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Evaluation of Olive Mill Waste Compost as a Soil Amendment for *Cynodon dactylon* Turf Establishment, Growth, and Anchorage

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***Abstract*. A field study evaluated composted olive mill waste (OMC) as a soil amendment in *Cynodon dactylon* (bermudagrass; C4) turf establishment and maintenance. The study comprised two substudies, each of which had discrete goals: 1) an evaluation of OMC effects on overall bermudagrass growth over the course of 2.5 years when established by seed and subsequently from sprouting of existing rhizomes (2002 to 2004); and 2) a reevaluation of OMC effects on bermudagrass establishment by seed (2003). Twenty-four plots (1.44 × 1.44 m) were filled with sandy-loam soil and supplemented with one of three OMC proportions (low= 12.5%, medium = 25%, and high = 50% by volume, indicated as substrates $S{:}OMC_L$, $S{:}OMC_M$, and $S{:}OMC_H$, respectively), and non-amended soil served as a control (S). The study evaluated: 1) the substrate's chemical and physical characteristics, including bulk density, water retention curves, pH, and electrical conductivity (EC) measurements; 2) the establishment rate of *C. dactylon*, either by seed or by sprouting of existing rhizomes after dormancy as determined by measurements that included vertical detachment force (VDF), root growth, and substrate moisture; and 3) the growth rate of *C. dactylon* as determined through measurements of visual quality, clipping dry weight, root growth, and VDF. The results show that OMC decreased substrate pH in proportion to the OMC supplementation rate and increased EC only at the end of the study and only in the plots with the highest supplementation rate ($S{:}OMC_H$). Water retention was improved by OMC incorporation except from $S{:}OMC_L$, which increased water retention only at low tensions. Compared with soil alone, bulk density decreased by 13.5%, 19.7%, and 32.8% as the OMC rate increased, respectively, from 12.5% to 50%. The OMC rate of 50% v/v resulted in a minor reduction in plant visual quality during the cold periods but in a slight improvement during the warm periods. The clipping dry weights were increased by OMC amendments in 2003, which was considered a disadvantage because of the insignificant visual quality differences between substrates during the 2 study years. In 2004, the clipping yields were unaffected by OMC rate. Root dry weight response to OMC varied. For the highest OMC rate, root dry weight was lower during the cold and wet periods, greater during the first stages of bermudagrass establishment by seed, and similar compared with soil without OMC during turf establishment from the sprouting of existing rhizomes after dormancy. The highest OMC rate reduced resistance to vertical detachment force at four sampling dates (of six) during the 2002–2003 study, because the reduced root dry weight and/or increased moisture of the substrate facilitated bermudagrass detachment. In contrast, OMC-supplemented substrates resulted in increased VDF at the first sampling date of establishment both by seed (2003) and by rhizome sprouting after dormancy (2004). It was concluded that, when speedy establishment is imperative (such as in sod farms) or when irrigation is limited, an OMC rate of 50% by volume should be selected. In contrast, for sustainable bermudagrass growth, a rate of 12.5% by volume is preferred, because it increases the visual quality of the grass and root growth.**

Substantial amounts of olive mill byproducts are produced annually in the Mediterranean region from the end of October until the end of January. Olive mill process byproducts include olive mill wastewaters (OMWW), olive stones, olive pomace, and olive leaves. The waste from olive mill processes (OMW) is considered a serious source of environmental pollution, because it is produced in large amounts during a brief period of the year that coincides with frequent and intense rainfalls. Chatjipavlidis et al. (1996) reported that, in the Messinia area in Peloponissos, which accounts for 14% of Greece olive oil production, 20,500 tons of OMWW were directly discharged into the sea without treatment. Similarly, Fiestas Ros de Ursinos and Borja-Padilla (1996) reported that 10 million m^3 of OMWW is annually produced in the Mediterranean basin, and it is estimated that solid byproducts of olive mill processes reach a volume of 6 million m^3.

The OMWW possesses phytotoxic capacities resulting from its increased carbon oxygen demand and polyphenol content (Ehaliotis et al., 1999). Several techniques such as evaporation, coagulation and flocculation, chemical oxidation, biological treatments with fungi and bacteria, and composting have been used to ameliorate the OMWW pollutant load (Ehaliotis et al., 1999). Of these techniques, the most promising bioremediation technique is the co-composting of the solid and liquid residues of the olive mill processes (Flouri et al., 1990; Mari et al., 2003), which returns some of the nutrients taken up during olive tree cultivation to the croplands (Tomati et al., 1996).

Composting and the subsequent use of olive mill byproducts (OMC) as soil amendments in agriculture have significant advantages, including a reduction in the annual amount of olive mill point source pollution to rivers, soils, and the sea; a reduction in organic loads to the landfills; and a reduction in peat use in horticulture. In addition, OMC soil amendments can increase the organic matter content in poor soils, improve soil chemical and physical characteristics (Ehaliotis et al., 1999) and increase nutrient absorption (Flouri et al., 1990).

Olive mill compost has been used for several horticultural crops with satisfying results. Ehaliotis et al. (2005) used OMC as a substrate on top of immature olive mill byproducts undergoing their thermophilic period to provide a natural means of heating cucumber (*Cucumis sativus*) cultivation in a greenhouse. The mature OMC increased soil organic matter, phosphorus and potassium availability, and cucumber productivity when applied at high rates. Garcia-Gomez et al. (2002) used compost made from the OMWW solid fraction and olive leaves. These researchers used the compost in different proportions with either peat or a commercially produced substrate made from composted grape marc to evaluate *Calendula officinalis* var. nana Bon-Bon and *Calceolaria herbeohybrida* var. C. Dainty growth. They concluded that OMC could be mixed up to 50% with either peat or the commercially produced substrate for the salt-tolerant species calendula, whereas for less tolerant species such as calceolaria, OMC supplementation should not exceed 25%.

Papafotiou et al. (2004, 2005) investigated the potential use of OMC as a partial replacement for peat in potted poinsettia plants and three other foliage plants. The authors found that OMC could replace up to 25% of peat for poinsettia (*Euphorbia pulcherrima*) and *Sygonium podophyllum* and up to 75% of peat for *Codiaeum variegatum* and *Ficus benjamina*.

In turfgrass culture, OMC has been tested in laboratory studies and under field conditions. In a field study, Constantinou et al. (1997) tested composted olive stone and chicken manure as potential soil amendments for sports

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turfs. The compost from olive stone was used at a single application rate (75% sand, 10% olive pit, and 15% native silty clay soil) and resulted in the best performance for the turf mixture's growth (20% *Lolium perenne*, 15% *Cynodon dactylon*, 50% *Festuca arundinacea*, and 15% *Poa pratensis*). The composted olive stone-amended substrate improved turf visual quality, color, shoot density, uniformity, and coverage. Alburquerque et al. (2007) in a controlled pot study investigated nutrient absorption by *Lolium perenne* that was grown in a variety of compost and fertilizer treatments and found that OMC increased ryegrass fresh weight. Montemurro et al. (2004) compared treated and untreated OMWW and OMC applications (olive pomace, poultry manure, and wheat straw in a proportion of 82%, 10%, and 8%, respectively) used as topdressing materials in field lysimeters turfed with *L. perenne*. They found that OMWW increased the cumulative clipping dry weight in both years of study, but OMC did not promote shoot growth as much.

