Improved soil quality after 16 years of olive mill pomace application in olive oil groves

García-Ruiz, M Ochoa, M Hinojosa, Gómez-Muñoz

Agron. Sustain. Dev. (2012) 32:803–810
DOI 10.1007/s13593-011-0080-7

RESEARCH ARTICLE

Improved soil quality after 16 years of olive mill pomace application in olive oil groves

Roberto García-Ruiz · M Victoria Ochoa · M Belén Hinojosa · Beatriz Gómez-Muñoz

Accepted: 21 December 2011 / Published online: 26 January 2012

Abstract This report shows notable improvements of soil physical, chemical, and biological properties after long-term soil application of olive mill pomace compost. About four million tons of olive mill pomace is produced annually in Andalusia, Spain. Olive mill pomace is a main by-product of the olive oil extraction industry. Composting is a promising strategy to manage the huge volume of this potentially environmentally harmful pomace. Converting olive mill pomace into a useful soil amendment in semiarid Mediterranean areas of olive oil farms, characterized by low organic matter content and subjected to progressive degradation, would be valuable. There is actually no data on the long-term effects of composted olive mill pomace application on soil physicochemical and biochemical properties. However, this information is needed to encourage the composting of this pomace. Here, a field study evaluated soil fertility and soil capacity to degrade organic compounds after the application of composted olive mill pomace. Olive groves received compost annually for 3, 4, 9, and 16 years. Soils were sampled and compared to olive groves without compost application. Soil physico-chemical properties and soil enzyme activities such as acid phosphatase, β-glucosidase, protease, invertase, and dehydrogenase, were analyzed. Our results show that soil organic matter, nitrogen, available phosphorus, cation exchange capacity, aggregate stability, and exchangeable potassium were between 1.4 and 3.3 times higher in the compost-treated farms. Soil enzyme activities in soils treated with compost was between 180% and 420% higher than in untreated soils. Moreover, there was a clear trend of increasing soil fertility and enzyme activities with years of compost application. Here, we conclude that the addition of composted olive mill pomace to olive groves markedly improved soil quality.

Keywords Composted olive mill pomace · Soil fertility · Soil enzyme · Olive oil farm · Olive oil industry · By-products

1 Introduction

There is a global trend towards developing sustainable agricultural production systems. This involves the more efficient utilization of inputs and the reduction of waste products, which is in line with current trends in the European waste policy aim of reutilization of biodegradable wastes from agro-industries (Council Directive 1999/31/EC). Ideally, organic by-products should be transformed into useful products by processes such as nutrient recycling, replenishment of soil organic matter, or generation of energy (Parr et al. 1986). In this context, the cost of waste disposal would be avoided and environmental pollution reduced. This has led to a widespread increase in value of agricultural waste products such as olive mill pomace.

The Andalusian (Southern Spain) olive oil industry generates annually about four million tons of an organic–

R. García-Ruiz (✉) · B. Gómez-Muñoz
Campus de Excelencia Internacional Agroalimentario, ceiA3,
Ecology section, University of Jaén,
Campus las Lagunillas s/n,
23071 Jaén, Spain
e-mail: rgarcia@ujaen.es

M. V. Ochoa
Biodiversity and conservation section,
University of Rey Juan Carlos,
Móstoles, Spain

M. B. Hinojosa
Centro de Investigaciones del Fuego,
Fundación General de Medio Ambiente de Castilla la Mancha,
Toledo, Spain

pasty–slurry called olive mill pomace. This large amount of pomace produced over such a short period of time (between November and March), presents important management and disposal problems. The direct disposal of olive mill pomace to the land is not allowed since it might cause serious environmental problems due to the phytotoxic and antimicrobial properties of the pomace (Perez et al. 1992).

Since most of the harvested nutrients remain in the olive mill pomace after oil extraction, it can be used as a soil fertilizer and organic matter amendment after composting. The process of composting olive mill pomace consists essentially of mixing it with a blend of natural organic residues, then maintaining it in aerated piles for 7 to 9 months. Figure 1 shows a visual aspect of the compost of olive mill pomace.

Low organic matter content is a common feature of Mediterranean soils, limiting their workability, long-term fertility, and productivity (Albaladejo et al. 1994). Therefore, agricultural practices based on periodic inputs of organic amendments are strongly recommended for Mediterranean agro-ecosystems. Traditional organic soil amendments, such as farmyard manure, are locally scarce (Saviozzi et al. 1999); however, composted olive mill pomace contains a large amount of organic matter, and thus, might be useful as an amendment to agricultural soils, potentially lowering the need for inputs of nitrogen, phosphorus and potassium fertilizer, and improving a range of soil properties. This strategy could be of special importance for the maintenance of the olive grove ecosystem in which the return of the organic matter to the soil, apart from its positive effect of storing carbon in the soil, would help to prevent problems associated with erosion (Pleguezuelo et al. 2009).

