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Potential Role of Fertilizer Sources and Soil Tillage Practices to Mitigate Soil CO_2 Emissions in Mediterranean Potato Production Systems

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Abstract: Agricultural practices should be approached with environmental-friendly strategies, able to restore soil organic matter and reduce the greenhouse gas emissions. The main objective of this study is to evaluate the environmental benefits, in terms of CO_2 emissions and carbon balance, of some agricultural practices for potato cultivation. A randomized complete block design was adopted where the treatments were: (a) tillage systems (plowing; subsoiler and spading); (b) fertilizer sources (mineral and organic). All treatments were replicated three times. Potato yield and its carbon content, soil CO_2 emissions, temperature, and volumetric water content were measured. The CO_2 emissions were higher in organic than in mineral fertilizer (0.60 and vs. 0.77 g m^{-2} h^{-1}, respectively), while they were low in spading compared to the other soil tillage (0.64 vs. 0.72 g m^{-2} h^{-1}, respectively). Carbon input was the highest in plowing and organic fertilizer 4.76 and 5.59 Mg C ha^{-1}, respectively. The input/output ratio of carbon varied according to the main treatments. The findings suggest that spading tillage and organic fertilizer might result in environmental and agronomical benefits, further research should be performed to evaluate to possibility to extend the results to other environments and crops.

Keywords: soil organic matter; soil amendment; intensive agriculture; sustainable agriculture

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1. Introduction

Nowadays, the adoption of farming practices that increase soil carbon (C) stocks are strongly recommended to improve the sustainability of the agricultural systems in all environments. Although intensive agricultural management has contributed to the economic and social development of modern society, it has also led to a progressive environmental degradation by increasing the greenhouse gas (GHG) emissions and reducing soil quality [1]. In general, agriculture is considered as one of the most important human activities that produce significant amount of GHG emissions, and the emissions released from soil into the atmosphere represent a large amount of carbon dioxide (CO_2) [2].

Soil represents the biggest terrestrial pool of C, and the soil tillage approach, mainly used for seedbed preparation and weeding, is the common practice adopted since the human became a farmer. Soil acts as a source of nutrients and water, but the modification of soil aggregation and structure due to the modern agricultural practices may increase considerably the surface runoff and losses of nutrients and soil [3]. According to Abdalla et al. [4], conventional soil tillage, based on deep and frequent operations, such as ploughing, is an energy-intensive practice and it contributes to enhance soil carbon losses through organic matter mineralization and CO_2 emissions. In fact, tillage determines soil disturbance and soil aggregates disruption, increasing the exposure of soil organic matter to microbial decomposition and hence speeding oxidization [5] with a consequent C loss from soils through the release of CO_2 into the atmosphere [6]. Consequently, soil tillage affects the mineralization rate of nutrients, implying the need to consider the negative effect of tillage practices also at the ecosystem level [7].

Conservation tillage is a general term assumed to describe a wide range of tillage practices that are able to reduce soil degradation generally occurring with conventional tillage [8]. Recently, tillage intensity is being gradually reduced under various farming systems by the application of more environmentally friendly strategies based on mechanized direct planters, cover crops, and longer crop rotation [9,10]. Thus, the main challenge for the modern agriculture is to develop and enhance a farming system that is able to maintain high net primary productivity, among the crops in rotation, and to add carbon stocks by phytomass or other sources that maximize the benefits regarding the promotion of C sequestration and soil quality [11]. This could be obtained through proper soil management and overall recycling of organic waste on land to protect agricultural soils. The use of composted organic waste helps to manage the organic matter into the soil and could represent a key for sustainable agriculture [12]. Accordingly, the European Commission (2010) is encouraging the reutilization of organic waste through agricultural land application in order to avoid disposal costs, recycle nutrients back into the agricultural production, and reduce the use of mineral fertilizers.

Recently, Hargreaves et al. [13] reported that the adoption of organic waste in agriculture, as soil amendment and fertilizer, may represent an ecological way for maintaining and restoring soil productivity, even if their use is connected to several factors such as the content of organic matter, nutrient and heavy metal availability, and transportation costs [12]. Although these variables could affect the utilization of the organic waste, generally it acts as an amendment in agricultural soil, affecting its fertility in different ways: directly, due to the properties of organic amendment, or indirectly, by affecting the soil's physical, chemical, and biological characteristics [14]. In fact, organic waste added into the soil acts as a sponge and maintains water in the top layer of the soil available for plant roots and promotes the development growth and activity of different beneficial microbes involved in the soil nutrient cycle [15]. Furthermore, organic waste application may be particularly important in the reduction in net agricultural GHG emissions [16]. However, the replacement of conventional mineral fertilizers with organic waste could represent several problems, especially for the crops that have high nutrient needs, determining the necessity to apply large amounts of organic waste to satisfy their overall crop needs [12].

Farming systems adopted for potato crop cultivation are generally based on excessive tillage operations with the production of low levels of crop residues that are detrimental to soil quality and fertility [17]. All these concerns have generated a need to assess alternative tillage systems, such as conservation tillage practices, even if they need to be developed for potato production systems [8]. Although it is well known that tillage operation and organic waste affect soil quality and crop productivity, information on the implications of specific tillage requirements and fertilizer type combination on potato performance in the Mediterranean environment is scarce. This study hypothesizes that reduced tillage practices and the organic waste application could represent a suitable efficient strategy, in terms of yield and carbon sequestration, for replacing potato cultivation under conventional farming practices. Therefore, the main objective was to assess the feasibility of using organic waste under different tillage practices as an alternative to the conventional practice for enhancing ecosystem services provided by the cultivation of potato crop in Mediterranean environment in central Italy.