Based on all of the mentioned evidence, the use of OMC as an organic amendment seems promising for horticultural uses. Therefore, the aims of the present study were: 1) to evaluate the effects of co-composted olive byproducts on selected soil properties as well as the establishment, growth, and quality of *Cynodon dactylon* monostand; and 2) to determine the best OMC rate for the specific turfgrass species.

Materials and Methods

The study, performed at the Agricultural University of Athens, comprised 24 plots arranged in a completely randomized design. Each plot was square in shape (1.44 m × 1.44 m), resulting in a total surface area of 2 m^2 per plot. The whole experimental area was 7 m × 7 m, and the central plot was not used in the study. Wooden boards (50 mm width × 250 mm height) were used to isolate each plot and prevent mechanical and hydrological continuity from occurring between adjacent plots and with the surrounding area.

The plots were equipped with three drainage trenches filled with perforated drainage pipe and gravel. The trenches and the whole surface of the study area were lined with a uniform drainage gravel layer with a depth of 10 cm. Irrigation was performed with nine static sprinklers (Rain Bird, US-400 UNI Spray with 12-VAN Series Nozzles; Bratis Bros Ltd, Athens, Greece) placed 3.5 m apart to secure uniform coverage of irrigation.

Table 1. Particle size distribution of olive mill compost.

Particle size distribution	
Millimeters	Percent
Greater than 4	2.1
4–2	28.9
2–1	38.8
1–0.5	15.3
0.5–0.25	9.7
0.25–0.10	3.9
0.10–0.05	0.9
Less than 0.05	0.4
Total	100.0

The experimental plots were filled to a depth of 0.25 m with the appropriate substrates that included different proportions of sandy loam soil [78.9% sand, 8.0% silt, 13.1% clay, 0.168% (w/w) organic mater, and a cation exchange capacity of 6.23 cmols·kg^{-1}] and OMC. The OMC was commercially produced from cocomposting olive stones, olive leaves, and olive mill wastewater by Messiniaki I.C.S.A. (Kalamata, Greece). The olive mill compost particle size distribution and chemical characteristics are listed in Tables 1 and 2. The substrates were created by uniformly mixing the sandy loam soil and OMC using a concrete mixer. The mixing proportions were: 1) 100% sandy loam soil (S) which served as the control; 2) S mixed with OMC at a low (L) proportion of 87.5:12.5% (v/v) (S:OMC$_L$); 3) S mixed with OMC at a medium (M) proportion of 75:25% (v/v) (S:OMC$_M$); and 4) S mixed with OMC at a high (H) proportion of 50:50% (v/v) (S:OMC$_H$).

During 2002, the whole area of each plot was used for evaluating OMC effects on bermudagrass establishment by seeding (Study A). In 2003, each experimental plot was divided in half with one section being used to evaluate bermudagrass growth from rhizome sprouting (continuation of Study A), whereas the other section was used to replicate establishment through seeding (Study B). In 2004, measurements were performed only in the Study A section for evaluating bermudagrass growth from rhizome sprouting for a second year. More specifically, the plots were sown on 6 Aug. 2002 (Study A) with *C. dactylon* var. Princess 77 at a rate of 9 g·m^{-2} and maintained until 31 Dec. 2004. To replicate the establishment study in the following year, half of the sod was

Table 2. Chemical properties of the olive mill compost at the initiation of the study.

Parameter	Value	Method of analysis
pH	6.64	Consort C 835 multichannel analyzer in a 1:2 (v:v) compost/water slurry
Electrical conductivity (μS·cm^{-1})	8,750	Consort C 835 multichannel analyzer in a 1:2 (v:v) compost/water slurry
Organic matter (%)	87.60	Loss on ignition method (LOI)
Total nitrogen (%)	2.93	Kjeldahl method
NH$_4$ (mg·kg^{-1})	19.60	Colorimetrically using a Hitachi U2001 spectrophotometer (Hitachi High-Technologies Corporation, Tokyo, Japan)
Total phosphorus (%)	0.17	Colorimetrically using a Hitachi U2001 spectrophotometer
Phosphorus extractable (mg·kg^{-1})	36.79	Colorimetrically using a Hitachi U2001 spectrophotometer
Total potassium (%)	0.664	Atomic absorption spectrophotometry (GBC 932A/A) (GBC Scientific Equipment Pty Ltd, Victoria, Australia)
Total calcium (%)	1.89	Atomic absorption spectrophotometry (GBC 932A/A)
Total magnesium (%)	0.187	Atomic absorption spectrophotometry (GBC 932A/A)
Total sodium (%)	0.033	Atomic absorption spectrophotometry (GBC 932A/A)
Exchangeable potassium (mg·kg^{-1})	9,406	Measuring the extractions of the dried compost samples (extracted with a 1 *M* NH$_4$OAc (ammonium acetate) solution at pH =7.00)
Exchangeable calcium (mg·kg^{-1})	4,714	Measuring the extractions of the dried compost samples (extracted with a 1 *M* NH$_4$OAc (ammonium acetate) solution at pH =7.00)
Exchangeable magnesium (mg·kg^{-1})	1,322	Measuring the extractions of the dried compost samples (extracted with a 1 *M* NH$_4$OAc (ammonium acetate) solution at pH =7.00)
Exchangeable sodium (mg·kg^{-1})	402	Measuring the extractions of the dried compost samples (extracted with a 1 *M* NH$_4$OAc (ammonium acetate) solution at pH =7.00)
Total iron (mg·kg^{-1})	1,142	Atomic absorption spectrophotometry (GBC 932A/A)
Total manganese (mg·kg^{-1})	34.6	Atomic absorption spectrophotometry (GBC 932A/A)
Total zinc (mg·kg^{-1})	32.0	Atomic absorption spectrophotometry (GBC 932A/A)
Total copper (mg·kg^{-1})	33.5	Atomic absorption spectrophotometry (GBC 932A/A)
Total boron (mg·kg^{-1})	34.5	Atomic absorption spectrophotometry (GBC 932A/A)

removed from each plot along with the whole depth of the substrate (0.25 m) to prevent shoot emergence from the dormant bermudagrass rhizomes. A vertical plastic divider was placed in the middle of the plot to prevent mechanical and hydrological continuity between established sod and newly seeded parts within each plot. Then, the empty half of each plot was filled with the appropriate mixture of soil and OMC and seeded on 25 June 2003 (Study B) in the exact manner as in Study A. In this way, half of each plot was used to evaluate bermudagrass establishment after seeding while the other half to evaluate regrowth from rhizomes after winter dormancy. In Spring 2004 (just before the end of dormancy), the aboveground plant parts (stems, leaves, and thatch) were removed to ground level from the whole plot. Then, bermudagrass was left to grow from the existing rhizomes to evaluate OMC effects on its growth and measurements were performed only in the Study A section.