There is a paucity of knowledge on the use of composted olive mill pomace as a soil amendment. Cabrera et al. (2005) assessed the potential mineralization of organic N of compost applied to two calcareous soils in a short-term pilot experiment, and more recently, Gómez-Muñoz et al. (2011) described the major properties of 7 out of the 11 composted olive mill pomace currently produced in Andalusia, and found that this compost was very rich in organic matter. They also found very low CO_2 respiration rates derived from this compost indicating the recalcitrant nature of the carbon. However, studies on the effects of compost application on indicators of soil fertility under field conditions are lacking.

We hypothesized that the application of organic matter-rich composted olive mill pomace will increase soil organic matter and soil fertility, and thus, the use of this transformed agro-industrial waste might represent a promising solution to overcome both the soil degradation in olive oil groves and a sustainable disposal of olive mill pomace, increasing the sustainability of the olive groves.

The objective of this field study was to evaluate the cumulative effects (from 3 to 16 years) of repeated applications of composted olive mill pomace on the soil physicochemical properties and the soil's potential capacity to degrade organic compounds (i.e., soil enzyme activities).

Fig. 1 Visual aspect of composted olive mill pomace

2 Material and methods

2.1 Experimental design and soil sampling

Four olive oil farms, which annually receive applications of composted olive mill pomace, were selected according to the number of years since this compost was first applied. These are not experimental farms and are managed using common management practices. The annual application of compost to the olive oil farm at Olvera, Reja, Tobazo, and Andújar has been made during the last 3, 4, 9, and 16 years, respectively. Each of the farms which received compost was paired with a nearby and comparable olive oil farm (in terms of climate, orientation, slope, soil type, and farm characteristics such as tree density and age), which received no compost. Thus, differences between pairs of olive oil farms within each site were attributed primarily to the application of composted olive mill pomace. All olive oil farms had a tree density of 90–110 trees per hectare, aged 35 to 45 years, and distributed in a regular arrangement with a canopy cover typically of about 30% of the farm area. The application of the compost consisted of the annual application of between 4.0 and 6.0 $t\,ha^{-1}$ (wet weight, water content typically around 20%) during October and November. The variability in the period and rate of application was due to the decision of each farmer, mainly depending on compost availability, climate conditions, and expected production during the following year. In each of the farms which received compost, the compost was always evenly spread on the soil in the intercanopy (approximately 70% of the farm area). Table 1 shows some properties of composted olive mill pomace. Fertilization on the farms which did not received compost consisted of the application of 50–70 kg $N\,ha^{-1}$ as urea or ammonium sulfate in the early spring and always under the tree canopy, never in the intercanopy.

Soil samples (top 10 cm) were collected in April. All farms were sampled over a period of 10 days. Each pair of comparable compost and non-compost farms was sampled in the same day. Sampling consisted of a random selection of five locations of the intercanopy per site, and in each location, a soil sample composed of four subsamples. Soil samples were transported to the laboratory in the same day, field moist sieved (<2 mm) within 8 h, and stored at 4°C for 2–3 weeks until further analysis.

2.2 Soil analyses

Soil pH was determined in a slurry with 0.01 M $CaCl_2$ (1:1; soil/$CaCl_2$). Water content was estimated by gravimetry. Particle size distribution was determined by the pipette method (Gee and Bauder 1986). Soil water-holding capacity (WHC) at −33 kPa was analyzed in a Richard's membrane–plate extractor (Klute 1986). Air-dried subsamples were used to analyze exchangeable potassium, according to Grant (1982), and soil available phosphorus content following the method proposed by Olsen and Sommers (1982). Soil organic matter content was estimated according to Nelson and Sommers (1982). An aliquot of the dried soil was ground to a fine powder (<1 mm), and soil total nitrogen was analyzed using a Leco CNH-932 analyzer. Soil organic carbon was determined after digesting the soil samples with dichromate and sulfuric acid following the method of Anderson and Ingram (1993). The pool of easily mineralized nitrogen in soil was analyzed according to Kandeler (1995). Cation exchange capacity was analyzed according to Rhoades (1982). The percentage of soil–water aggregate stability was determined by the method described by Lax et al. (1994).