2. Materials and Methods

2.1. Study Site and Soil Characteristics

The research was conducted at the experimental farm "Nello Lupori" of the University of Tuscia located in central Italy (latitude 45°25′, longitude 12°04′ and altitude 310 m a.s.l.) during the 2015 and 2016 cropping seasons. The climate of the area is typically Mediterranean, with warm and wet winters and hot and dry summers. The average temperature is 14.5 °C, with minimum temperatures just below 0 °C in February and maximum temperature above 35 °C in July. Annual rainfall is on average 752 mm (last 30 years), mainly spread from September to May (569 mm). The soil of the experimental area is of volcanic origin and classified as *Typic Xerofluvent* [18]. The particle size distribution of the soil in the surface horizon (0–30 cm depth) were 76.3% sand, 13.3% silt, and 10.4% clay and indicate the soil as loamy sand. The soil had 0.97% and 0.12% of total organic C and N content, respectively, and pH (H_2O) 6.9.

2.2. Experimental Design

A 2-year crop rotation durum wheat (*Triticum durum* Desf.)–Potato (*Solanum tuberosum* L.), typical of the study area, was established in 2013 in order to compare soil tillage practices and fertilizer sources. The treatments consisted of (a) three tillage systems (conventional tillage based on mould-board plough; reduced tillage based on subsoiler; reduced tillage based on the spading machine), and (b) two fertilizer sources (mineral fertilization as performed in conventional farming and organic fertilization by means of municipal organic waste). The treatments were replicated three times according to a randomized complete block design. Considering that both crops in rotation were simultaneously cropped, the experimental field included 36 plots (two crops × three soil tillage × two fertilizer source × three blocks). Each experimental plot was 60 m^2 (6 × 10 m) and they were separated by 3 m wide alleys to allow for equipment operations.

2.3. Field Setup and Crop Management

Every year in April, before planting potato tubers, the soil was tilled according to the selected treatments. All tillage operations were performed to a depth of 20 cm and then followed by a seedbed preparation with a disk harrowing (10 cm of soil depth) carried out just prior to potato planting. Potato cv. Monalisa was planted by using seed pieces of tuber previously cut. Potato tuber pieces were hand planted in open furrows on 13 April 2015 and 31 March 2016, respectively, at the density of 7.14 plants m^{-2} with the spacing of plant rows and plant in rows of 0.70 m and 0.20 m, respectively. The same plant geometry was adopted in all experimental treatments. In the mineral fertilizer treatments, fertilizers were applied twice; the first time, at potato planting, 100 kg ha^{-1} of P_2O_5 as triple perphosphate, 50 kg ha^{-1} of K_2O as potassium sulphate, and 100 kg ha^{-1} of N as urea, while the second fertilizer rate was applied 6 weeks after planting, at hilling stage, using the equivalent of 70 kg ha^{-1} of N as ammonium nitrate. For organic fertilization treatments, an amount of 18 Mg ha^{-1} of mature organic waste was totally applied at planting before seedbed preparation. In both fertilization source treatments, potato received identical amounts of total N. The rate of fertilization was calculated based on the demand of 170 kg ha^{-1} of N according to the common practices adopted by the farmers in the study area [19] and considering the mineralization rate. Hilling up was performed a month after the planting, using a tractor-mounted cultivator. Irrigation water was supplied when soil moisture reached 65% of the soil field capacity in each experimental year and stopped 2 weeks before tuber harvesting. A sprinkler irrigation system was used to irrigate the potato crop five times in 2015 and four in 2016, respectively. Potato tubers were harvested on 28 July 2015 and 4 August 2016, when about 70% of haulms were dry.

2.4. Data Collection and Analysis

Weather data characteristics (minimum, maximum and mean temperature, and precipitations) for the entire growing seasons of potato in both 2015 and 2016 years were measured by a meteorological station located at 500 m from the experimental site. Fluxes of CO_2 emissions from all experimental treatments were measured during both potato growing seasons, from April to July, using a portable dynamic closed-chamber infrared gas analyzer system [20]. A non-steady-state through-flow chamber (SRC-1, PP Systems, Stofold, UK) with a volume of 1334 cm^3 and a cover area of 78.5 cm^2 was used to perform soil CO_2 emission measurements. The chamber had only one opening to the soil and the soil CO_2 emission readings were performed placing the chamber on a small permanent PVC frame carefully placed in a central area of each plot in a potato row between two consecutive plants [21,22]. The area inside the PVC collar was kept weed-free by clipping weeds whenever necessary. Measurements were conducted weekly at the same time (between 8:00 a.m. and 10:00 a.m.) in order to reduce diurnal variation by means of a sensitive infrared gas analyzer instrument (EGM-4, PP Systems, Stofold, UK) [23]. Each measurement took about 180 s and varied based on the respiration rate of the soil. The amount of soil CO_2 emissions was estimated by fitting a quadratic equation to the relationship between the increasing CO_2 concentration and elapsed time. The values obtained were considered as the net carbon mineralization since the autotrophic component was included. The estimation was determined considering two consecutive measurements in a linear interpolation and their integration over time (trapezoid rule) as previously adopted by Mancinelli et al. [24].

