Natural volcanic tuff as a soil mulching: effect on plant growth and soil chemistry under water stress

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Abstract

Efficient water management in agricultural sector necessitates the manipulation of all possible options for water supply and demand management methods. The purpose of this study was to determine the usefulness of using natural volcanic tuff as a soil mulching on plant and soil properties under different water levels. The experiments were performed using 1-year-old olive transplants planted in barrels filled with silty clay soil. Half of the barrels were covered with a coarse volcanic tuff, while the other samples were remained without covering and considered as control. The two sets of barrels were irrigated with four levels of water which correspond to 75%, 65%, 55%, and 45% of the field capacity. The treatments were arranged in a randomized complete block design with three replications. Results revealed that plant height, number of branches, trunk diameter, shoots length, shoot diameter, number of leaves, and plant weight for soil covered with volcanic tuff were significantly greater than control plants after the fifth growing season. The leaf water potential and relative water content of plants grown in mulched soil were significantly greater than those of control. An increase in nutrient contents of soil and plant tissues was found as a result of soil amendment with volcanic tuff. In summary, a positive influence of volcanic tuff additions on olive growth, leaves water status, and soil nutrient levels was determined.

Keywords Mulching · Zeolite · Olive tree · Water conservation · Volcanic tuff

Introduction

Water and food are the most important needs for life survival. So providing both products for the consumers has the highest priority and is the main challenge for global economy. A dramatic increase in the world population accompanied by industrialization and urbanization resulted in a sharp increase in water and food demand, while the available

sources were gradually diminished. An agricultural sector consumes huge amounts of water reaching more than 70% of total water consumption in some countries such as in Jordan (Al-Tabbal and Al-Zboon 2012). Efficient water management in the agricultural sector is the key point in reducing consumption, controlling network losses and decreasing the evaporation.

Several techniques have been adopted to reduce water evaporation from agricultural soil such as tillage, well-designed drip, trickle irrigation system, windbreak, weed control, anti-transparent (stomata closing, film-forming type, and growth retardant), and mulching (McMillen 2013).

Mulching is the most widely used method to control evaporation from soil. In addition to evaporation reduction, the mulch layer has many other benefits such as prevention of growth of weed seedling, reduction in soil salinity, erosion, and impact of some diseases, and moderation of temperature (McMillen 2013). Many materials have been used successfully in mulching such as: plastic, dust, composted pellet paper, paper fiber, cardboard, and stones. The new generation of researches turns toward using natural low-cost materials such as agricultural waste, zeolite, and volcanic tuff.

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Recycling of agricultural by-products and waste for mulching showed high efficiency in reducing evaporation, increasing water holding capacity of soil, providing a sustainable solution of waste, and enhancing soil organic content which is considered as a cost-effective practice. Wheat straw, cotton stalks, grass clippings, rice straw, date palm residue, pine needles, bark, pea straw, sugarcane, and leaf debris are common organic materials used for mulching (Al-Rawahy et al. 2011). Zeolite showed high capacity in adsorption and storage of metals (Al-zboon et al. 2016), phosphate (Aljbouir et al. 2017), and gases (Al-Harabsheh et al. 2014). In an agricultural field, it was reported that soil amendment with zeolite reduces the impact of saline water on barley plant due to the capability of zeolite for enhancing water and salt holding capacity of soil (Al-Busaidi et al. 2008). Jakab and Jakab (2010) used grinded zeolite tuff with different doses for amendment of soil at depths of 20–25 cm under furrow. The results showed that the zeolite volcanic tuff increased the soil N as well as the mobile K by 2–3 times. A significant increase in N, P, K, and Ca concentrations in the plant leaves was detected, whereas a moderate increase in sugars, acids, and vitamin C in the fruit of apple orchards was also noticed.

Furthermore, volcanic tuff showed a high capability of buffering pH of acid soil accompanied with either increasing soil humidity or Ca, Mg, and K concentrations. At the same time, the biomass production and grain yield of oat plant increased significantly as the tuff dose increased (Rădulescu 2013).

Ozbahce et al. (2015) found that zeolite has a positive impact on the bean yield and N, K, Zn, Mn, and Cu in leaf samples. Similarly, Bybordi and Ebrahimian (2013) found that zeolite application increased yield components, improved photosynthesis and respiration of canola, and promoted nitrate reduction activity, whereas oil yield decreased.

Al-Qarallah et al. (2013) showed that the utilization of zeolite as a soil substrate has a high impact on the cultivar's stem elongation, stem diameter, and the leaf area of tomato. Also, zeolite minimized the negative effect of the draught stress. Water consumption by salvia plant decreased significantly by 46.5–63.0% and 50.7–67.8% in case of using weathered and fresh volcanic tuff, respectively (Owais et al. 2013).

In contrast, the application of weathered and fresh volcanic tuff to the soil resulted in significant reductions in vegetative growth and root dry weight of salvia, plant height, leaves area per plant, main stem diameter, and average number of branches per plant (Owais et al. 2013).

