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How Does Sustainable Management Practices Affect Weed Flora and Tuber Yield of Potato Crop in Mediterranean Environment?

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Abstract

Intensive potato cultivation affects weed species composition by selecting dominant and competitive weeds that represent a constraint of potato productivity. Field experiments were conducted during 2015 and 2016 growing seasons to examine the effects of soil tillage (plowing (PL), spading (SM), sub soiling (SS)) and fertilizer source (mineral (Min) and organic (Org)) on potato yield and weed community under Mediterranean environment. A randomized complete block design with three replications was adopted. Weed density and biomass were measured at the potato harvesting time. Weed density was highest in SS, intermediate in SM, and lowest in PL (43.8, 40.3, and 28.8 plants m^{-2}). Similar trend was observed in weed biomass. Weed density and biomass were higher in Org than Min (42.1 *vs*. 36.4 plants m^{-2} and 129.6 *vs*. 117.9 g m^{-2}, respectively). Perennial, monocot, and dicot weed species were the most abundant in subsoiling (13.1, 9.3 and 34.5 plants m^{-2}). Density of perennial and dicot species were higher in Org than Min. Monocots were mostly linked with Min, while dicots were mainly associated with Org. Although tuber yield was higher in PL and Min (481.9 and 627.5 g m^{-2} of DM), it was affected by growing season and might be associated to SM and Org. Although the study shows that increased weed biodiversity in the system, achieved with more sustainable practices, proves to be an obstacle to potato production, the adoption of spading machine applied in combination with mineral and organic fertilizers could be a valid alternative to plowing. Further studies are required to develop sustainable agricultural techniques able to improve the competitive capacity of crops and reduce the selection of dominant weed species.

Keywords Potato · Soil cultivation · Weed management · Crop yield · Sustainable agriculture · Fertilization

Introduction

The basis of the modern sustainable vision is the assumption that resources are limited and that the focus should be on maintaining the dynamic balance of human and natural systems (Thomsen 2013). Environmental sustainability can thus be defined as a condition of balance and resilience (Hobbs et al. 2008). Sustainable agricultural management aims to produce adequate quantities of high-quality food, conserve resources and the environment, and achieve system-appropriate profitability. To accomplish these objectives, scientists are working to maintain the land healthy by applying sustainable practices that minimize dependency on non-renewable energy, reduce chemical usage, and save scarce resources (Tuğrul 2019).

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Currently, the excessive use of agronomic inputs leads to a significant increase in productivity, but at the same time to increased environmental pressure (Donati and Tukker 2022). Sustainable practices try to overcome this obstacle by aiming for minimal disturbance of the natural balance of agroecosystems by limiting the use of external inputs agrochemicals for plant protection, and intensive soil tillage (Mondelaers et al. 2009). Agricultural soils managed under sustainable practices, such as reduced soil tillage and organic fertilization, show higher numbers of microbial populations than soils under conventional management (Mäder et al. 2002; Liu et al. 2007).

Weeds have an important ecological role to play in sustainability as a component of biodiversity in the agroecosystems (Fawad et al. 2022; Pollnac et al. 2009) and weed diversity is indicative of the sustainability of the cropping system (Storkey and Neve 2018). Indeed, weeds can contribute to more efficient utilization of nutrients, regulate the microclimate, soil quality, and local hydrological processes, and provide ecological niches for the development of microfauna (Petroselli et al. 2021). It can therefore be argued that increasing weed diversity can be beneficial from an agronomic and environmental point of view (Ofosu et al. 2023). However, it is critical to keep weed infestation below the harmfulness threshold to prevent severe economic losses through soil tillage, fertilizer supply, and herbicide use as part of an integrated weed management approach.

Potato (*Solanum tuberosum* L.) is the fourth-largest crop produced worldwide after rice, wheat, and maize (FAOSTAT 2021). Tillage is required at various planting and growth stages of potatoes for seedbed preparation and weed control (Petroselli et al. 2021). Under conventional management practices, commercial potato production involves heavy machinery and equipment during the whole growing season for various operations such as cultivation, agro-chemical application, and harvest, exposing the soil to compaction. Soil compaction, delayed emergence, reduced rooting density, slowed the rate of leaf appearance and ground cover expansion, shortened canopy cover duration, and limited light interception, all of which leads to lower tuber yield, mainly where compaction was shallow (Djaman et al. 2021). Huntenburg et al. (2021) discovered that adverse compacted soil conditions hampered potato shoot development. The findings of Carter et al. (2009) showed the influence of various tillage strategies on potato growth, weed management, yield, and the tendency to reduce tillage up to no-till in potatoes for system sustainability.

Potato farming is a very intensive crop and needs a much higher rate of nutrients due to higher dry matter yield, and sufficient fertilization is critical for increasing yield and achieving higher tubers (Hussain et al. 2022). As a result, the nutritional requirements of the potato crop are high and the use of mineral or organic fertilizers is regarded as critical for obtaining economic and better yields (Petropoulos et al. 2020). Potato growers have recently shown an increasing interest in determining the appropriate fertilization regimes to optimize total yield while reducing production costs and maintaining high quality (Fontes et al. 2016). A sufficient supply of nutrients (1) can boost the potato plant against unfavorable growth conditions, (2) is critical for obtaining high yield, and (3) is required for producing potatoes that satisfy the specified quality standards (Koch et al. 2020).