Soil temperature at 0–5 cm depth and soil volume water content at 0–30 cm depth was measured simultaneously to soil CO_2 emissions near to the chamber by using STP1 soil temperature Probe connected to EGM-4 instrument and TDR 300 Soil Moisture Meter (Spectrum Technologies, Inc. Plainfield, IL, USA), respectively.

At potato harvesting, five soil cores (0–20 cm depth) were collected from each plot and pooled together for the soil analysis. Soil samples were taken from the central inter-row of each plot, sieved (<2 mm) and stored at 4 °C until their use for total organic carbon (TOC) and total nitrogen (TN) determination. The TOC and TN contents were determined using an elementar analyzer (Thermo Soil NC–Flash EX1112).

Tuber yield and aboveground biomass of potato were sampled in 2 m^2 of a central area of each plot and crop physiological maturity. Tubers were classified as marketable (graded by tuber diameter between 40 and 75 mm) and unmarketable tubers (cull tubers with a diameter <40 mm). Samples were oven-dried at 70 °C until constant weight and finely ground, in order to determine the carbon (C) content by means of an elementar analyzer (Thermo Soil NC–Flash EX1112).

The ration of carbon input and carbon output (C input/C output) was determined considering the carbon produced by straw and tubers of potato crop (C input) and the carbon content in the CO_2 emissions during the potato growing season (C output). The ratio offers an evaluation of the direction of the carbon cycle. Values higher, equal to, or lower than 1 mean increasing, stable or decreasing soil carbon content in the system, respectively. The ratio between the cumulative carbon dioxide emissions and the tuber yield was used to evaluate the amount of CO_2 emissions per unit of potato yield. The lower values mean lower soil CO_2 emission per unit of tuber yield [21].

2.5. Statistical Analysis

Analysis of variance was performed for the data on soil tillage and fertilization source obtained from the experimental fields. The JMP statistical software package 4.0 [25] was used for the statistical analysis. The ANOVA was conducted for the 2 year period applying a randomized complete block design with three blocks. A two-way factorial experimental design was performed for measured characteristics where the soil tillage and fertilization source were the treatments, and the year was considered as a repeated measure [26]. Means were compared adopting the Fisher's protected least significant difference (LSD) at $p \leq 0.05$. The soil CO_2 flux, soil temperature and soil volumetric water content are presented as means of the considered treatment ± standard error (SE). A second-order polynomial regression model of soil CO_2 emissions by soil temperature and soil volume water content were performed separately for each soil tillage and fertilization source treatments.

3. Results

3.1. Weather Conditions during Potato Growing Seasons

The potato growing period was from March to August and lasted for 106 days in 2015 and 126 days in 2016, respectively. The weather variables as air temperature and rainfall were recorded during the whole potato growing period in both experimental seasons (Figure 1). The cumulated precipitation was higher in 2016 than 2015 (181.0 vs. 147.8 mm, respectively), even if they tended to be distributed differently between the potato growing seasons. Indeed, the precipitation in 2015 growing seasons was mainly concentrated in the first month after potato sowing (about 60% of the total precipitation), while in 2016 the precipitation was mainly distributed in May–June (about 70% of the total precipitation). As expected, minimum and maximum temperatures tended to gradually increase from March to August when the air temperature reached the highest values of the year (35.3 °C and 32.9 °C in 2015 and 2016, respectively). The mean air temperature was higher in 2015 than in 2016 potato growing season (on average 19.0 °C vs. 18.2 °C, respectively).

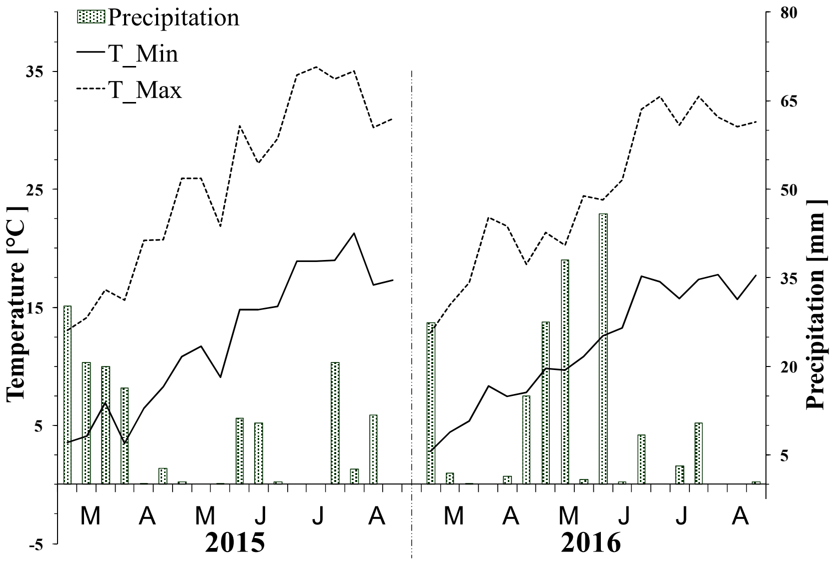

Figure 1. Decadal minimum [—] and maximum [- - -] temperatures (°C), and rainfall [■] (mm) at the experimental site, throughout the periods of study in 2015 and 2016.