Plots were fertilized with granular fertilizer (Complesal 12-12-17, having 6.5% as NH_4^+-N and 5.5% as NO_3^--N; 12N–5.2P–14.1K–1.2Mg–8.0S; Agrevo Hellas S.A., Athens, Greece). Granular fertilizer applications were applied at approximately monthly intervals during the growing season at a rate of 50 $g \cdot m^{-2}$ except from the last fertilization of the season (October) when the application rate was 25 $g \cdot m^{-2}$. In Study A, fertilizer application totaled 15 nitrogen (N), 6.6 phosphorus (P), and 17.7 potassium (K) ($g \cdot m^{-2}$) in 2002 during the establishment by seed (three applications over the 3 months of growth since bermudagrass was sown in August), whereas in 2003 and 2004 growing seasons, fertilizer application concerning Study A was 33 N, 14.5 P and 38.9 K ($g \cdot m^{-2}$) (six applications over the 7 months of growth). In 2003, for the re-evaluation of bermudagrass establishment by seed (Study B), fertilizer application totaled 21 N, 9.24 P, and 24.7 K ($g \cdot m^{-2}$) (four applications over the 5 months of growth since bermudagrass was sown in June). Plots were irrigated as needed to prevent moisture stress. Air temperature and precipitation were monitored by the weather station of the Laboratory of General and Agricultural Meteorology of the Agricultural University of Athens located 20 m away from the experimental plots (Fig. 1).

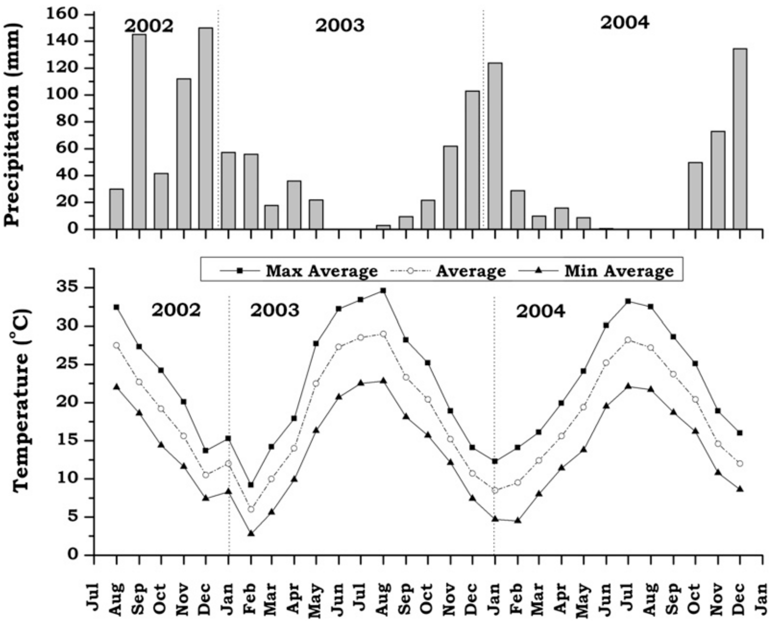

Fig. 1. Monthly average, maximum and minimum air temperature and monthly precipitation as recorded by the weather station (Laboratory of General and Agricultural Meteorology, Agricultural University of Athens).

The evaluation of OMC soil amendment effects on bermudagrass establishment and growth was performed through turf visual quality ratings, clipping yields, root growth, and vertical detachment force measurements. In addition, substrate properties were also evaluated and included water retention curves, bulk density, pH, EC, and soil moisture (determined during the vertical detachment force measurements).

Turfgrass visual quality ratings were assessed from Study A section in 2003 and 2004 on a scale of 1 to 9 (1 = dead, 9 = ideal, and 6.5 = minimum acceptable turf quality) taking into account color, uniformity, texture, and density. Visual quality assessments were performed on monthly or bimonthly intervals, depending on bermudagrass growth.

Monitoring of sward growth was accomplished by removing clippings from an area of 0.35 m^2 using an electric lawnmower (ASM32 Bosch; Robert Bosch GmbH, Stuttgart, Germany). Bermudagrass was mowed at a height of 30 mm at biweekly intervals in 2002 (Study A) and 2003 (Studies A and B) and twice a week in 2004 (Study A). Clippings were collected from Study A in 2002 (seeded) and 2003–2004 (rhizome sprouting) and from Study B (re-evaluation of seeding) in 2003. Clippings were oven-dried for 48 h at 75 °C for dry weight determinations. After the collection of clipping samples, the whole experimental site was uniformly mowed to the same height of 30 mm.

Root sampling was performed with a soil sampler (48-mm internal diameter) that removed soil cores from the whole profile depth (0.25 m). The root system was washed off carefully from the substrate using a metal screen and pressurized water. The root parts were collected from the screen and oven-dried for 48 h at 75 °C. The dried roots were then weighed on an electronic balance to the fourth decimal place (Mettler PJ3600 DeltaRange; Mettler Instruments, Zurich, Switzerland).

The establishment rate and growth of bermudagrass were also monitored using the VDF technique according to Nektarios (2005). Six stainless steel metal frames (160 mm × 160 mm × 20 mm) with a grid (10-mm aperture size) were buried into the substrates and leveled with the soil surface. The plots were then seeded (Years 2002 and 2003) or left to be turfed by rhizome growth after dormancy (Year 2004). Then, on every sampling date, one metal frame from each plot was pulled with a pulley to detach the frame and its sod from the plot. The vertical detachment force was determined through an "S-type" load cell (LC101; Omega Engineering Limited, Manchester, U.K.) connected to a digital indicator (DP41-S; Omega Engineering Limited). The VDF was determined as the maximum value that occurred before the detachment of the turf after subtracting the weights of the frame, detached soil, and sod. Vertical detachment force measurements were performed simultaneously with root sampling and soil moisture determinations to obtain useful correlations between measurements (Nektarios, 2005).

Substrate moisture was determined using a 16-cm long TDR probe (P2G; TRIME FM, Ettlingen, Germany) that was inserted adjacent to each detached frame at the time of VDF determination. The soil volume sampled using this specific probe was a cylinder of 16 cm depth × 8.8 cm diameter.

Substrate EC was determined in a water saturated paste, and pH was determined in a 1:1 soil:water solution. Bulk density was determined on substrate cores removed from the entire depth of each substrate (0.25 m) with a 48-mm diameter soil sampler. Water retention curve was determined for each substrate in disturbed samples using Buchner funnels from 0 to 9.81 kPa tension (Richards, 1949).

Experimental units were arranged in a completely randomized plot design. Analysis of variance was performed on the data collected with the JMP® Version 8 statistical software (SAS Institute Inc., Cary, NC). For the cumulative clipping dry weight, a repeated measurements model was used with OMC treatments as the main plots and time (sampling dates) as the subplots. For all other measurements (turf visual quality, root growth, VDF, and substrate moisture), the main research interest was focused on OMC effects within each separate sampling date. Therefore, statistical analyses were performed using analysis of variance (JMP® Version 8 statistical software) to compare OMC effects within each separate sampling date. Treatment means for all statistical analyses were compared using the Fisher's protected least significant difference at a probability level of $P < 0.05$.