Farming systems used for potato crop cultivation are often based on excessive tillage operations that lead to low levels of weeds biodiversity that harm soil quality and fertility (Petroselli et al. 2021). All these problems have required evaluating alternative tillage systems, such as conservation tillage practices, even if they must be designed for potato production systems (Djaman et al. 2021). Although it is commonly accepted that tillage and fertilization impact soil quality and crop production, research on the effects of specific tillage requirements and fertilizer type combinations on potato performance in the Mediterranean environment is lacking. Recently, Petroselli et al. (2021) observed that soil tillage and fertilization sources represent two agronomical factors that significantly affect grain yield and weed spectrum in durum wheat crop in Mediterranean environment. Similarly, this study hypothesizes that under the same experimental design combining sustainable practices (soil tillage and fertilizer source) could contribute to more effective use of agronomic practices to manage weeds and to support sustainable management practices of potato crop for replacing conventional practices with a viable alternative to enhance resource use efficiency while maintaining and improving crop yield. The main objective of the current study is to evaluate the impact of soil tillage regime and fertilization practices on weed species composition and their relationship with tuber yield of potato crop.

Materials and Methods

Site Description and Experimental Design

Field trials were carried out on potato (*Solanum tuberosum* L.) crop in the 2015 and 2016 growing seasons at the research farm of the University of Tuscia located in Viterbo (lat. 42°42', long. 12°07' and alt. 310 m a.s.l.), Italy. In both growing seasons, field experiments were carried out in an Entisol soil with a sandy-loamy texture (USDA) classified as a *typical Xerofluent* of volcanic origin with the following particle size distribution in the 0–30 cm of the soil layer: 760 g kg^{-1}of dry sand, 130 g kg^{-1}of dry silt, 110 g kg^{-1}of dry clay. The soil was characterized by 0.97% organic matter content, 0.15% total nitrogen and 6.9 pH (H_2O). The experimental area is typical of potato cultivation in Mediterranean environment of central Italy with an average temperature of 14 °C and an annual rainfall of 780 mm (average of the last 30 years).

The study was carried out in a 2-year crop rotation based on durum wheat (*Triticum durum* Desf.)—Potato (*Solanum tuberosum* L.) as commonly adopted by the farmers of the area. The following treatments were applied: (a) three soil tillage (plowing (PL), spading (SM) and subsoiling (SS)); and (b) two fertilization sources (mineral (Min) and organic (Org)). The experimental treatments were applied following a randomized complete block design with a factorial arrangement of treatments. Each treatment was replicated three times for a total of 18 plots (3 soil tillage × 2 fertilization management × 3 blocks). The plot size was 60 m^2 (10 × 6 m) and alleys of 5-m-wide was included in the field trials to perform all required farming operations. A field experimental plan of 2015 and 2016 potato growing seasons have been reported in Fig. 1.

Experimental Field Management

In both growing seasons, the potato seedbed was prepared about two weeks before the potato sowing according with the main soil tillage treatments. All main soil tillage operations (PL, SS, SM) were carried out at a depth of 20 cm by means of APS M35 (Angeloni, Italy), 005 series 100 (Tortella, Italy) and RHP-5 M (Dondi, Italy) for plowing

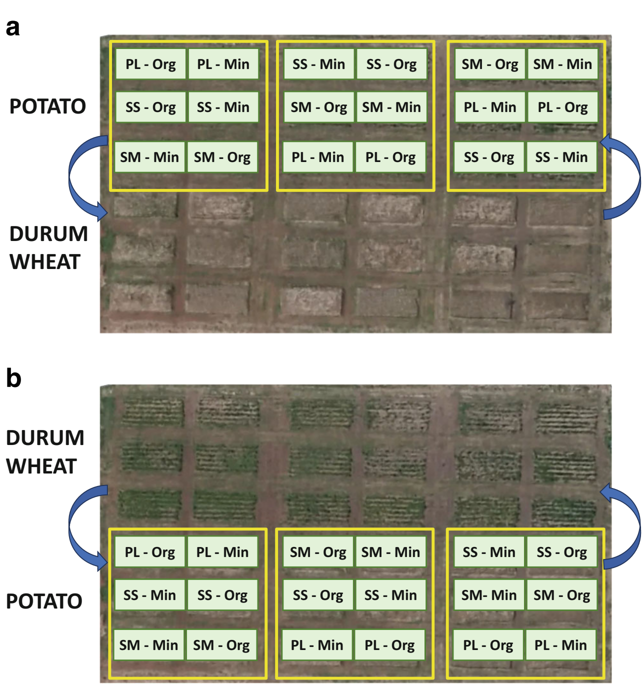

Fig. 1 Experimental field plan Adopted in 2015 (**a**) and 2016 (**b**) potato growing seasons. *Min* mineral fertilization, *Org* Organic fertilization, *PL* plowing, *SS* subsoiling, *SM* spading machine