3.2. Soil CO_2 Emissions, Temperature and Volumetric Water Content during the Potato Growing Season

3.2.1. Effect of Fertilizer Sources

The flux of soil CO_2 emissions, soil temperature and soil volume water content during the potato growing seasons under organic and mineral fertilizer sources are reported in Figure 2. The soil CO_2 emissions showed different values and trends between the 2015 and 2016 growing seasons. In 2015, the CO_2 emissions trend slightly increased in both fertilizer sources, reaching the highest value in May (on average 0.71 g m^{-2} h^{-1}), then it gradually decreased showing the lowest value of CO_2 emissions just before potato harvesting (on average 0.38 g m^{-2} h^{-1}). In 2016 the CO_2 emissions rapidly increase after potato sowing reaching a peak after one month in May, with an average value between the fertilizer sources of 1.01 g m^{-2} h^{-1}, then the flux of CO_2 emissions tended to decrease slowly until the potato harvesting (on average 0.42 g m^{-2} h^{-1}, Figure 2). Although the trend was similar in mineral and organic fertilizer sources, the soil CO_2 emissions were generally higher in organic than in mineral fertilizer (on average 0.65 and 0.81 vs. 0.54 and 0.72 g m^{-2} h^{-1} in 2015 and in 2016, respectively).

However, the biggest differences were observed at the beginning of the potato cultivation in 2015 and from the middle potato season in 2016 (Figure 2). Soil temperature followed the weather conditions and tended to increase from the potato planting (on average 15.6 °C and 15.7 °C in 2015 and in 2016, respectively) to harvesting (on average 29.7 °C and 27.6 °C in 2015 and in 2016, respectively). Few differences were observed on soil temperature between organic and mineral fertilizer sources (Figure 2). The regression analyses reported in Figure 3A showed that the temperature dependency of soil CO_2 flux is well described through polynomial regression analysis. The range of values measured over the two years of experimentation, the polynomial regression curve shows the highest level of soil CO_2 emission at optimum soil temperature in the organic fertilizer source (0.80 g m^{-2} h^{-1}, $R^2 = 0.1926$, $p < 0.001$) compared with mineral fertilizer (0.68 g m^{-2} h^{-2}, $R^2 = 0.1416$, $p < 0.001$, Figure 3A). Similarly, the volumetric water content of the soil followed the climatic conditions, in particular the precipitation events. In fact, it was high after potato planting in 2015, while the volumetric water content of soil tended to be low at the beginning of potato cultivation and before potato harvesting, but there were peaks in the middle of potato growing seasons (Figure 2). The trend of the soil volumetric water content was similar between the organic and fertilizer sources. A polynomial regression analysis reported in Figure 3B showed the dependency of soil CO_2 flux on soil volumetric water content in all fertilizer treatments. The curve, obtained with the values measured over the two years of experiments, showed the highest level of soil CO_2 emissions at optimum soil volume content in the organic fertilizer source (0.82 g m^{-2} h^{-1}, $R^2 = 0.1462$, $p < 0.001$) with respect to mineral fertilizer source (0.76 g m^{-2} h^{-1}, $R^2 = 0.1468$, $p < 0.001$, Figure 3B).

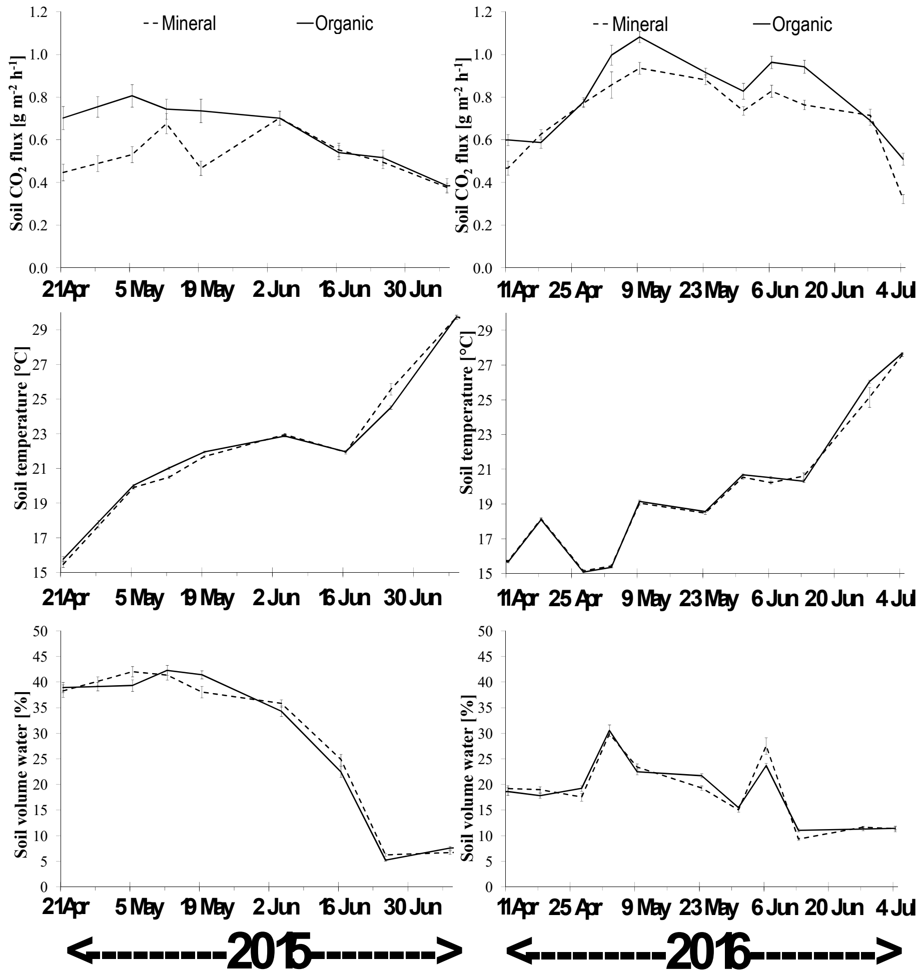

Figure 2. Soil CO_2 emission, soil temperature, and soil volume water content in the two soil fertilization treatments (Mineral and Organic), during the 2015 and 2016 potato cycles. Bars are standard errors ($n = 9$).