Results and Discussion

Soil physical and chemical characteristics. At the initiation of the study, substrate pH decreased proportionally with the OMC supplementation rate as a result of the relatively low pH of the OMC (6.64). This trend remained unaltered through the end of the study (Table 3). There was a pH increase in all substrates in Year 2003, and pH then decreased to the initial values in the next year (2004).

The EC was relatively low and was similar for all substrates at the start of the test period but exhibited a continuous increase throughout the study with no significant differences among the four substrates (Table 3). At the termination of the study, substrate S:OMC$_H$ had an EC that was significantly higher than that of the other substrates. The overall increase in the ECs of all four substrates in the second year and at the end of the study was probably the result of the accumulation of salts from fertilizers and irrigation water in conjunction with a lack of rainfall during the summer of 2004. The higher EC in substrate S:OMC$_H$ was attributed to its increased water retention, which caused a slower leaching of salts compared with that caused by the other substrates.

Table 3. Bulk density, pH, and electrical conductivity (EC) alteration for substrates: 1) 100% sandy loam soil (S); 2) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); 3) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and 4) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$).[z]

	pH			EC (dS·m^{-1})			
Substrate	24 Oct. 2002	12 June 2003	1 Aug. 2005	24 Oct. 2002	12 June 2003	1 Aug. 2005	Bulk density (kg·m^{-3})
S	7.94 a	8.19 a	7.63 a	1.76	1.93	3.63 b	1490 a
S:OMC$_L$	7.61 ab	8.14 ab	7.45 b	1.73	2.03	3.87 b	1289 b
S:OMC$_M$	7.37 bc	7.76 bc	7.12 c	1.82	1.95	3.37 b	1197 c
S:OMC$_H$	7.08 c	7.54 c	6.88 d	1.91	1.95	4.90 a	1002 d

[z] Values are the mean of three replicates. Means in columns followed by the same letter are not significantly different at a probability level of $P < 0.05$.

OMC = olive mill waste.

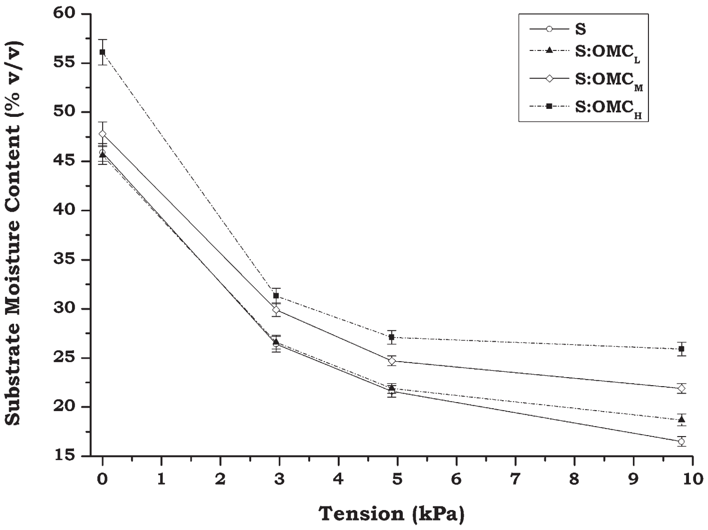

Fig. 2. Moisture characteristic curve of substrates as affected by OMC amendments: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$). Values are the means of three replicates (± SE). OMC = composted olive mill waste.

Soil supplementation with OMC had beneficial effects on most of the physical characteristics of the soil. More specifically, OMC amendments substantially reduced the bulk density of the soil as a result of the much lower bulk density of OMC. The reductions, compared with the non-amended soil (S), were 13.5%, 19.7%, and 32.8% for S:OMC$_L$, S:OMC$_M$, and S:OMC$_H$, respectively (Table 3). The water retention capacity of a substrate increased at 50% and 25% OMC supplementation, whereas the 12.5% OMC substrate only increased water retention at –9.81 kPa tension. The S:OMC$_H$ substrate had greater water retention than did the other substrates at all tension levels (from 0 to 9.81 kPa) except at –2.94 kPa tension. At –2.94 kPa tension, its water retention was similar to that of S:OMC$_M$ (Fig. 2). Substrate S:OMC$_M$ retained more water compared with substrate S:OMC$_L$ and the non-amended control (S). In contrast, substrate S:OMC$_L$ had identical water retention compared with the non-amended control at all tensions except the –9.81 kPa tension in which the S:OMC$_L$ retained 2.2% more moisture than the S. More specifically, the augmentation of water retention capacity of the mixes with OMC can be attributed more to the inherent water-holding capacity of the OMC itself rather than to the redistribution of the pore size and space of the soil mixes. Based on the particle size distribution of OMC (Table 1), it is obvious that OMC is a coarse-textured material with more than 85% of its particles ranging in size from 0.5 to 4 mm. With this particle distribution, if OMC did not possess the capacity to absorb water, it would be expected to reduce the water-holding capacity of the soil mixes. These findings are similar to those of Johnson et al. (2006) that used composted dairy manure as topdressing material after aeration on *Poa pratensis* turf. They found that topdressing rate of 99 and 66 m^3·ha^{-1} increased volumetric water content of the substrate, whereas the low application rate of 33 m^3·ha^{-1} had similar water content with the control soil. However, in our case, the data were limited to –9.81 kPa tension, whereas Johnson et al. (2006) extended their measurement range up to –1500 kPa.

Visual quality ratings. In both study years, the visual quality ratings of bermudagrass increased starting in mid-April and reached the minimal acceptable quality of 6.5 by late May. However, in 2004, the visual quality ratings were significantly higher than in 2003 (average of 6.24 and 7.41 for Years 2003 and 2004, respectively, $P < 0.001$; Fig. 3). This difference was attributed to the increased frequency of mowing in 2004 (Beard, 1973). During the 2-year study, the differences in visual quality among the four substrates were minimal but were found to be statistically significant for seven dates. On five of those seven dates, substrate S:OMC$_H$ treatments had inferior visual quality ratings compared with those of the other substrates. These dates were either in the spring (13 and 26 Apr. 2003 and 15 May 2004) or in the winter (6 and 21 Dec. 2004). In contrast, bermudagrass grown in S:OMC$_H$ and S:OMC$_L$ had higher visual quality ratings on 11 May 2003 and 13 June 2004. Despite the small size of the visual quality differences, it is interesting to note that, during the cold periods of the study, substrate S:OMC$_H$ provided lower turf visual quality ratings. In contrast, during the warm periods of the study (May 2003 and June 2004), substrate S:OMC$_H$ improved the visual quality of the turf. These results could be explained by the bulk density and water-holding capacity of the four substrates (Fig. 2). More specifically, the increased water retention of OMC-amended substrates is expected to retard substrate heating and cooling in cold periods as a result of the increased heat capacity of water. Similarly, the reduced bulk density of OMC-amended substrates is expected to moderate heating and cooling of the substrate as a result of low thermal conductance and diffusivity of the substrate (Hillel, 1998; Tsiotsiopoulou et al., 2003). As a result, when the ambient temperature was low (e.g., in April; Fig. 1), the S:OMC$_H$ substrate could have moderate substrate heating and cooling as a result of both the reduced bulk density and the increased water-holding capacity. Thus, bermudagrass growth that broke through dormancy was retarded because dormancy is a temperature-controlled physiological procedure.