(PL), spading (SM) and subsoiling (SS), respectively. Then, all plots were subjected to harrowing operations by means of a disk harrow at a depth of 10 cm applied twice, to break the soil clods and leave a uniform seedbed for potato sowing. Potato tuber seeds of Monalisa cultivar were used in the field trials. Tuber seeds were manually planted in furrows opened the day before on 13 April 2015 and 31 March 2016, respectively. In all plots, potato tuber seeds were planted in rows at 0.70 m of distance from each other and 0.20 m between two consecutive potato tubers within the rows and at the 10 cm of soil depth. Under mineral fertilization, triple superphosphate (46% of P_2O_5), potassium sulfate (50% of K_2O) and urea (46% of N) were applied at the time of tuber sowing at the rate of 100 kg P_2O_5 ha^{-1}, 50 kg K_2O ha^{-1} and 100 kg N ha^{-1}, respectively. In addition, six weeks after plants emergence corresponding to hilling stage, 70 kg ha^{-1} of N as ammonium nitrate (33% of N) was applied. Organic fertilization was applied in the form of mature organic waste obtained from municipal waste at the rate of 18 Mg ha^{-1}applied at seedbed preparation. The same amount of nitrogen (170 kg ha^{-1}) was applied for both the fertilizers, according to the common practice adopted by local farmers. In all plots, weeds were left grown and subjected to agricultural practices adopted in potato crop. Irrigation was performed by means of sprinkler irrigation to reintegrate the 70% of maximum evapotranspiration, estimated by a class A pan and adjusted by crop coefficients during the potato growth cycle (Allen et al. 1998). In both experimental years, the amount of water supplied by irrigation was the same in all plots regardless the experimental treatments. The irrigation was stopped in all plots 2 weeks before harvest, at physiological maturity of potato. The same amount of water was applied in all experimental treatments. Potato crop was harvested on 17 August 2015 and 21 August 2016, respectively.

Measurements

Weather data were collected by a station 500 meter far from the experimental trials. At potato harvesting, in each plot a two 1-meter-long adjacent potato rows corresponding to 3.4 m^2 placed in the central and representative part of each plot were used to collect the following measures: number of weed species, weed density total and per species, weed aboveground biomass, potato tuber yield and straw (Mancinelli et al. 2020). All weeds within the sampled area were collected manually and then divided by species to determine the species composition and the specific density of each species. Total weed density has been determined as the sum of the density of each weed species detected. After the analysis of weed species composition all weeds were collected and oven-dried at 80 °C for 72 h to assess the weed biomass. After weed assessment, potato plants placed in the same sampling area were manually harvested. Dry matter of potato tuber and straw were determined by means of the oven-dry method (80 °C). The tuber yield and straw were calculated as a product of total yield and the content of individual elements.

Data Handling and Analysis

All data collected were analyzed by performing the analysis of variance (ANOVA) using JMP v. 4.0 software (SAS 1996). A randomized complete block design with three replications was used for the analysis. Bartlett's test was carried out to check for equality of variance between the data. The data of weed density were square-root transformed ($\sqrt{x}+0.5$) prior to analysis to homogenize the variance and then back transformed for interpretation of the results (Gomez and Gomez 1984). All data were subjected to analysis by adopting a factorial experimental design, where soil tillage, fertilization source and growing season represented the three factors subjected to the analysis. Fisher's least significant difference (LSD) test with a probability of 0.05 was adopted to compare interaction effects.

Weed species composition was tested by means of Multi-Response Permutation Procedure (MRPP) to evaluate difference within soil tillage and fertilizer source treatments (Cade and Richards 2001). The MRPP analysis was performed using BLOSSOM software, which provides a T-statistic values aimed to show the separation among tested groups (the more negative T is, the stronger the separation is) and its associated significance (McCune and Grace 2002). The association between each weed species and experimental treatments were studied by means of canonical discriminant analysis (CDA). The results of CDA analysis are reported in the canonical diagram where the appearance of weed species and treatments in the same ordination space indicates the association between them (Kenkel et al. 2002).

Results

Weather Conditions During the Potato Cultivation

The potato growing season lasted for 126 and 143 days in 2015 and 2016 potato growing seasons, respectively. Mean air temperatures tended to increase from tuber sowing to potato tuber harvesting reaching the highest values in August 2015 and July 2016 (22.5 and 24.4 °C, respectively, Fig. 2). Although mean air temperature follows the long-term trend, the 2016 growing season was hotter compared with the long-term values (20.2 vs. 19.0 °C, respectively). Total rainfall was 426 mm in 2015 and 186 mm in 2016 showing in both growing seasons considerable variation

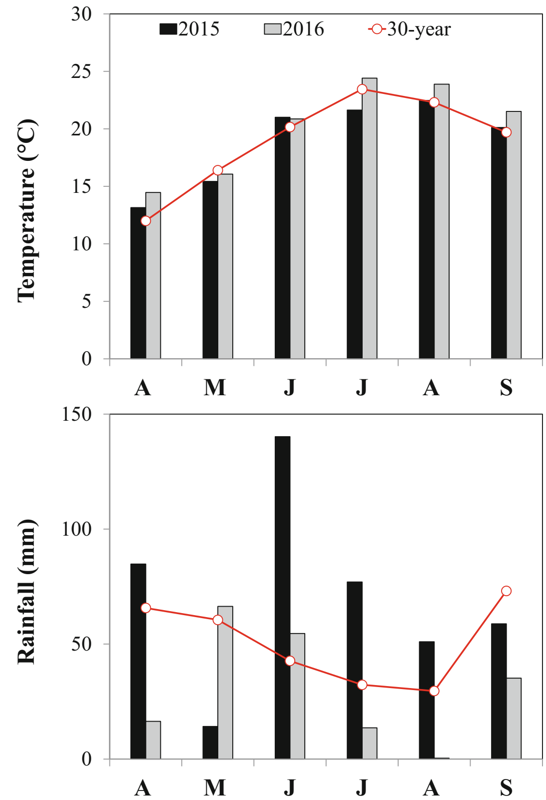

Fig. 2 Monthly average values of rainfall and mean air temperature during potato growing seasons in 2015 and 2016, respectively, in comparison with the average values over the last 30-year period