Soil enzyme activities were measured using 1 g air-dried soils. Acid phosphatase (EC 3.1.3.2, orthophosphoric-monoester phosphohydrolase, acid optimum) and β-glucosidase (EC 3.2.1.21, β-D-glucosidase glucohydrolase) activities were determined according to Tabatabai (1982) and reported as microgram *p*-nitrophenol (*p*NP) per gram per hour. Invertase activity was assayed following the method described by Mersi and Schinner (1995), using sucrose as a substrate and measuring the equivalents of glucose after an incubation period of 3 h at 50°C. Protease activity was determined on 1 g of soil following Kandeler (1995) using casein as a substrate and measuring the equivalents of tyrosine after 2 h at 50°C. Dehydrogenase was determined as described by Casida et al. (1964). The potential rate of soil nitrification was determined on 3.5 g soil following Kandeler (1995).

Table 1 Some properties of composted olive mill pomace

Properties	Mean±standard deviation
Organic matter (%)[a]	50.1±7.2
Total carbon (%)[b]	27.7±4.0
Total nitrogen (%)[b]	1.66±0.18
Carbon-to-nitrogen ratio	18.3±4.5
Potential mineralized nitrogen (% of total nitrogen)[c]	1.31±0.3
Water-soluble carbon (μg $C\,g^{-1}$)[d]	6.43±2.1
Polyphenols (%)[e]	14.5±2.1
Lignin (%)[f]	21.6±5.9

Compost of olive mill pomace has high organic matter and carbon, medium levels of total nitrogen, and a relatively low carbon-to-nitrogen ratio. Polyphenol contents are low and values for lignin were medium

[a] Loss on ignition (550°C for 5 h)

[b] CNH autoanalyzer (Carbon Erba NA 200, Milan Italy)

[c] Analyzed in fresh samples following Lober and Reeder (1993)

[d] Determined after Ghani et al. (2003)

[e] Total extractable polyphenol contents were determined using Folin–Ciocalteu reagent (Anderson and Ingram 1993)

[f] Acid detergent lignin were measured following Van Soest (1963)

Values of enzyme activities and the potential nitrification rate are reported on an oven-dry soil weight basis. Since soil enzymes differ in origin, function, and location within the soil matrix, and respond to different key environmental signals, it would be useful to condense the information that they provide into a single numerical value. We used the geometric mean of the assayed soil enzyme activities and potential nitrification rate for this purpose. This index has been used to determine the soil quality in soils subjected to different agricultural management practices (García-Ruiz et al. 2008). For each soil sample, the geometric mean of the assayed enzyme activities and potential nitrification rate was calculated as:

$$\sqrt[6]{\text{phosphatase} \times \text{invertase} \times \text{glucosidase} \times \text{protease} \times \text{dehydrogenase} \times \text{potential nitrification}}$$

2.3 Statistical analyses

The effects of compost application, site, and the interaction between both on individual physico-chemical and biological soil properties were tested by a two-way factorial analysis of variance (ANOVA). Differences among levels of treatments were tested using the Fisher's least significant difference test. Assumptions of ANOVA (homoscedasticity and normality) were tested and assured by using transformed datasets [log (dependent variable value +1)] when necessary. Significance was accepted at $P<0.05$ in all cases. Statistical analyses were performed using STATISTICA 6.0 scientific software.

3 Results and discussion

3.1 Effects of composted olive mill pomace application on physico-chemical properties of soils

Texture was not significantly different between each pair of olive oil farms (with compost versus without compost of olive mill pomace), except at the Andújar site, where soil sand content was higher in the farm treated with compost (Table 2). Thus, main differences in soil properties between each pair of farms were attributed to compost application, except for the Andújar site. In general, soil pH was significantly lower in the soils which received compost although it depended on the number of years of application (Table 2). The soil pH value of the 4-, 9-, and 16-years compost-treated soils were 0.31, 0.23, and 1.47 units lower than in the comparable untreated soils, respectively, whereas no differences were found in the soil treated for 3 years with compost. This result is consistent with those found by López-Piñeiro et al. (2008), who found that soil pH decreased between 0.12 and 0.17 units after 5 years of olive mill pomace application. Piotrowska et al. (2006) also showed a temporarily decline in soil pH after application of olive mill pomace. The decrease in pH in soils receiving this compost may be due to the phenolic and carboxylic groups resulting from organic matter decomposition of compost, which act as weak acids.

Overall, composted olive mill pomace application significantly increased soil organic matter compared to the soils

Table 2 Physico-chemical properties of soil which received or not composted olive mill pomace at Olvera, Reja, Tobazo and Andújar