In contrast, when the ambient temperature increased, (e.g., in June; Fig. 1), the OMC-amended substrates promoted bermudagrass growth and quality because temperature was increased and therefore water availability became more important. Angle et al. (1981) evaluated the use of sludge compost as a soil amendment for a *P. pratensis* and *F. rubra* turf mixture and reported a steady increase in turf quality as the proportion of compost in the mix increased from 0 to 360 to 720 mT·ha^{-1}. Similarly, Linde and Hepner (2005) reported that increasing the sewage sludge compost proportion (249, 510, and 759 m^{3}·ha^{-1}) that was tilled into the soil improved the cover, color, and density of *P. pratensis* that was established by seeding and that the beneficial effects lasted and improved during the 2 study years.

Cumulative clipping dry weight. In both study years, turfgrass yielded clippings starting in late May and ending in late November. In 2004, the clipping yield was significantly increased compared with 2003 (total of 258.0 g·m^{-2} and 861.5 g·m^{-2} for Years 2003 and 2004, respectively, $P < 0.001$; Fig. 4). This increase was probably caused by the more frequent mowing in 2004. Beard (1973) summarized the effects of mowing frequency on turfgrass growth reported across several literature sources and concluded that increasing the mowing frequency increased shoot density but decreased shoot growth. In our case, it seems that the expected increase in shoot density was more significant compared with the expected reduction in shoot growth because the clippings yield in 2004 was 2.5 times more than the 2003 yield.

Differences between the 2 study years were also observed with respect to the clipping yield response of the four tested substrates, because in 2003, the yield increased in proportion to the OMC supplementation rate, but in 2004, there were no differences among the four substrates (Fig. 4). More specifically, in 2003, for substrate S:OMC$_{\text{H}}$, the clipping yield was greater than that for the non-amended control (S) from early July until the end of November. In addition, the clipping weights of S:OMC$_{\text{H}}$ plots were greater than those of S:OMC$_{\text{M}}$ from early August until the end of November. The abrupt increase in clipping yield from S:OMC$_{\text{H}}$ in late June 2003 is shown by the steep slope of the line showing the cumulative clipping yield over time (from 7 to 24 June 2003; Fig. 4) and was in accordance with the improved turf visual quality rating for S:OMC$_{\text{H}}$ (on 11 June 2003; Fig. 3). The lack of any further differences in clipping yield in summer was indicated by the similar slopes of cumulated clipping yield over time for the substrates and resulted in similar turf visual quality ratings (Figs. 3 and 4). The total yield of S:OMC$_{\text{H}}$ was 31.8% more than that of the non-amended control (S). The temporal replication of bermudagrass establishment by seed (Year 2003) provided clipping yield that was proportional to OMC supplementation with S:OMC$_{\text{H}}$ providing the greatest shoot growth, S:OMC$_{\text{M}}$ and S:OMC$_{\text{L}}$ providing moderate shoot growth, and the non-amended control (S) providing the least shoot growth (Fig. 5).

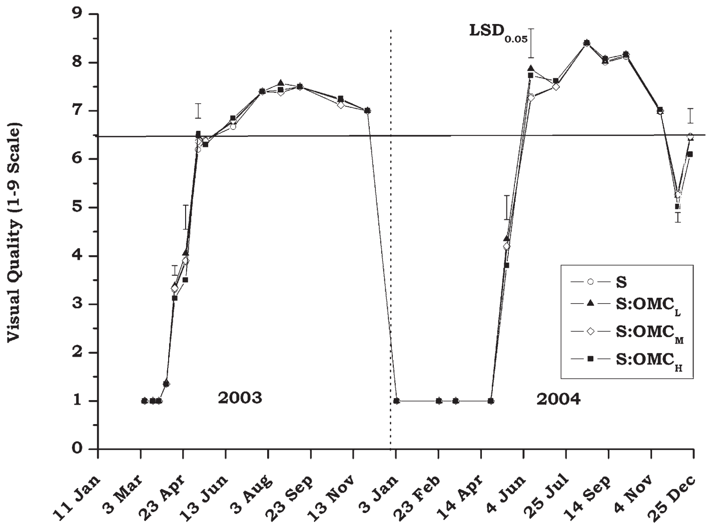

Fig. 3. Visual quality ratings (scale is from 1 to 9 with 1 = dead turf, 9 = ideal turf, and 6.5 = minimum acceptable quality) of *C. dactylon* turf as affected by OMC amendments (Study A): (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_{\text{L}}$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_{\text{M}}$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_{\text{H}}$). Values are the means of six replicates. Bars represent the Fisher's protected least significance differences (LSDS) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

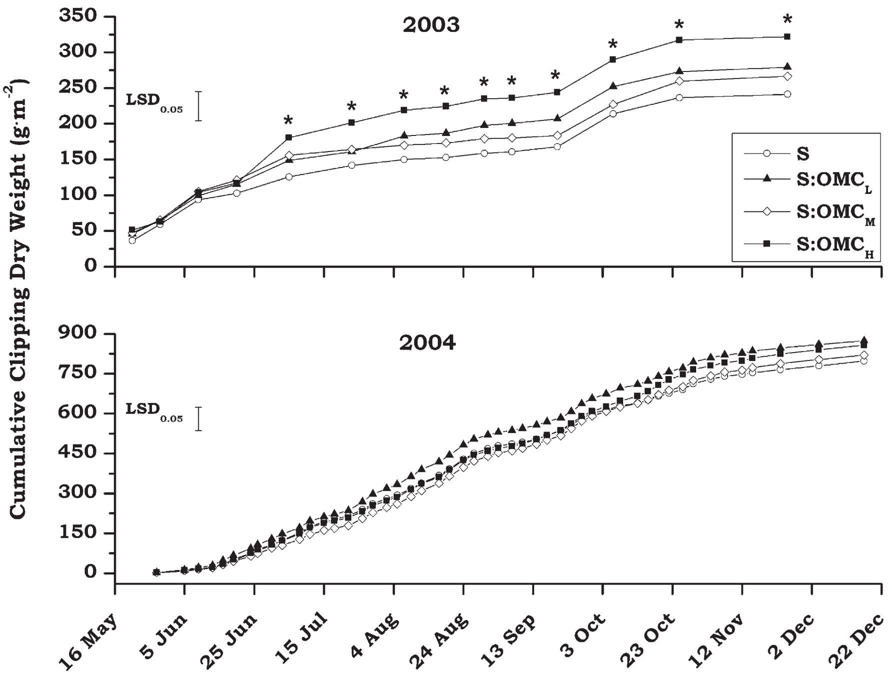

Fig. 4. Clippings' dry weight (g·m^{-2}) of *C. dactylon* turf during the 2 study years (2003 and 2004) as affected by OMC amendments (Study A): (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_{\text{L}}$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_{\text{M}}$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_{\text{H}}$). Values are means of six replicates. Bar represent the Fisher protected least significance difference (LSD) at a probability level $P < 0.05$ using the repeated measures model. Asterisk (*) indicates the dates that substrate means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