compared the long-term data (303 mm). In 2015, rainfall was high during the whole potato growing seasons, especially in June and July where has been observed two peaks of precipitations (140 and 77 mm, respectively, Fig. 2). Conversely, in 2016 the dried months were April, July, and August (16, 14 and 0 mm, respectively).

Weed Characteristics in Potato Crop

Weed Density and Biomass

The result of the analysis of variance showed that weed density and weed biomass were significantly affected by all the main treatments. However, there was a significant interaction between soil tillage × fertilizer sources. In addition, weed biomass was affected by the growing season × soil tillage and growing season × fertilization source (Table 1).

At potato harvesting, weed density tended to be higher in Org compared with Min fertilizer source (on average 42.1 *vs*. 36.4 plants m^{-2}, respectively), however under SM soil tillage no differences were detected on weed density (on average 40.3 plants m^{-2}). Among the soil tillage treatments, weed density was higher in SS and SM than in PL (on average 42.1 vs. 28.8 plants m^{-2}, respectively, Table 1).

Table 1 The interaction effects of soil tillage × fertilizer source on weed density and weed aboveground biomass in potato

	Weed density			Weed biomass		
	Min	Org	Means	Min	Org	Means
	Plants m^{-2}			$g\,m^{-2}$ of DM		
PL	29.0$^{(\pm 1.5)}$ bB	38.5$^{(\pm 1.8)}$ bA	33.8$^{(\pm 1.8)}$ b	104.6$^{(\pm 5.7)}$ bA	103.2$^{(\pm 7.4)}$ cA	103.9$^{(\pm 4.6)}$ c
SM	39.3$^{(\pm 1.4)}$ aA	41.2$^{(\pm 1.7)}$ bA	40.3$^{(\pm 1.1)}$ a	113.4$^{(\pm 7.6)}$ bA	129.2$^{(\pm 11.4)}$ bA	121.3$^{(\pm 6.9)}$ b
SS	41.0$^{(\pm 2.0)}$ aB	46.5$^{(\pm 1.6)}$ aA	43.8$^{(\pm 1.5)}$ a	135.7$^{(\pm 3.0)}$ aB	156.3$^{(\pm 6.1)}$ aA	146.0$^{(\pm 4.5)}$ a
Means	36.4$^{(\pm 1.2)}$ b	42.1$^{(\pm 1.6)}$ a	–	117.9$^{(\pm 4.5)}$ b	129.6$^{(\pm 7.0)}$ a	–

Values belonging to the same characteristics without common letters in row for fertilizer source (upper case letter) and in column for soil tillage regime (lower case letter) are statistically different according to LSD ($p \leq 0.05$)
Min Mineral fertilizer, *ORG* Organic fertilizer, *PL* Plowing, *SM* = Spading machine, *SS* Subsoiler. In brackets ± standard error

Weed density under Min fertilizer source, weed density in SS and SM soil tillage treatments tended to be similar and higher the PL (Table 1), conversely under Org fertilizer source SS showed the higher weed density than SM and PL (on average 46.5 vs. 39.9 plants m^{-2}, respectively).

Weed biomass measured at potato harvesting was higher in Org compared with Min fertilizer source (on average 129.6 *vs*. 117.9 g m^{-2}, respectively), even if the significant differences were observed only in SS treatment (Table 1). Under mineral fertilization, weed biomass was higher in SS than SM and PL (146.0, 121.3, and 103.9 g m^{-2}, respectively, Table 1). Weed biomass in Organic treatments was significantly different among the soil tillage treatments based on the following order PL < SM < SS (103.2 g m^{-2}, 129.2 g m^{-2}, and 156.3 g m^{-2} respectively).

Weed Flora Composition

The analysis of variance in weed community composition data showed a significant effect of soil tillage and fertilizer source treatments on species richness, annual weeds, perennial weeds, monocots weeds and dicots weeds (Table 2). In addition, annual weeds, monocots weeds and dicots weeds were affected by growing seasons (Table 2).