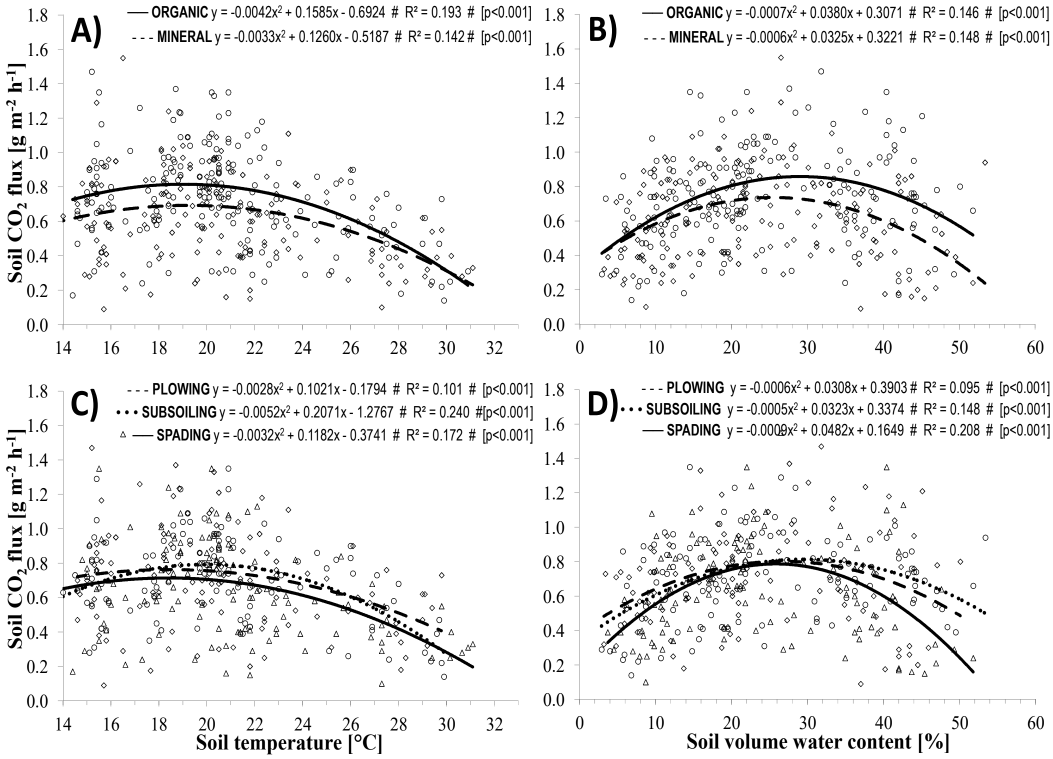

Figure 3. Soil CO_2 flux plotted in the two soil fertilization treatments (Organic (dotted line) and Mineral (solid line)) against soil temperature (**A**) and soil volume water content (**B**) and the soil CO_2 flux plotted in the three soil tillage treatments (Plowing (dotted line), Subsoiling (solid and dotted line) and Spading (solid line)) against soil temperature (**C**) and soil volume water content (**D**) during the two potato cycles. The data fit with second-order polynomial regression models.

3.2.2. Effect of Soil Tillage Management

In Figure 4, the flux of soil CO_2 emissions, temperature, and soil volume water content during the potato growing seasons under various treatments are reported. In both potato growing seasons, the soil CO_2 emissions were generally low in spading compared with other soil tillage (on average 0.64 vs. 0.72 g m^{-2} h^{-1}, respectively), even if the biggest differences were observed in 2015 (0.51 vs. 0.63 g m^{-2} h^{-1}, respectively, Figure 4). In both potato growing seasons, soil temperatures were similar in the tillage treatments, especially in the period from potato sowing to flowering, while few differences on soil temperature were observed before potato harvesting (Figure 4). The regression analyses reported in Figure 3C showed that the soil temperature dependency of soil CO_2 flux was well described through a polynomial regression analysis. The polynomial regression curve, obtained using the range of values measured over the two years of experimentation, showed the highest level of soil CO_2 emission at optimum soil temperature in the subsoiling tillage (0.79 g m^{-2} h^{-1}, R^2 = 0.2398, $p < 0.001$), intermediate in plowing (0.75 g m^{-2} h^{-1}, R^2 = 0.1011, $p < 0.001$) and the lowest in spading (0.0.72 g m^{-2} h^{-1}, R^2 = 0.1722, $p < 0.001$, Figure 3C).