The growth response of turfgrass to composted soil amendments seems to vary depending on the type of compost, turfgrass species, application rate, and time since application. Angle et al. (1981) found an increased clipping yield when using sewage sludge compost at an incorporation rate up to 720 mT·ha^{-1}. For forage bermudagrass, Muir et al. (2010) found an increased dry matter yield during the first year of composted dairy manure application at

18, 36, and 72 Mg·ha^{-1} without inorganic N input. However, in the second year, only the highest application rate of 72 Mg·ha^{-1} increased dry matter production, whereas the use of inorganic fertilizer applications provided similar yields between compost amended and non-amended control. Brink et al. (2002) found that broiler litter compost increased bermudagrass dry matter in proportion to its application rate over 2 years of study.

Root dry weight. Bermudagrass root dry weight followed a typical curve for C_4 turfgrasses by initiating its growth in March, peaking in summer and fall, and reducing its growth in December as a result of the induction of dormancy. However, root dry weight was more than doubled in Year 2003 compared with 2004 (Fig. 6). The twofold increase in Year 2003 was attributed to the decreased clipping yield of that year, because it is known that increased defoliation by mowing depletes carbohydrate reserves and decreases root dry weight (Crider, 1955). In addition, root dry weight has been found to increase when mowing frequency is reduced (Beard, 1973; Crider, 1955).

Differences in bermudagrass root dry weight between the substrates were evident only during the dormancy period (February to April), during which S had more root growth, compared with that of the other substrates, in both study years. On those sampling dates, the trend in bermudagrass root growth was inversely related to the OMC supplementation rate (Fig. 6). This trend can be explained by the fact that the OMC-amended substrates retained more water during winter, and therefore, they are expected to either retard substrate heating and cooling and/or to be prone to hypoxic conditions. Both low temperature and hypoxia are known to increase turf root senescence, although bermudagrass is considered to be among those turfgrass species that are most tolerant of waterlogged conditions (Beard, 1973; Tan et al., 2010).

In contrast, OMC-supplemented substrates provided increased root dry weight in Study B (the replication of bermudagrass establishment through seeding), which took place in the summer (Fig. 7). These differences were significant during the first three sampling dates (8, 22, and 31 Aug. 2003). On those dates, substrate S:OMC$_H$ provided the greatest root growth, whereas substrates S:OMC$_M$ and S:OMC$_L$ provided moderate root growth, and the non-amended control provided the least root growth. The trend in root dry weight was similar in subsequent sampling dates for the four substrates, but the differences were not significant. The differences in between-treatment responses concerning bermudagrass root dry weight between years can be explained on the basis of the seeding times (6 Aug. in Year 2002, Fig. 6, and 25 June in Year 2003, Fig. 7). The increased soil moisture retained by OMC-supplemented substrates may have facilitated and promoted greater germination, seedling emergence, and growth of turf for soil amended with the highest OMC rate during 2003, when bermudagrass establishment was initiated in early summer. In contrast, OMC water retention did not provide any advantage concerning root dry weight for the highest OMC rate in 2002, because the August seeding was followed by September's lower temperatures and the occurrence of rainfall events.

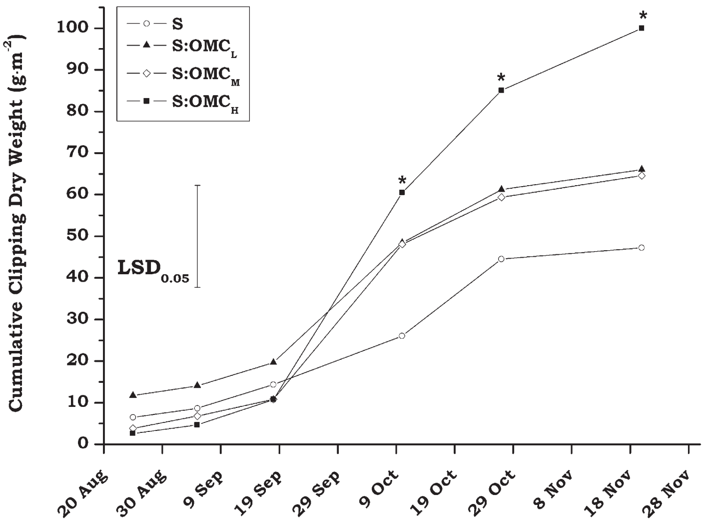

Fig. 5. Clippings' dry weight (g·m^{-2}) of *C. dactylon* turf during re-establishment (2003, Study B) as affected by OMC amendment: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$). Values are means of six replicates. Bar represent the Fisher protected least significance difference (LSD) at a probability level $P < 0.05$ using the repeated measures model. Asterisk (*) indicates the dates that substrate means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

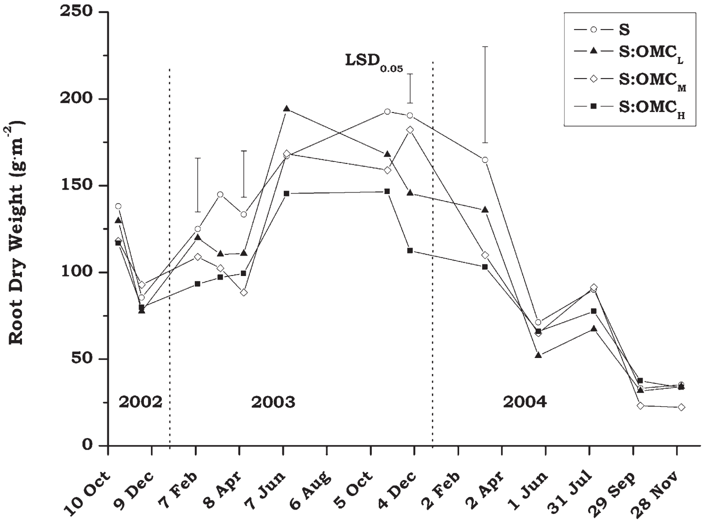

Fig. 6. Root dry weight (g·m^{-2}) of *C. dactylon* turf (2002–2004) as affected by OMC amendments (Study A): (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$). *Cynodon dactylon* was established by seeding (6 Aug. 2002), and re-growth after dormancy was accomplished through existing rhizomes in 2003 and 2004. Values are the means of six replicates. Bars represent the Fisher's protected least significance differences (LSDs) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

Anchorage. The vertical detachment force measurements differed between the 2 study years as a result of the different seeding times. The first seeding was performed on 6 Aug. 2002, and VDF was used to evaluate the fluctuation in bermudagrass strength over the course of the season (Fig. 8). For this year, six frames of bermudagrass turf were pulled to detachment from the substrates over the course of 8 months. In contrast, the second seeding was performed on 25 June 2003, and its VDF measurements were used to evaluate bermudagrass strength immediately after seeding and during an establishment period of 3 months (Fig. 9). The third set of VDF measurements determined root anchorage when bermudagrass was established