Species richness observed at potato harvesting was similar between the 2015 and 2016 growing seasons (on average 11.5), while it was the highest in SS (13.3 n. m^{-2}) and Org (12.1 n. m^{-2}) treatments. The annual weeds were higher in 2016 than 2015 growing season (33.1 *vs*. 29.1 plants m^{-2}, respectively) and they were greater in PL compared with SM and SS (on average 32.5 *vs*. 30.4 plants m^{-2}, respectively). The densities of annual weeds were higher in Org than Min fertilizer source (31.7 *vs*. 30.4 plants m^{-2}, respectively). Perennial weeds were similar between the growing seasons, while, among the soil tillage, they were high in SS, intermediate in SM and low in PL (13.1, 10.3 and 1.3 plants m^{-2}, respectively). Organic treatments showed a greater number of perennial weeds compared with mineral fertilization (10.4 *vs*. 6.0 plants m^{-2}, respectively, Table 3). Similarly, the analysis of variance shows significant differences between the monocotyledonous and dicotyledonous weeds, with higher values observed in the 2016 growing season (8.7 and 33.1 plants m^{-2}, respectively). Among soil tillage treatments, SS showed the highest values of monocots and dicots weed species (9.3 and 34.5 plants m^{-2}, respectively) followed by SM (31.8 and 8.5 plants m^{-2}, respectively) and low in PL tillage (28.9 and 5.0 plants m^{-2}, respectively), even if no differences were detected between SS and SM

Table 2 The main effect of growing season, soil tillage, and fertilizer source on weed characteristics in terms of annual weeds, perennial weeds, monocot weed species, dicot weed species, specie richness and Brillouin index

	Species richness	Weed characteristics			
	Species m^{-2}	Annual (Plants m^{-2})	Perennial	Monocots	Dicots
Growing season					
2015	11.3$^{(\pm 0.6)}$ a	29.1$^{(\pm 0.9)}$ b	7.7$^{(\pm 1.4)}$ a	6.4$^{(\pm 0.8)}$ b	30.3$^{(\pm 1.6)}$ b
2016	11.6$^{(\pm 0.4)}$ a	33.1$^{(\pm 1.2)}$ a	8.7$^{(\pm 1.6)}$ a	8.7$^{(\pm 1.2)}$ a	33.1$^{(\pm 1.6)}$ a
Soil tillage					
PL	9.8$^{(\pm 0.5)}$ b	32.5$^{(\pm 1.7)}$ a	1.3$^{(\pm 0.4)}$ c	5.0$^{(\pm 0.7)}$ b	28.9$^{(\pm 2.2)}$ c
SM	11.4$^{(\pm 0.4)}$ a	30.1$^{(\pm 1.1)}$ b	10.3$^{(\pm 1.2)}$ b	8.5$^{(\pm 1.4)}$ a	31.8$^{(\pm 1.4)}$ b
SS	13.3$^{(\pm 0.6)}$ a	30.7$^{(\pm 1.3)}$ b	13.1$^{(\pm 1.5)}$ a	9.3$^{(\pm 1.3)}$ a	34.5$^{(\pm 1.3)}$ a
Fertilizer source					
Min	10.8$^{(\pm 0.4)}$ b	30.4$^{(\pm 1.2)}$ b	6.0$^{(\pm 1.7)}$ b	10.2$^{(\pm 0.7)}$ a	26.2$^{(\pm 0.9)}$ b
Org	12.1$^{(\pm 0.6)}$ a	31.7$^{(\pm 1.1)}$ a	10.4$^{(\pm 1.0)}$ a	4.9$^{(\pm 0.9)}$ b	37.2$^{(\pm 0.9)}$ a

Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$)
MIN Mineral fertilizer, *ORG* Organic fertilizer, *PL* Plowing, *SM* Spading machine, *SS* Subsoiler. In brackets ± standard error

Table 3 Test statistics from multi-response permutation procedures (MRPP) for multiple paired comparisons to evaluate the main effects of fertilization source and soil tillage on weed community composition in 2015 and 2016 growing seasons of potato crop

	2015		2016	
	T	P	T	P
Fertilization source				
Mineral (Min)*vs*. Organic (Org)	–2.586	0.023	–6.356	< 0.001
Soil tillage				
Plowing (PL) *vs*. Spading (SM)	–4.293	0.001	–3.850	0.003
Plowing (PL) *vs*. Subsoiling (SS)	–6.290	< 0.001	–3.950	0.003
Spading (SM) *vs*. Subsoiling (SS)	–0.918	0.169	0.113	0.429

T is the T-statistic and describes the separation among groups. *P* is the probability of significant differences among groups. *MIN* Mineral fertilizer, *ORG* Organic fertilizer, *PL* Plowing, *SM* Spading machine, *SS* Subsoiler

on monocot weeds (Table 2). Regarding the fertilization source, the monocots were great under mineral fertilization (10.2 plants m^{-2}) and the dicots were higher under organic fertilization source (37.2 plants m^{-2}, Table 2).

The MRPP analysis performed on weed community observed at potato harvesting showed that based on the fertilization source Mineral and Organic groups were composed of a different weed assemblage, even if the magnitude of the differences tended to be greater in 2016 than 2015 growing season (–6.356 *vs*. –2.586, Respectively, Table 3). In addition, the T-statistic of soil tillage groups indicated differences between PL *vs*. SM and PL *vs*. SS comparisons in both potato growing seasons (Table 3). No differences were observed between SM *vs*. SS paired comparisons (Table 3).