Site	Years of compost application	Soil pH	Water-holding capacity (%)	Sand content (%)	Clay content (%)	Silt content (%)	Soil organic matter (%)	Soil organic carbon (%)	Soil organic nitrogen (%)
Olvera	3	7.74^a (0.05)	26.3^a (0.8)	14.8^a (1.2)	42.1^a (0.8)	43.1^a (0.5)	3.95^a (0.95)	2.29^a (0.39)	0.25^a (0.04)
	0	7.80^a (0.05)	22.3^b (0.3)	17.3^a (1.1)	40.4^a (1.1)	42.3^a (2.1)	3.45^a (0.85)	2.00^a (0.49)	0.27^a (0.03)
Reja	4	7.83^a (0.20)	21.8^a (1.3)	39.3^a (0.9)	30.9^a (1.7)	29.8^a (2.5)	8.34^a (3.67)	4.84^a (1.90)	0.29^a (0.03)
	0	8.14^b (0.05)	20.5^b (1.7)	30.6^a (1.3)	30.6^a (1.0)	33.2^a (1.0)	3.96^b (1.09)	2.30^b (0.57)	0.23^a (0.02)
Tobazo	9	7.67^a (0.03)	23.6^a (0.5)	30.5^a (4.3)	40.6^a (5.1)	28.8^a (2.1)	6.31^a (2.22)	3.66^a (1.15)	0.25^a (0.08)
	0	7.90^b (0.08)	20.5^b (0.8)	36.3^a (1.3)	32.7^a (6.1)	31.0^a (6.6)	2.39^b (0.62)	1.39^b (0.32)	0.10^b (0.02)
Andújar	16	6.62^a (0.26)	30.2^a (0.5)	76.9^a (1.0)	12.2^a (1.8)	10.9^a (1.3)	16.1^a (3.49)	8.49^a (2.11)	0.74^a (0.33)
	0	8.09^b (0.07)	28.7^a (1.3)	43.4^b (5.9)	24.4^b (0.1)	32.2^b (5.8)	1.88^b (0.41)	1.09^b (0.21)	0.05^b (0.02)

Data are the mean of five replicates and standard deviation is shown between brackets. Different superscript letters for each site means significant differences between compost-treated and untreated soils (one-way ANOVA; $P<0.05$). For most of the analyzed properties, differences between treated and untreated were significant, especially after 4 years of compost application. Magnitude of differences for soil organic matter, carbon, and nitrogen tended to increase along the number of years since compost was applied which did not received compost (Table 2), except at the Olvera site which received compost for only 3 years. Indeed, soil organic matter in soils treated for 4, 9, and 16 years with compost (i.e., Reja, Tobazo, and Andújar sites) was 2.1 to 8.5 times greater than that of the respective untreated soil. Given the high organic matter content of this compost (Table 1), the increase of soil organic matter after continuous application is not surprising. This increase is important in semiarid conditions where agricultural soils are poor in organic matter and are subject to intense degradation, as is the case in many areas of olive oil farms. Our data confirm previous results, which indicated that soil organic matter increased after the amendment with olive mill waste during the first weeks after application (Piotrowska et al. 2006) or after several years (López-Piñeiro et al. 2008). Soil organic carbon was higher in the soils treated with composted olive mill pomace (Table 2), indicating that the decomposition rates of organic carbon of this compost were relatively low, lower than the rates of annual application of compost carbon. Brunetti et al. (2004) has shown that during the composting of olive mill pomace, there was an increase in the content of condensed aromatic compounds, and more recently, Plaza et al. (2007) found that in the final steps of composting of olive mill pomace, the COOH, phenolic OH contents, and aromaticity increases. These recalcitrant compounds might contribute to the reduced rate of carbon decomposition of this compost at field conditions. This low decomposition rate indicates that the application of this compost to soils of olive oil groves is an appropriate strategy to sequester organic carbon into the soil that should be further evaluated.

Other soil properties directly or indirectly linked to soil organic matter content also increased with the compost treatment, although it depended on the number of years of compost application. Thus, soil organic nitrogen in the compost-treated soil was higher than untreated soil when compost was consecutively applied for more than 9 years (Tobazo and Andújar sites) (Table 2), and is in agreement with the findings of López-Piñeiro et al. (2008) and Cabrera et al. (2005), who found a significant increase in the soil organic nitrogen after application of olive mill pomace. This result suggests that organic nitrogen in the composted olive mill pomace is very resistant to mineralization, and therefore is retained in the soil. Indeed, Gómez-Muñoz et al. (2011) showed for seven types of composted olive mill pomace that organic nitrogen of the compost was not released in available forms during decomposition, although the C-to-N ratio of the compost ranged from 10 to 33. These results indicate that after continuous application of composted olive mill pomace, the overall microbial demand for ammonium to be immobilized is higher than that which is nitrified. Therefore, the application of this compost may result in a short-term reduction of N availability in olive grove soils, suggesting that the initial application of composted olive mill pomace to the soils should be accompanied by another source of available nitrogen.