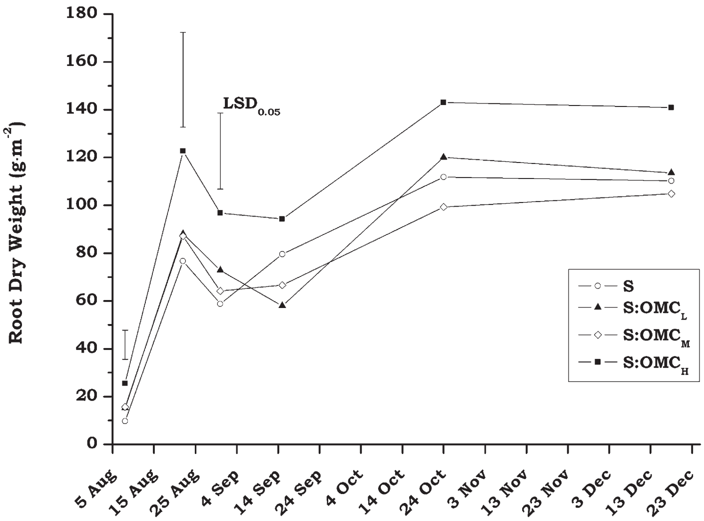

Fig. 7. Root dry weight ($g·m^{-2}$) of *C. dactylon* turf during the re-evaluation of establishment from seed (Study B, seeding date 25 June 2003) as affected by OMC amendments: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v ($S:OMC_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v ($S:OMC_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v ($S:OMC_H$). Values are the means of six replicates. Bars represent the Fisher's protected least significance differences (LSDS) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

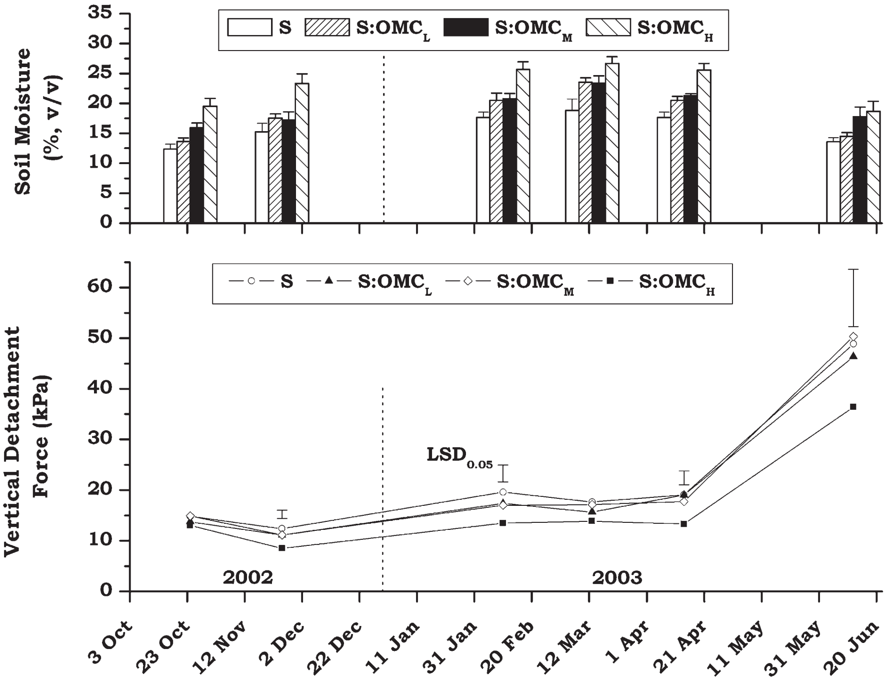

Fig. 8. Vertical detachment force (kPa) of *C. dactylon* turf and substrate moisture (% v/v) during Study A (2002–2003) as affected by OMC amendments: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v ($S:OMC_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v ($S:OMC_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v ($S:OMC_H$). Values are the means of six replicates. Bars represent the Fisher's protected least significance differences (LSDS) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

from existing rhizomes that sprouted after dormancy (Fig. 10).

In 2002–2003 (Study A), the VDF was low (less than 15 kPa) during the whole dormancy period, but it increased substantially by the last sampling date (12 June 2003) and reached 51, 49, 45m and 35 kPa for $S:OMC_M$, S, $S:OMC_L$, and $S:OMC_H$, respectively (Fig. 8). Differences between substrates were detected for four dates (25 Nov. 2002; 10 Feb., 14 Apr., and 12 June 2003); the VDF for $S:OMC_H$ was lower than that for all of the other substrates (Fig. 8). The cause of the VDF reduction by $S:OMC_H$ was twofold: 1) on two dates, the VDF reduction coincided with reduced root dry weight in the $S:OMC_H$ substrate (10 Feb. and 14 Apr. 2003; Fig. 6); and 2) the increased moisture of the $S:OMC_H$ substrate that acted as a lubricant and facilitated the detachment of the sod (Nektarios, 2005).

In the 2003 re-establishment study by seed (Study B), the VDF steadily increased from August until the end of October (Fig. 9). However, in this case, a significant difference was detected between the substrates only once (at the first sampling date, 8 Aug. 2003). On this date, the OMC-amended substrates had greater VDFs than did the non-amended control. The observed differences in VDFs correlated well to difference in root growth, but the differences were greater for the root dry weight measurements (Fig. 7) compared with the VDF measurements. Subsequent root dry weight differences between substrates may not have been detected, because the increased substrate moistures could have hindered or minimized the translation of root dry weight differences into VDF measurements (Nektarios, 2005). This was probably true for substrate $S:OMC_H$. Substrate $S:OMC_H$ had the highest root dry weight at the first three sampling dates (Fig. 7) but had similar VDF measurements to the other substrates, because its increased moisture content reduced its VDF (Fig. 9).

In 2004, $S:OMC_L$, S, and $S:OMC_H$ substrates had greater VDFs than did the $S:OMC_M$ substrate on only the first sampling date (12 June 2004) during the evaluation of bermudagrass turf establishment from the sprouting of existing rhizomes (Fig. 10). In this case, the root dry weight was similar for all substrates (data not presented), and thus the observed difference could not be correlated to root dry weight.

Weed encroachment. In the spring of 2003 and at the end of the dormancy period, the noxious weed *Conyza albida* was observed in the experimental plots. *Conyza albida* has been reported to constitute an emerging threat for turfgrass cultures (Economou et al., 2007). It is certain that *C. albida* was not transported through the addition of OMC, because the OMC was found clear of any kind of weed species in preliminary laboratory testing. It was noticed that *C. albida* was more prolific in the OMC-amended plots, and its population density increased as the amount of the OMC supplementation increased (Table 4). However, in the following years, the *C. albida* population was diminished in all plots.

It is suspected that the invasion of *C. albida* was related to the increased moisture of the OMC-amended plots. Even though it has been proven that *C. albida* imposes different degrees of allelopathic effects on C_3 turfgrass species (Economou et al., 2007), this has not been substantiated for bermudagrass.