The study showed a total number of 20 different weed species, of which the majority (70%) were annuals and dicotyledons (85%). The CDA analysis performed on weed species observed at potato harvesting explained 53% of the total variance for soil tillage and 61% for the fertilizer sources (Fig. 3a, b). Data regarding the soil tillage, the CDA analysis showed that several weed species such as *Amaranthus retroflexus* L. (AMARE), *Portulaca oleracea* L. (POROL), *Datura stramonium* L. (DATST), *Setaria viridis* (L.) P. Beauv. (SETVI), *Chenopodium album* L. (CHEAL), *Sinapis alba* L. (SINAL) were mainly associated with PL tillage, while the other weed species seems to be associated to SM and SS tillage as they are in the same ordination space, especially some perennial weeds such as *Malva sylvestris* L. (MALSI), *Cirsium arvense* L. (CIRAR) and *Convolvolus arvensis* L. (CONAR) are associated to SS tillage (Fig. 3a). Based on the fertilizer source, SETVI, CHEAL, *Echinocloa crus-galli* (L.) P. Beauv. (ECHCG), *Poligonum aviculare* L. (POLAV), *Solanum nigrum* L. (SOLNI), *Sonchus arvensis* L. (SONAR) and *Digitaria sanguinalis* (L.) Scop. (DIGSA) are associated to Min fertilization regardless of the growing season, while the other weed species, mainly *Lamium amplexicaule* L. (LAMAM), POROL, *Xanthium spinosum* L. (XANSP), *Convolvolus arvensis* L. (CONAR), MALSI, CIRAR are placed in the same orientation space of Org fertilizer source (Fig. 3b).

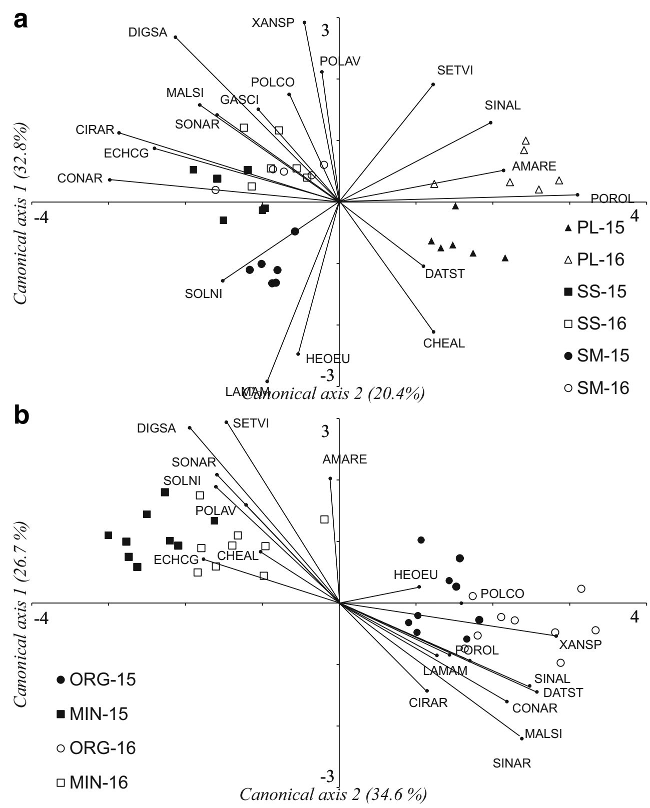

Fig. 3 Canonical discriminant analysis (CDA) of the weed species based on soil tillage (**a**) and fertilizer source (**b**) observed in 2015 and 2016 growing seasons of potato crop. *Min* Mineral fertilizer, *Org* Organic fertilizer, *PL* Plowing, *SM* Spading machine, *SS* Subsoiler. AMARE = *A. retroflexus*; CHEAL = *C. album*; SOLNI = *S. nigrum*; DATST = *D. stramonium*; XANSP = *X. spinosum*; SINAL = *S. alba*; POLCO = *F. convolvulus*; POLAV = *P. aviculare*; POROL = *P. oleracea*; LAMAM = *L. amplexicaule*; HEOEU = *H. europaeum*; GASCI = *G. ciliata*; SYLMA = *S. marianum*; MALSI = *M. sylvestris*; CONAR = *C. arvensis*; SONAR = *S. arvensis*; CIRAR = *C. arvense*; ECHCG = *E. crus-galli*; DIGSA = *D. sanguinalis*; SETVI = *S. viridis*

Potato Tuber Yield and Straw

The results of the ANOVA analysis showed that potato tuber yield was significantly affected by soil tillage, fertilizer source and the growing seasons (Table 4) as main treatments. In addition, growing season × soil tillage and

Table 4 The main effect of growing season, soil tillage, and fertilizer source on potato tuber yield and potato straw

	Tuber yield $g\,m^{-2}$ of DM	Potato straw
Growing season		
2015	$401.6^{(\pm 22.3)}$ b	$108.3^{(\pm 7.3)}$ a
2016	$793.0^{(\pm 33.9)}$ a	$169.1^{(\pm 7.8)}$ a
Soil tillage		
PL	$690.2^{(\pm 62.1)}$ a	$165.2^{(\pm 8.5)}$ a
SM	$620.0^{(\pm 74.6)}$ b	$131.5^{(\pm 14.0)}$ b
SS	$481.9^{(\pm 52.9)}$ c	$119.3^{(\pm 12.1)}$ c
Fertilizer source		
Min	$627.5^{(\pm 60.6)}$ a	$144.3^{(\pm 10.8)}$ a
Org	$567.2^{(\pm 48.7)}$ b	$133.0^{(\pm 10.2)}$ b

Mean values belonging to the same factor without common letters are statistically different to LSD ($p \leq 0.05$)
MIN Mineral fertilizer, *ORG* Organic fertilizer, *PL* Plowing, *SM* Spading machine, *SS* Subsoiler. In brackets ± standard error

growing season × fertilizer source interactions are reported in Fig. 3. Similarly, potato straw was affected by the main treatments, except for soil tillage (Table 4).