The higher soil water holding capacity in the soils treated with compost (Table 2), due to the relatively higher level of soil organic matter, reflect the effect of organic matter on the increased potential for a soil to retain water which was previously described by Hollis et al. (1977) for 77 soil profiles. Soil–water aggregate stability was also significantly higher after the application of composted olive mill pomace, with values between 1.5 and 2.5 times greater than for untreated soils, except for the soil which received compost for 16 years (Andújar site) where no significant difference was detected (Table 3). However, when soil aggregate stability was normalized by soil sand content (i.e., soil aggregate stability on a sand-free basis), the value for the

Table 3 Soil cation exchange capacity, water aggregate stability, available phosphorus, exchangeable potassium, and potential mineralized N in soils of olive oil farms which received or not composted olive mill pomace at Olvera, Reja, Tobazo and Andújar

Site	Years of compost application	Soil cation exchange capacity (meq 100 g^{-1})	Soil aggregate stability (%)	Available phosphorus (μg Pg^{-1})	Exchangeable potassium (meq 100 g^{-1})	Potential mineralized N (μg Ng^{-1})
Olvera	3	22.2^{a} (1.22)	51.8^{a} (2.0)	10.6^{a} (0.04)	1.33^{a} (0.01)	40.7^{a} (9.9)
	0	20.8^{b} (0.21)	34.0^{b} (1.6)	9.3^{a} (0.03)	1.02^{b} (0.01)	9.6^{b} (14.9)
Reja	4	25.3^{a} (3.83)	57.9^{a} (1.8)	30.3^{a} (0.03)	0.99^{a} (0.3)	46.8^{a} (20.8)
	0	18.6^{b} (0.27)	37.1^{b} (0.9)	11.5^{b} (0.02)	0.44^{b} (0.04)	17.4^{b} (5.4)
Tobazo	9	21.1^{a} (3.46)	56.7^{a} (0.2)	6.9^{a} (0.01)	1.44^{a} (0.22)	75.2^{a} (31.5)
	0	15.4^{b} (2.06)	22.6^{b} (0.6)	7.6^{a} (0.02)	0.85^{b} (0.1)	13.8^{b} (9.3)
Andújar	16	23.3^{a} (6.9)	23.9^{a} (1.0)	57.4^{a} (0.33)	1.32^{a} (0.4)	132.1^{a} (40.0)
	0	10.6^{b} (1.2)	23.7^{a} (1.5)	3.57^{b} (0.02)	0.18^{b} (0.07)	12.5^{b} (27.0)

Data are the mean of five replicates. Standard deviation is shown between brackets. Different superscript letters for each site means significant differences between treated and untreated soils (one-way ANOVA; $P<0.05$). Differences between treated and untreated soils for the analyzed soil properties were significant. Magnitude of differences for soil cation exchange capacity, exchangeable potassium, and potential mineralized N tended to increase along the number of years since compost was applied

Table 4 Soil enzyme activities and potential nitrification rate in soils of olive oil farming treated and untreated with composted olive mill pomace at Olvera, Reja, Tobazo and Andújar

Site	Years of compost application	Phosphatase (μg*p*NP g^{-1} h^{-1})	β-glucosidase (μg*p*NP g^{-1} h^{-1})	Protease (μg tyrosine g^{-1}2 h^{-1})	Invertase (μg glucose g^{-1} h^{-1}24 h^{-1})	Dehydrogenase (μg TPF g^{-1} h^{-1})	Potential nitrification (μg Ng^{-1} h^{-1})
Olvera	3	193.5^{a} (28.3)	377.5^{a} (26.2)	13.0^{a} (4.5)	219.6^{a} (19.6)	136.8^{a} (25.9)	0.56^{a} (0.15)
	0	123.5^{a} (30.0)	282.9^{b} (72.3)	8.0^{a} (4.5)	130.8^{b} (30.3)	82.0^{b} (8.8)	0.63^{a} (0.18)
Reja	4	231.5^{a} (16.4)	272.8^{a} (20.9)	26.2^{a} (6.2)	212.3^{a} (27.7)	160.8^{a} (76.8)	0.41^{a} (0.11)
	0	140.3^{b} (32.5)	179.6^{b} (27.2)	11.4^{b} (2.9)	100.4^{b} (18.7)	92.6^{b} (14.3)	0.49^{a} (0.15)
Tobazo	9	236.7^{a} (76.4)	380.6^{a} (77.3)	13.0^{a} (2.3)	324.3^{a} (106)	342.3^{a} (94.3)	0.96^{a} (0.37)
	0	69.0^{b} (20.1)	149.0^{b} (61.6)	0.0^{b} (0.0)	47.9^{b} (17.4)	62.9^{b} (8.4)	0.33^{b} (0.13)
Andújar	16	626.0^{a} (182)	406.2^{a} (63.8)	25.7^{a} (15.8)	369.1^{a} (90.7)	501.5^{a} (81.0)	0.61^{a} (0.25)
	0	50.6^{b} (9.7)	186.1^{a} (129)	1.24^{b} (1.27)	47.9^{b} (17.4)	42.4^{b} (5.2)	0.10^{b} (0.08)