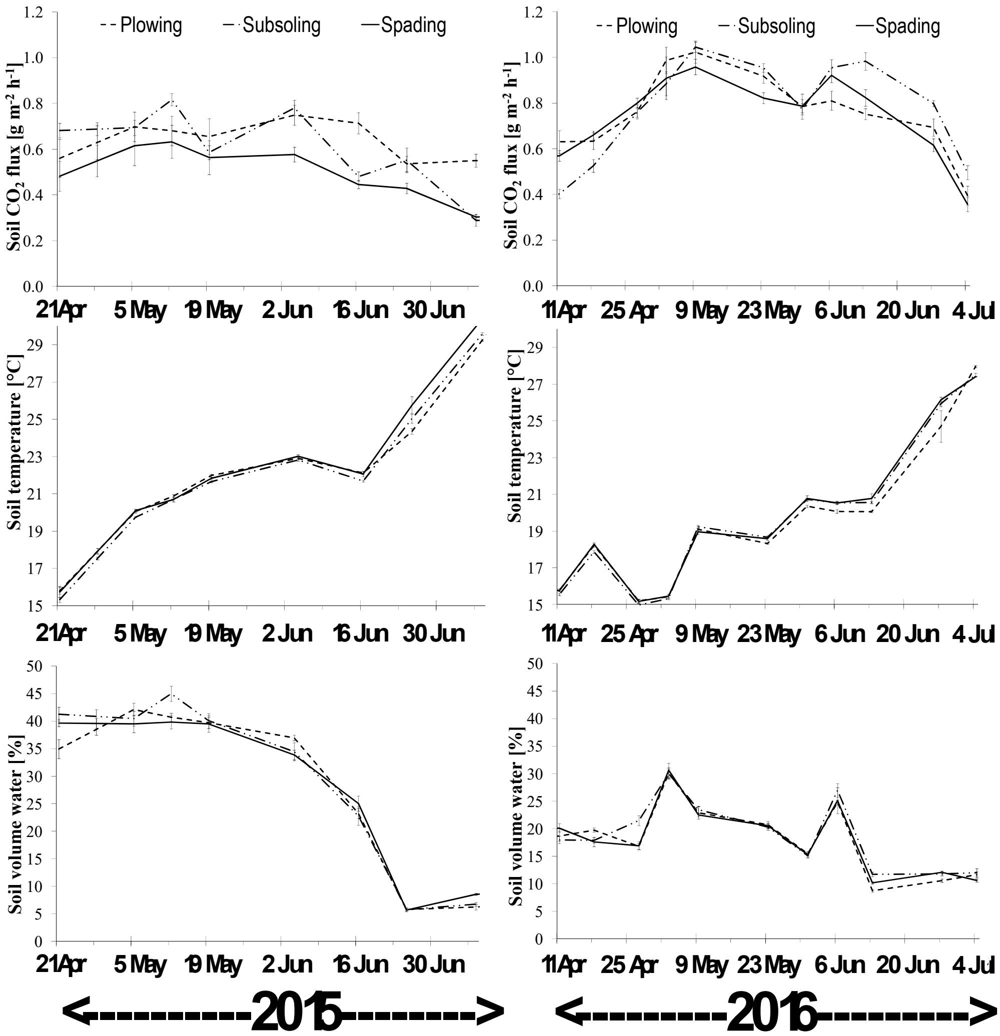

Figure 4. Soil CO_2 emission, soil temperature, and soil volume water content in the three soil tillage treatments (Plowing, Subsoiling and Spading), during the 2015 and 2016 potato cycles. Bars are standard errors ($n = 9$).

The volumetric water content of soil was similar among the soil tillage treatments (Figure 4). A polynomial regression analysis, reported in Figure 3D, showed the dependency of soil CO_2 flux on soil volumetric water content in all tillage treatments. The curve, obtained with the values measured over the two years of experimentation, showed the highest level of soil CO_2 emissions at optimum soil temperature in the subsoiling tillage (0.86 g m^{-2} h^{-1}, $R^2 = 0.1476$, $p < 0.001$), intermediate in plowing (0.81 g m^{-2} h^{-1}, $R^2 = 0.2084$, $p < 0.001$) and the lowest in spading (0.79 g m^{-2} h^{-1}, $R^2 = 0.0951$, $p < 0.001$, Figure 3D).

3.3. Potato Yield and Agro-Ecosystem Carbon Balance

Marketable potato tuber yield was affected by treatments and significant interactions were observed with years (year x soil tillage and year x fertilizer sources) (Figure 5). The potato yield was higher in 2016 than in 2015 (on average 3.49 vs. 1.78 kg m^{-2} of FW), but there was a different trend among the soil tillage and fertilizer source treatments within the year. In 2016, the marketable tuber yield of potato was higher in plowing and spading tillage compared with subsoiling [on average 2.88 vs. 2.15 kg m^{-2} of fresh weight (FW), respectively], while in 2015 it was the highest in plowing, intermediate in spading and low in subsoiling (2.20, 1.70 and 1.34 kg m^{-2} of FW, respectively). In the fertilizer source x year interaction, the highest value of potato yield was observed in 2016 under mineral fertilizer followed by organic fertilizer (on average 3.63 vs. 3.35 kg m^{-2} of FW, respectively), while no differences were detected in 2015 between the fertilizer treatments.