The tuber yield was higher in 2016 compared with 2015 growing season (793.0 $g\,m^{-2}$ and 401.6 $g\,m^{-2}$ respectively), while no significant differences were detected for the potato straw (on average 138.7 $g\,m^{-2}$ of DM, Table 4). Regarding the soil tillage, the potato tuber yield was the highest in PL, intermediate in SM and low in SS (690.2, 620.0 and 481.9 $g\,m^{-2}$ of DM, respectively). Similar trend was observed in the potato straw (Table 4). Potato tuber yield and straw were always higher in Min fertilization source (627.5 and 144.3 $g\,m^{-2}$ of DM, respectively) compared with

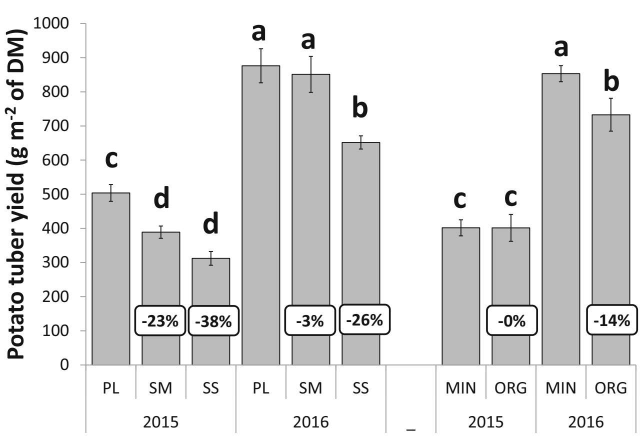

Fig. 4 The interaction effects of growing season × soil tillage and growing season × fertilizer source on potato tuber yield. Values belonging to the same characteristic followed by the same letter are not statistically different according to LSD ($p \leq 0.05$). *Min* Mineral fertilizer, *Org* Organic fertilizer, *PL* Plowing, *SM* Spading machine, *SS* Subsoiler. *Bars* represent standard error. The percentage data indicate the relative yield reduction in comparison of PL for soil tillage treatments and Min for soil fertilizer sources

Org treatment (567.2 and 133.0 $g\,m^{-2}$ of DM, respectively, Table 4).

The effects of the interaction between growing season × soil tillage and between growing season × fertilizer on tuber production is prominent. In general, higher yields were obtained in 2015 with PL-SM-MIN. Regarding tillage, there were no significant differences between plowing and spading in 2016 and spading and subsoiling in 2015 (Fig. 4). The production, as far as processing is concerned, showed the following trend PL-SM 2016 > SS 2016 > PL 2015 > SM-SS 2015. Concerning production in the growing season × fertilizer interaction, here too the highest production was obtained in 2016 (Fig. 4). In addition, 2016 showed a significant difference between the fertilizations, which did not happen in 2015 where average yields tend to be low in both cases (Fig. 4).

Discussions

Several cultivation and land management strategies are commonly used in integrated weed management. Estimating weed species' response to these practices is critical for agro-biodiversity preservation (Travlos et al. 2018). Therefore, different management practices, such as tillage and fertilization, can significantly impact the composition and structure of weed communities. Apparently, the highest number of annual species had a positive correlation with the plowing and the highest number of dicotyledons was found in subsoiling. This result is consistent with the findings of Wilson et al. (2003). Annual broadleaf species are often more abundant in frequently disturbed conventional tillage systems (Streit et al. 2003). It is well known that annual weeds are favoured by more impactful agronomic regimes, such as plowing, as they tend to have an agronomic advantage over perennial plants, which grow best when there is little soil disturbance that does not interfere excessively with root growth (Petroselli et al. 2021). According to previous studies, under reduced tillage practices perennial weed species increase in terms of densities and diversity more than plowing (Feldman et al. 1998; Nichols et al. 2015; Jorgensen 2018). The result of this study showed as some perennial weeds, such as MALSI, CIRAR, and CONAR, were found to be primarily associated with the subsoiling. Less invasive tillage systems, such as spading and subsoiling, promote noticeable improvements in soil biological processes, resulting in increased weed biodiversity (Radicetti et al. 2013). Similarly, Thomas et al. (2017) observed that perennial species such as *C. arvense* and *S. arvensis* were associated with reduced- and zero-tillage, whereas annual species were associated with a variety of tillage systems. In the case of density, the lowest values were obtained in the interaction between PL and Min, while in the case of biomass, with plowing, statistically equal values were obtained in both the Min and ORG regimes. On the other hand, the highest values of density and weed biomass were always found with the SS-ORG interaction. The spading machine only worked the soil to a depth of 20 cm, allowing the weed seeds to germinate in the active layer of the soil. Furthermore, the presence of some perennial weed species under spading machine treatments could be explained by spading, which chopped and spread the plant's reproductive parts, such as stolons or rhizomes, resulting in increased density, i.e. CIRAR.