Data are the mean of five replicates and standard deviation is shown between brackets. Different superscript letters for each site means significant differences between treated and untreated soils at each site (one-way ANOVA; $P<0.05$). Overall, application of compost increased the analyzed soil enzyme activities. Magnitude of differences tended to increase along the number of years since compost was applied for phosphatase, β-glucosidase, protease, invertase, and dehydrogenase activities

compost soil at the Andújar site was three times higher than that of the unamended soil. This result agrees with the findings of López-Piñeiro et al. (2008) who showed that the application of olive mill pomace increased soil stable aggregates from 64% to 73% after 5 years. The direct contribution of organic matter on soil–water aggregate stability has been widely described (Molope et al. 1985). Thus, in our study, soil aggregate stability was highly positively correlated with soil organic matter ($r=0.85$; $P<0.01$). The increase of soil–water aggregate stability after compost application might contribute to the reduction of soil erosion in a region with typically high slope aspects.

Soil cation exchange capacity and potential mineralized nitrogen were all significantly higher in the compost-treated soil, even those that received this compost for 3 years (Table 3). Overall, soil available phosphorus in the compost-amended soil was higher than that of the unamended soil (Table 3). In the Olvera, Reja, and Andújar sites, soil available phosphorus in the compost-amended soils was 13.9%, 260.3%, and 1,607% higher than that of untreated soils, whereas no significant difference was found at the Tobazo site. The overall increase in the soil content of available phosphorus attributable to compost application is also consistent with the results of other studies with other types of organic wastes. Paredes et al. (2005) reported that available phosphorus content tended to increase with the total phosphorus added to soil through composted materials (olive mill wastewater, cotton gin waste, and sewage sludge), and López-Piñeiro et al. (2008) observed a 100% increase in available phosphorus content in soil treated with olive mill pomace after 5 years.

At all sites, soil exchangeable potassium was significantly higher in the compost-treated soils than in the unamended soils (Table 3). This result is consistent also with the results of other studies using treated and untreated residues from olive mill pomace (López-Piñeiro et al. 2008). Thus, the application of composted olive mill pomace to the soil could be used as an alternative supply to potassium poor soils.

3.2 Effects of composted olive mill pomace application on soil enzyme activity

Soil enzyme activities have been proposed as a tool to assess soil quality and health (Dick 1994). Acid phosphatase, β-glucosidase, protease, invertase, and dehydrogenase activities were all significantly higher in soils amended with compost (Table 4). Phosphatase, β-glucosidase, dehydrogenase,

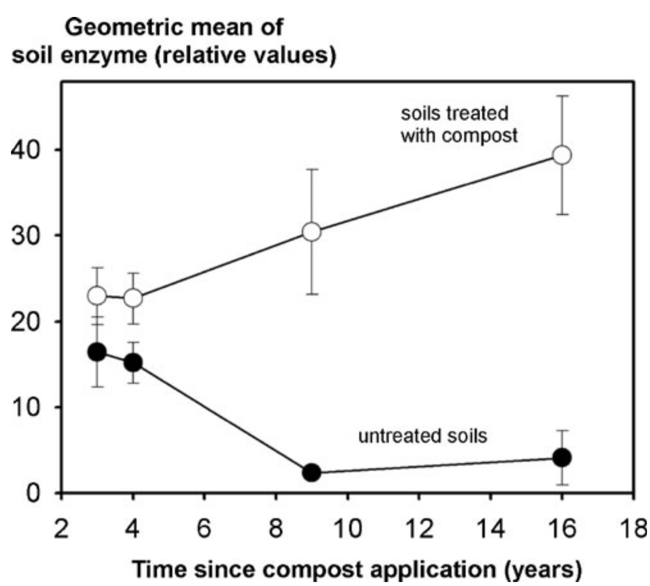

Fig. 2 Geometric mean of assayed soil enzyme for soils which received compost of olive mill pomace for different number of years and for non-compost soils. The geometric mean was higher in the compost-treated soils and differences between treated and untreated increased along the number of years compost was applied

protease, and invertase were on average 3.3, 1.8, 4.0, 3.6, and 3.2 times higher in the soils treated with composted olive mill pomace, respectively. The higher values of dehydrogenase, which is considered to be a measure of a soil's microbiological activity, can be attributed to greater microbial biomass due to the addition of available organic carbon within the compost. The higher β-glucosidase and invertase in the soils treated with compost could indicate that compost-amended soils have gained a capability to utilized carbohydrate material added with the compost. The significant increase in soil phosphatase, which plays an essential role in the mineralization of organic phosphorus, and protease activities after compost application can be explained by the fact that compost stimulates bacterial growth and enzyme production, including those involved in phosphorus and protein turnover.