Conclusion

Olive mill waste compost can be used as a substrate amendment for bermudagrass growth and establishment. Although OMC additions were found to clearly reduce bulk density and pH and increase moisture retention,

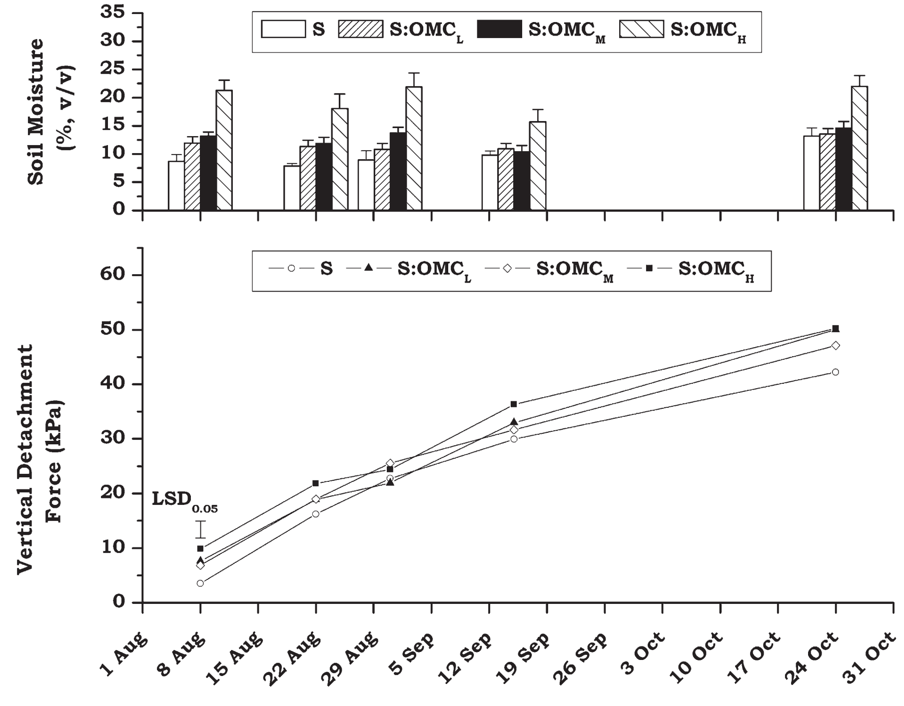

Fig. 9. Vertical detachment force (kPa) of *C. dactylon* turf and substrate moisture (% v/v) during the re-evaluation of establishment (Study B, 2004) as affected by OMC amendments: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$). Values are the means of six replicates. Bar represent the Fisher's protected least significance difference (LSD) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

Table 4. Quantification of *Conyza albida* weed invasion (6 May 2003) as affected by the substrates: 1) 100% sandy loam soil (S); 2) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); 3) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and 4) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$).^{z}

Substrate	*C. albida* Plant number/m^2
S	14.58 c
S:OMC$_L$	20.92 bc
S:OMC$_M$	27.50 b
S:OMC$_H$	48.00 a

^{z}Values are the mean of six replications. Means in column followed by the same letter are not significantly different at a probability level of $P < 0.05$.
OMC = composted olive mill waste.

effects on plant growth differed between the establishment and maintenance periods.

In cases in which the speed of establishment is of major importance such as in sod farms, substrate S:OMC$_H$ could be used, because it provided the best initial rooting as well as the highest initial resistance to vertical detachment. Substrate S:OMC$_H$ should also be recommended in cases in which irrigation is limited, because it has higher water-holding capacity. In contrast, for sustainable bermudagrass growth, substrate S:OMC$_L$ is recommended, because it produced reduced clipping yields that would require reduced maintenance and disposal needs while at the same time improving the turf visual quality and root growth.

When irrigation and fertilization are sufficiently supplied, it seems that an OMC amendment is not necessary for bermudagrass grown on a sandy loam soil. Under those conditions, the non-amended soil provided the greatest root dry weight and resistance to vertical detachment along with a reduced clipping yield without any decrease in visual quality ratings. However, further research should proceed to evaluate the capacity of the amended substrates under water deficits and under traffic conditions.

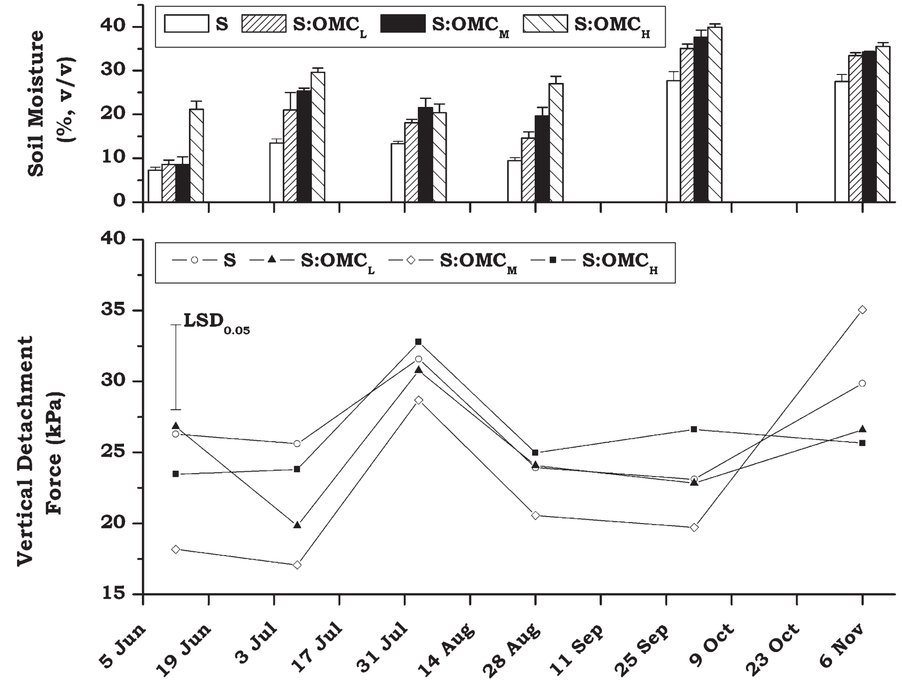

Fig. 10. Vertical detachment force (kPa) of *C. dactylon* turf and substrate moisture (% v/v) during and after establishment from rhizome sprouting after dormancy (Study A, Year 2004) as affected by OMC amendments: (**A**) 100% sandy loam soil (S); (**B**) sandy loam soil amended with OMC at a proportion of 7:1 v/v (S:OMC$_L$); (**C**) sandy loam soil amended with olive mill compost at a proportion of 3:1 v/v (S:OMC$_M$); and (**D**) sandy loam soil amended with olive mill compost at a proportion of 1:1 v/v (S:OMC$_H$). Values are the means of six replicates. Bar represent the Fisher's protected least significance difference (LSD) when treatment means are significantly different at a probability level of $P < 0.05$. OMC = composted olive mill waste.

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