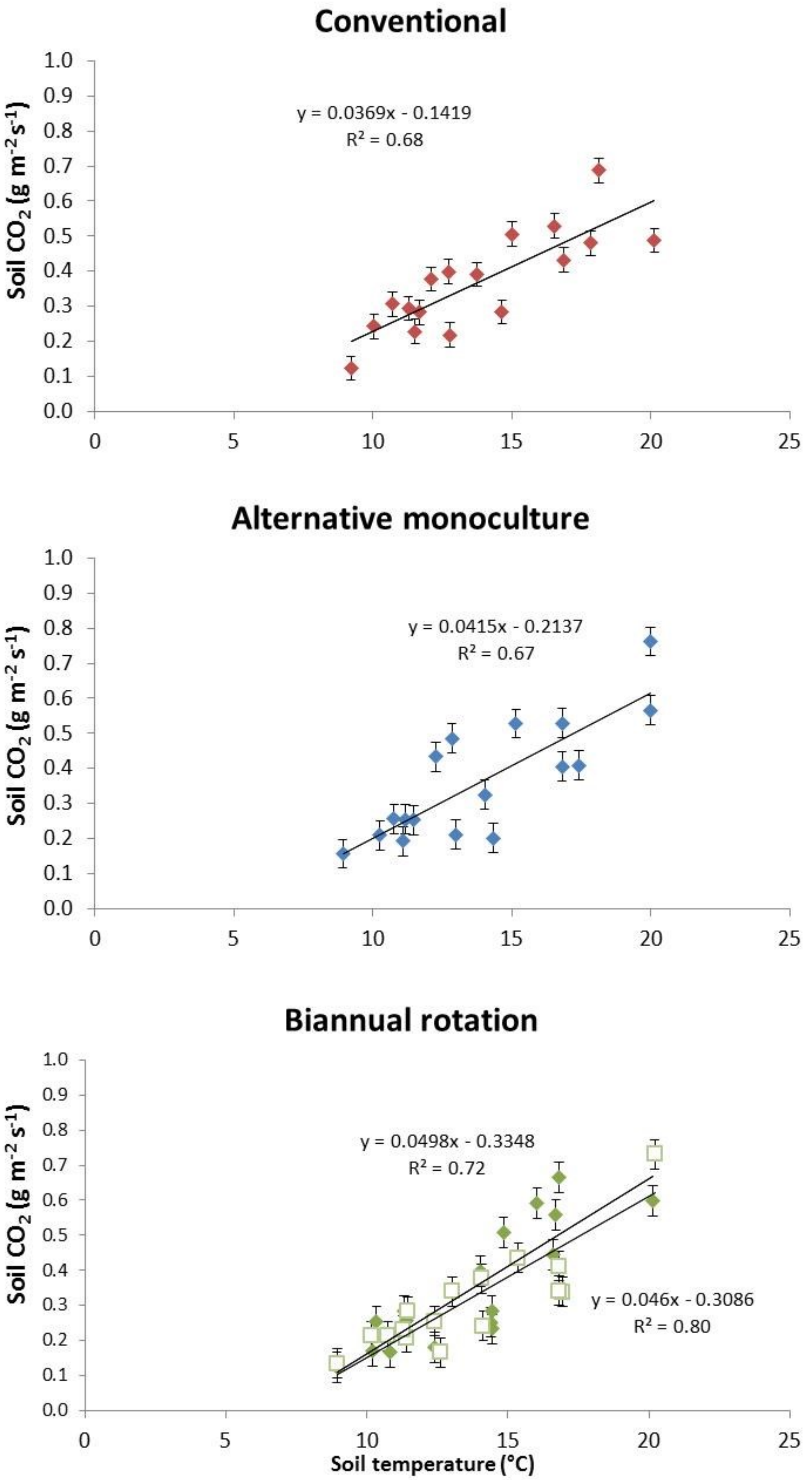

Figure 7 Correlation between soil respiration and soil temperature over the whole monitored period (2014-15 and 2015-16 growing seasons). Error bars indicate standard error of the means.

4. Conclusions

Here we show that fertility management using organic catch- and cover crops during artichoke production promotes similar soil quality compared with conventional practices. Our results confirm that the use of building-fertility crops have the potential to maintain soil quality in alternative monoculture as well as biannual rotation systems. After 10 years of experimental activity, plots grown with catch- and cover crops had comparable soil traits with respect to plots grown with urea. This corresponds with previous studies that have demonstrated that soil incorporation of plant byproducts can enhance soil biological activity compared with inorganic fertilizers in exposed agricultural settings. Soil respiration was largely controlled by soil temperature in conventional system, and primarily by fresh residues addition in non-fertilized systems.

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