Potential soil nitrogen nitrification was significantly higher (between 2.8 and 5.7 times) in the soils of Tobazo and Andújar, which received compost annually for the last 9 and 16 years, whereas similar values were recorded for the compost and non-compost soils of the Olvera and Reja sites (i.e., 3 and 4 years of compost amendments) (Table 4). Thus, nitrifying bacteria was only stimulated after long-term application of composted olive mill pomace.

In this study, soil values of the geometric mean of the assayed enzymes under compost were significantly higher than in untreated soils (Fig. 2), and thus, the overall capacity of soil to recycle organic carbon, phosphorus, and nitrogen was increased after the addition of compost of olive mill pomace. Moreover, there was a clear tendency of increasing differences between treated and untreated soils along the number of years since compost was applied (Fig. 2).

3.3 Effects of compost application period on soil variables

Generally, soil enzyme activities were more sensitive to compost application than other variables. Indeed, soil invertase, β-glucosidase, and the geometric mean of assayed enzymes were significantly higher in the farms which received compost for at least 3 years, whereas soil organic carbon, cation exchange capacity, soil organic nitrogen, the soil pool of potential mineralized nitrogen, potential nitrification, phosphatase, and dehydrogenase were significantly higher in compost-treated soils after 4 or 9 years of application. The fact that the geometric mean of enzymes, a combined index of soil enzyme activities and potential nitrification rate, were higher in the compost-treated soils after 3 years of applications indicates that compost improved the capacity of soil to cleave organic compounds in the short term. Moreover, differences between treated and untreated soils in most of the soil physico-chemical properties tended to increase along the number of years since compost was applied. These increases in differences are not surprising taking into account that Mediterranean soils are generally poor in organic matter; thus, it is expected that continuous application of compost causes rapid and pronounced changes in variables directly or indirectly linked to organic matter. These results also indicate that the improvement of soil quality following compost application was not asymptotic at least for the first 16 years and, therefore, the potential for further soil quality progress exists.

4 Conclusion

Short- and long-term application of composted olive mill pomace to olive grove soils had positive effects on its physical, chemical, and biochemical properties due to the high organic matter content of this compost. The soil capacity to retain water, the water aggregate stability, soil organic carbon and nitrogen, and phosphorus and potassium availability were higher in the soil treated with compost. In addition, the soil capacity to cleave organic compounds (i.e., soil enzyme activities related to the recycling of carbon, nitrogen, and phosphorus) increased after application of this compost. Moreover, there was a clear tendency for increasing soil fertility and quality indicators according to the number of years since the first annual application of this compost. Therefore, use of composted olive mill pomace as an organic amendment in olive groves should be considered as a viable option for the safe disposal of the main waste of the olive oil industry and for the restoration of frequently degraded olive grove soils. Nevertheless, these results suggest that after the application of composted olive mill pomace, soil pH should be controlled, as after 4 years, a significant decrease in soil pH was observed.

Acknowledgments We would like to thank Jose Maria Álvarez de la Puente for the technical assistance. This project was financed by the Consejería de Agricultura y Pesca (Junta de Andalucía).

References

Albaladejo J, Martínez-Mena M, Castillo V (1994) Changes in soil physical properties induced by soil degradation. Transaction of the 15th World Congress of Soil Science, vol 2b. ISSS Publisher, Acapulco, pp 250–252

Anderson JM, Ingram JSI (1993) A handbook of methods. CAB International, Wallingford, Oxfordshire, p 221

Brunetti G, Plaza C, Mondelli D, Senesi N (2004) Reclamation of degraded soils by olive pomace amendment. Effects on soil humic acids. In: Faz A, Ortiz R, García G (eds) Ext. Abstr., Fourth International Conference on Land Degradation. Quaderma, Murcia, Spain

Cabrera F, Martín-Olmedo P, López R, Murillo JM (2005) Nitrogen mineralization in soils amended with composted olive mill sludge. Nutr Cycl Agroecosyst 71:249–258

Casida LE, Klein DA, Santoro R (1964) Soil dehydrogenase activity. Soil Sci 98:371–376

Council Directive 1999/31/EC. On landfill of waste. Official J. LI82: 1–19

Dick RP (1994) Soil enzyme activities as indicators of soil quality. In: Defining soil quality for a sustainable environment. SSSA Special Publication no. 35

García-Ruiz R, Ochoa V, Hinojosa MB, Carreira JA (2008) Suitability of enzyme activities for the monitoring of soil quality improvement in organic agricultural systems. Soil Biol Biochem 40:2137–2145