Fertilization influences soil fertility and nutrient uptake, resulting in increased agricultural yields as well as changes in weed communities (Allan et al. 2015). The type of fertility inputs differs between conventionally (mineral) and organically-managed systems and weed species richness and abundance are thought to be strongly related to organic farming when compared to conventional farming (Hyvönen et al. 2003). In the current study, higher species richness was found with the organic fertilizer, which favoured the growth of all weeds except monocotyledons, which grew in more significant quantities under mineral fertilization. Organic farming often improves species richness, with an average 30% higher species richness than conventional farming systems (Bengtsson et al. 2005). According to Kakabouki et al. (2015), both manure treatment or inorganic fertilizer increased overall weed density and biomass. Berner et al. (2008) stated that delayed nitrogen release by solid farmyard manures appears to favor weeds more than early nitrogen requiring crops. Moreover, Than et al. (2017) investigated the impact of several fertilizer treatments on weed density and richness indexes; they discovered that the N and P fertilizer applications had a greater influence on the weed community than the K application. Counter results were found by others (Gough et al. 2000; Suding et al. 2005; Bilalis et al. 2010), they found greater weed communities in low than in high input systems. However, Santn-Montanyá et al. (2013) observed no significant influence of mineral fertilization on weed abundance and diversity.

It is important to emphasize that environmental and weather conditions also influence weed and crop growth. Moreover, soil temperature, quality, water content, and light influence plants' germination and presence (Ciuberkis et al. 2007). Nevertheless, comparing the two growing seasons, there was an increase in both weed and potato tuber production in the year with higher temperatures (2016). A previous study revealed that variation in weather conditions greatly affects weed composition and crop productivity (Fawad et al. 2022). Apparently, the interaction between growing season × soil tillage and growing season × fertilizer source resulted in higher tuber production with PL-SM-Min in the 2016 season, while in the 2015 year.

The plowing-tillage system showed a certain advantage with respect to potato yield, which was much greater than the SM and SS systems. However, the tuber yield in SM treatments are only about 10% less compared with the yield observed in PL treatment, while for SS, the marketable tubers were 25–30% less. Therefore, tuber yield in SM seems to be quite competitive to PL, especially, when thinking about tillage costs, which are much lower in SM than in PL. Deep soil tillage, such as plowing and ridging, promotes plant growth, macronutrient absorption and translocation in potato tubers (Boligowa and Glen 2003; Nunes et al. 2006). Potato producers commonly use deep plowing before seedbed preparation and ridging to provide enough loose-structured soil, which is essential for optimal tuber formation and quality (Djaman et al. 2022). The sub-soiling tillage gave the lowest results of marketable tuber yield. Holmstrom and Carter (2000) reported that subsoiling did not boost potato yield or quality. Compared to conventional plowing, Pierce and Burpee (1995) found that no-tillage in the spring increased marketable yields, but not overall yields. Ghosh and Daigh (2020) concluded that potato yield and quality improvements from subsoiling are rare, temporary, and highly variable, with the only exception being when moisture is known to be the major limiting factor in a field. A similar trend was observed in the potato straw. Because nutrients in mineral fertilizers are more effective than the equivalent amount of nutrients in farmyard manure (Baniuniene and Zekaite 2008), mineral fertilizer efficacy for potatoes was considerably higher than that of organic fertilizer (Baniuniene and Zekaite 2008). The tubers of crops fertilized with mineral, rather than organic fertilizers accumulated the largest dry matter (Srikumar and Ockerman 1990).

Conclusions

This study shows that the adoption of alternative agricultural practices in substitution of conventional ones could be subjected to a significant change in weed community composition. Indeed, the adoption of shallow tillage and organic fertilization sources tends to increase weed biomass and weed density compared to ploughing and mineral fertilization practices. Although conventional practices are characterized by a low weed density, these practices tended to be associated to highly competitive annual weed species such as *A. retroflexus, P. oleracea, C. album, S. alba* and *D. stramonium*. In the long-term period, the evidence of these dominant weed species will contribute to the establishment of competitive environment for crop growth determining a decrease of sustainability of those agroecosystems. On the other hand, the adoption of alternative practices tended to favour the growth also of other weed species reducing the development of the main competitive annual weed species and the results showed how these practices are associated to a wide range of weed species and their distribution. Alternative soil tillage, such as spading and subsoiling showed an increased number of monocots and dicots weed density. Similar result was observed also when organic fertilization source has been applied.

Plowing and mineral fertilizer were used in the experiment, which resulted in higher tuber yields, while sustainable agronomic practices, such as spading in 2016 and organic fertilizer in 2015, were able to compare with the production results obtained from conventional practices. The next challenge will be related to the development of soil management practices that support the productivity of the agro-ecosystem and at the same time ensure the establishment of a wide range of weed species less competitive with the main cash crop. Although the study shows that increased weed biodiversity in the system, achieved with more sustainable practices, proves to be an obstacle to potato production, the adoption of spading machine applied in combination with mineral and organic fertilizers could be a valid alternative to plowing. In any case, the results showed that there is widespread recognition and agreement that reduced tillage is associated with higher risks of weed proliferation and further studies are required to evaluate how additional management could support the development of sustainable agricultural techniques able to improve the competitive capacity of crops and reduce the selection of dominant weed species.

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