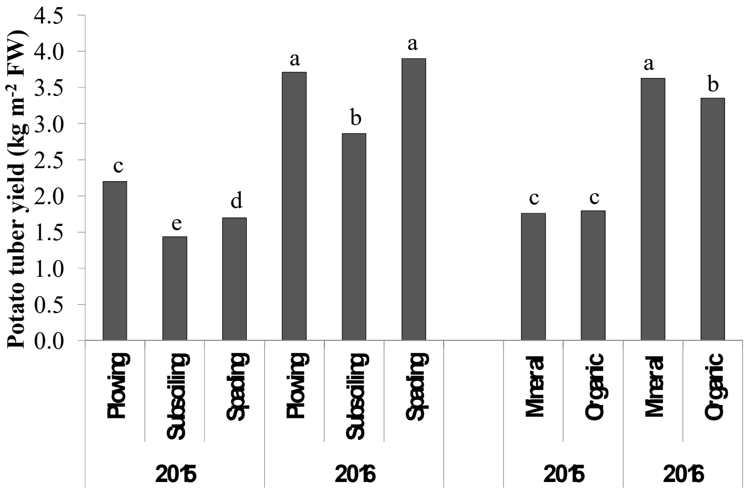

Figure 5. Potato tubers yield in the interactions tillage X years and Fertilization X year. In the same interaction, values with different letters are statistically different according to LSD (0.05).

The total biomass produced by potato crop at harvesting (straw + tubers), determined as the C input obtained by the system, was affected by year, soil tillage, and fertilizer source as main treatments adopted in this study (Table 1). It was higher in 2016 than in 2015 (4.63 vs. 4.35 Mg C ha^{-1}, respectively). Among the soil tillage treatments, the C input produced by biomasses was higher in plowing compared to subsoiling and spading (on average 4.76 vs. 4.36 Mg C ha^{-1}, respectively), while considering the fertilizer source, it was greater in organic than in mineral fertilizer source (5.59 vs. 3.40 Mg C ha^{-1}, respectively).

Table 1. The effect of the soil tillage method, soil fertilization and year on the C balance in the two experimental years. Values belonging to the same parameter and treatment with different letters (a,b) in columns are statistically different according to LSD (0.05).

	C-Input by Biomasses (Mg C ha^{-1})	C Output by CO_2 Emission (Mg C ha^{-1})	C Input/C Output	CO_2 Emission/Yield
Soil tillage				
Plowing	4.76 a	3.85 a	1.24 ab	0.59 b
Subsoiling	4.40 b	3.91 a	1.12 b	0.89 a
Spading	4.32 b	3.45 b	1.25 a	0.57 b
Fertilizer source				
Mineral	3.40 b	3.51 b	0.97 b	0.75 a
Organic	5.59 a	3.97 a	1.41 a	0.62 b
Year				
2015	4.35 b	3.08 b	1.41 a	0.57 b
2016	4.63 a	4.39 a	1.05 b	0.80 a

The C output in the experiment was represented by the carbon loss with the CO_2 emissions during the potato cultivation. Generally, the total C from CO_2 was greater in 2016 than in 2015 growing seasons (4.39 vs. 3.08 Mg C ha^{-1}, respectively). However, the plowing and subsoiling tillage showed similar C output by CO_2 emissions (on average 3.88 Mg C ha^{-1}), which was greater compared to the C output by CO_2 emissions measured under spading treatments (3.45 Mg C ha^{-1}, Table 1). Moreover, the organic fertilizer source determined higher C output by CO_2 than mineral fertilizer source (3.97 vs. 3.51 Mg C ha^{-1}, respectively).

The C input/C output ratio of potato crop varied according to the main treatments. It was the highest in spading (1.25), intermediate in plowing (1.24), and low in subsoiling (1.12), while between the fertilizer source it was greater under organic compared with mineral fertilizer source (1.41 vs. 0.97, respectively, Table 1). In 2016, the C input/C output ratio was higher than in 2015 potato growing season (1.41 vs. 1.05, respectively).

The cumulative CO_2/tuber yield ratio was greater in 2015 than in 2016 (on average 0.80 vs. 0.57, respectively). However, it was larger in subsoiling compared to plowing and spading soil tillage (on average 0.89 vs. 0.58, respectively), while organic fertilizer source showed a greater CO_2 emission/yield ratio compared with mineral fertilizer source (0.75 vs. 0.62, respectively, Table 1).

4. Discussion

Management practices adopted for agricultural production have a direct implication on soil functions, by modifying the diversity and abundance of soil microorganisms with consequences on the ecosystem services and, therefore, on the sustainability of agro-ecosystems [27]. As any management practice shows effects on crop production, it can also influence agro-ecosystems environmental aspects; for this reason, the intensification of agricultural practices as required in the modern agriculture, especially related to soil tillage and fertilization practices, represent a serious issue that should be adequately approached to avoid losses of soil fertility and quality associated with elevated greenhouse gas emissions, mainly carbon dioxide [28]. According to this perspective, recently, Radicetti et al. [21] underlined the importance of some agronomical techniques based on ecological approaches, such as cover cropping and conservation tillage, to enhance the soil C sequestration and to reduce soil CO_2 emissions. Although it is well known that the benefit of reduced tillage practices and fertilization source is their being environmentally friendly practices [21,27–29], this is one of the few studies that focused on the effect of the soil tillage and fertilization source on soil CO_2 emissions and C balance during potato cultivation in the Mediterranean environment of central Italy. In fact, on one hand, the adoption of reduced tillage systems are strongly encouraged because they save money and labor, improve soil biological properties, and prevent soil compaction [30] on the other hand, their effect on crop yield should be adequately evaluated to avoid severe yield losses.