Gee GW, Bauder JW (1986) Particle-size analysis. In: Klute A (ed) Methods of soil analysis. Part 1. Physical and mineralogical methods. American Society of Agronomy, Madison, pp 383–411

Ghani A, Dexter M, Perrott KW (2003) Hot-water extractable carbon in soils: a sensitive measurement for determining impacts of fertilisation, grazing and cultivation. Soil Biol Biochem 35:1231–1243

Gómez-Muñoz B, Hatch DJ, Bol R, Dixon E, García-Ruiz R (2011) Gross and rates of nitrogen mineralisation in soil amended with composted olive mill pomace. Rapid Commun Mass Spectrom 25:1–7

Grant WT (1982) Exchangeable cations. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: chemical and microbiological properties, 2nd edn. American Society of Agronomy Inc., Wisconsin, pp 159–165

Hollis JM, Jones RJA, Palmer RC (1977) The effects of organic matter and particle size on the water-retention properties of some soils in the west midlands of England. Geoderma 17:225–238

Kandeler E (1995) Potential Nitrification. In: Schinner F, Öhlinger R, Kandeler E, Margesin R (eds) Methods in soil biology. Springer, Heidelberg, p 426

Klute A (1986) Water retention: laboratory methods. In: Klute A (ed) Methods of soil analysis, Part 1. Physical and Mineralogical Methods Soil Science Society of America, Madison, pp 635–688

Lax A, Díaz E, Castillo V, Albaladejo J (1994) Reclamation of physical and chemical properties of a salinized soil by organic amendment. Arid Soil Res Rehabil 8:9–17

Lober RW, Reeder JD (1993) Modified waterlogged incubation method for assessing nitrogen mineralization in soils and soil aggregates. Soil Sci Soc Am J 57:400–403

López-Piñeiro A, Albarrán A, Nunes JM, Barreto C (2008) Short and medium-term effects of two-phase olive mill waste application on olive grove production and soil properties under semiarid Mediterranean conditions. Bioresour Technol 99:7982–7987

Mersi WV, Schinner F (1995) Invertase activity. In: Schinner F, Öhlinger R, Kandeler E, Margesin R (eds) Methods in soil biology. Springer, Heidelberg, p 426

Molope MB, Page ER, Grieve IC (1985) A comparison of soil aggregate stability tests using soils with contrasting cultivation histories. Commun Soil Sci Plant Anal 16:315–322

Nelson DW, Sommers LE (1982) Total carbon, organic carbon, and organic matter. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: chemical and microbiological properties, 2nd edn. American Society of Agronomy, Inc., Wisconsin, pp 643–698

Olsen SR, Sommers LE (1982) Phosphorus. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: chemical and microbiological properties, 2nd edn. American Society of Agronomy, Inc., Wisconsin, pp 403–427

Paredes C, Cegarra J, Bernal MP, Roig A (2005) Influence of olive mill wastewater in composting and impact of the compost on a Swiss chard crop and soil properties. Environ Int 31:305–312

Parr JF, Papendick RI, Colacicco D (1986) Recycling of organic wastes for a sustainable agriculture. Biol Agric Hortic 3:115–130

Perez J, de la Rubia T, Moreno J, Martinez J (1992) Phenolic content and antibacterial activity of olive mill wastewater. Environ Toxicol Chem 11:489–495

Piotrowska A, Iamarino G, Rao MA, Gianfreda L (2006) Short-term effects of olive mill waste water (OMW) on chemical and biochemical properties of a semiarid Mediterranean soil. Soil Biol Biochem 38:600–610

Plaza C, Senesi N, Brunetti G, Mondelli D (2007) Evolution of the fulvic acid fractions during co-composting of olive mill wastewater sludge and tree cuttings. Bioresour Technol 98:1964–1971

Pleguezuelo CRR, Zuazo VHD, Raya AM, Martínez JRF, Rodríguez BC (2009) High reduction of erosion and nutrient losses by decreasing harvest intensity of lavender grown on slopes. Agron Sustain Dev 29:363–370

Rhoades JD (1982) Cation exchange capacity. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis: chemical and microbiological properties, 2nd edn. American Society of Agronomy, Inc., Wisconsin, pp 167–169

Saviozzi A, Biasci A, Riffaldi R, Levi-Minzi R (1999) Long-term effects of farmyard manure and sewage sludge on some soil biochemical characteristics. Biol Fertil Soils 30:100–106

Tabatabai MA (1982) Soil Enzymes. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis, part 2, chemical and microbial properties, 2nd edn. Soil Science Society of America, Madison, pp 903–947

Van Soest PJ (1963) Use of detergents in the analysis of fibrous feeds II: a rapid method for the determination of fibre and lignin. J Assoc Offic Agric Chem 46:829–835