The data showed that the marketable potato yield was significantly affected by soil tillage in both growing seasons, with the greater values observed in plowing and spading soil tillage compared to subsoiling. According to Mundy et al. [31] subsoiling tends to increase soil bulk densities compared to conventional tillage, and it can decrease potato yield due to reduced potato root growth to mechanical resistance of the soil, as well as the reduced resistance to periods of water stress. Although subsoiling is encouraged under sustainable management of agro-ecosystems for improving soil biological and physical conditions that could potentially benefit soil quality, this practice seems not recommended for potato cultivation under soil conditions similar to the experimental site. The lowest marketable potato yield observed under subsoiling tillage associated with the highest cumulated CO_2 emissions, and C output determined also low C input/C output ratio and high CO_2 emission/yield ratio, making it doubtful as an environmental-friendly strategy for potato cultivation. However, Carter et al. [30] reported similar potato yield among different soil tillage; probably the soil conditions of the experimental area do not allow the adoption of subsoiling for potato cultivation, even if further research should be carried out to evaluate the effect in other kinds of soil in the same environmental conditions. In any case, the C input/C output ratio (>1) among all tillage treatments indicates that plowing, subsoiling, and spading could serve as a temporary sink of C, in according with the findings of Mancinelli et al. [24]. On the contrary, plowing and spading tillage showed high and similar potato yield in both growing seasons, even if under spading tillage conditions the C output resulted the lowest compared with the other tillage treatments. According to Giordano et al. [32] in Mediterranean areas, the spading machine has a discrete success due to the absence of a compact layer at the bottom of the tilled soil and the reduced drawbar pull required. The results are in agreement with the findings reported by Laudicina et al. [33], where the spading machine is effective in preserving soil organic matter pool and in improving soil quality; indeed spading treatment showed the highest C input/C output ratio and the lowest cumulated CO_2 emission/potato yield ratio. Furthermore, in suitable soil conditions, a single passage of spading machine could be enough for seed bed preparation reducing the fuel requirements and energy consumption as normally required with plowing. According to Usaborisut and Prasertkan [34], field operations represent the main expensive operation in crop production and the adoption of inadequate soil tillage operations may result in an excess of fuel consumption and inefficient use of energy. Recently, Fox et al. [35] showed that 7.5 cm of deeper tillage increased the fuel consumption of 50% without any increase in the crop yield.

The biggest yield of marketable potato tubers observed in 2016 could be due to well distributed precipitation throughout potato growing season and reduced temperature compared with 2015. In fact, potato is a shallow rooted crop extremely sensitive to water stress and high temperature, especially in late season when the potato canopy is dry and the soil is highly exposed to solar radiation [36]. Increased emissions of CO_2 in the potato growing season were observed regardless to the applied experimental treatments; the increase could be related to the higher soil temperature and moisture during the potato cultivation, especially in 2016. In fact, the results showed that soil CO_2 emission rates were significantly correlated with volumetric soil water content and soil temperature and varied according to soil tillage and fertilizer source treatments.

The obtained results suggest that the incorporation of organic fertilizer increases soil CO_2 emissions compared with mineral fertilizers throughout the potato growing seasons. In agreement with Mancinelli et al. [29] the difference on soil CO_2 emission among the fertilizer sources could be due to the organic materials that affect biological properties and organic mineralization of the soil. Despite the high soil CO_2 emission rate measured under organic fertilizers, the high C input by biomasses ensure a high C input/C output ratio (>1). These results prove that by applying organic fertilizer, the soil could become a carbon sink, and this therefore represents a possible solution for reducing the soil CO_2 emissions in sustainable agro-ecosystems. Moreover, the use of organic urban waste as source of organic fertilizer is strongly encouraged because it increases the economic value of a waste material, and it is seen as a way of food production by adopting the principles of circular economy [13]. In addition, the low cumulated CO_2 emission/yield ratio indicates that the same amount of potato tubers is produced with low soil CO_2 emissions in the mineral fertilization treatment. The tuber yield differences observed in 2016 could be due to the nutrient availability, mainly nitrogen, between the fertilization sources (data not shown). These results are in line with the findings of Campiglia et al. [9], which observed similar yield between organic and mineral fertilization during the shortage period of rainfall and soil water content and higher yield in mineral than organic fertilization under high level of precipitation and soil water content. In fact, the nutrient availability under organic fertilization has high sensitivity on the mineralization process, driven also by weather conditions. On the contrary, mineral fertilizer was applied when the weather conditions were suitable for potato crop in order to supply nutrients at the right moment for the crops need [37].

5. Conclusions

This study provides useful information on the behavior of soil tillage and fertilizer source on soil CO_2 emissions and C balance in potato cultivation agro-ecosystem under the Mediterranean environment in central Italy. In particular, this study highlights how it is possible to reduce soil CO_2 emissions in the agro-ecosystems and improve the sustainability of intensive systems. The findings showed that all soil tillage evaluated are environmentally friendly (input/output ratio >1), even if the potato yield results suggest to prefer spading tillage for seed bed preparation of potato crop. Indeed, through soil spading for potato seed bed preparation, it is possible to obtain adequate tuber yield and reduced carbon losses by carbon dioxide. Moreover, the results suggest that spading tillage and organic fertilization could achieve environmental benefits, in terms of reduced soil CO_2 emissions, and enhance agronomical benefits, in terms of marketable tuber yield of potato. Moreover, the findings are of practical application for the farmers because of reduced costs due to tillage by saving energy and fuel and valorizing organic waste in agricultural application. Further studies should be performed to evaluate also the effect on microbial biomass and soil carbon sink, with the aim to choose the most suitable agronomical practice for potato cultivation that could maintain crop yield and shift the carbon balance in favor of soil C accumulation over a long period. Moreover, these findings may also be extended to other environments and crops which have similar requirements to potato in terms of the crop's nutritional and environmental conditions.

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