This research aims to determine the usefulness of using natural volcanic tuff as a mulching on plant and soil properties under different water levels. This will open the researches' door for using an available, low-cost material for soil amendment in the arid region. Field works included monitoring the change in physiological and morphological

parameters of olive plant during 5 years of the experimental period. To the best of the authors' knowledge, this is the first time where a long-term effect of tuff on olive plant is reported.

Materials and methods

The experiment was conducted at Al-Huson University College of Al-Balqa Applied University in the northern part of Jordan (32°27'N, 35°27'E) which receives an average annual rainfall of 450 mm. The experiments were performed using 1-year-old olive transplants of the cultivar "Nabali Baladi," which is a widely planted variety in Jordan. All trees which had a uniform height of 1 m were obtained from Faisal Nursery (a government nursery) and planted in barrels filled with 20-L silty clay soil. The moisture content at field capacity and permanent wilting point for soil used in this experiment was 29.2% and 14.5% by weight, respectively. Half of the barrels (S2) were covered with a 10-cm layer of coarse tuff, while the other samples (S1) were remained without covering and considered as control. Tuff material consisted of 44.56% SiO₂, 11.74% Al₂O₃, 10.78% Fe₂O₃, 10.46% CaO, 8.81% MgO, 1.5% K₂O, 0.52% P₂O₅, 2.63% TiO₂, 1.87% Na₂O, and 0.11% MnO and had an average bulk density of 1872 kg/m³ and a water absorption ratio of 12.7% (Al-zboon et al. 2016; Al-Zboon and Zou'by 2017). Control soil is classified as silty clay (54:43%) with sand content of 3%. pH of the control soil was 7.8, and organic matter N, K, P, EC, and C/N were 0.74%, 0.05%, 420 mg/kg, 10.2 mg/kg, 0.35 dS/ml, and 12.5 respectively (Al-Tabbal et al. 2017). The two sets of barrels were irrigated with four levels of water (W1, W2, W3, and W4) which corresponded to 75%, 65%, 55%, and 45% of the field capacity.

The water contents of the soil were determined gravimetrically by weighing soil samples before and after oven-drying to a constant weight at 105 °C according to the standard method AS 1289 B1.1-1977. These values were then used to calibrate all measurements of moisture content of the soil in the pots. Field capacity (FC) was determined 48 h after irrigation and was calculated according to the equation of Paquin and Mehuys (1980). The level of water was then maintained by manual irrigation and was checked by weighing individual barrel each day to maintain the required level of moisture.

The experimental treatments were named according to the irrigation regime and soil mulching as SiW_j, where S refers to the soil, i represents soil type (control S1 and mulched S2), W refers to the water, and j is the water field capacity (75%, 65%, 55%, and 45%). The treatments were arranged in a randomized complete block design (RCBD) with three replications. To improve root growth, the trees

were irrigated to the field capacity for 1 month before beginning the experiment.

Morphological measurements

Plant weight (which includes trunk, shoot, and leaves) and the number of leaves per plant were determined at the end of the 5-year period, whereas trunk diameter (around 10 cm above the soil surface), number of branches per plant, main shoot diameters, and main shoot lengths (labeled shoot) were measured annually from the year of planting (2012) to the end of 2016, and the measurements of plant height were started from the second year of the experiment.

Plant water relations measurements

Relative water content

Relative water content was determined in ten fully expanded young leaves per plant that were being cut from the upper site along the shoots every week, using three replicate trees per treatment. The leaves were placed in polythene bags and transferred to the laboratory as fast as possible, to minimize water losses due to evaporation. The middle section of about 4 cm² was cut and placed in a pre-weighed airtight vial and weighed to obtain leaf fresh weight (FW). The leaf sections were floated in distilled water in a petri dish for 4 h under low light at room temperature to obtain turgid weight (TW), and the dry weight (DW) was measured after oven-drying the leaves for 2 days at 60 °C or until a constant weight is achieved, and then, relative water content (RWC) was calculated from the following equation:

$$\text{RWC} = \left(\frac{\text{FW} - \text{DW}}{\text{TW} - \text{DW}} \right) \times 100$$

Leaf water potential

For determining leaf water potential (Ψ_w), the top fully expanded leaves per plant, with three replicates per treatment, were collected every week between 11.00 and 12.00 h and conveyed quickly to the laboratory in a cold polythene bag for determining leaf water potential. Leaf water potential was measured using a Scholander pressure chamber (Fernandes-Silva et al. 2016).

Soil and plant chemistry measurements

Soil samples were taken at the end of the 5-year experimental period to determine treatment effects on pH, electrical conductivity (EC), Na, Ca, Mg, N, P, K, exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR), total cations, CaCO₃, and organic matter.

Each sample consisted of five cores (2 cm diameter, 15 cm deep) taken up to 10 cm soil depth for each treatment, air-dried at room temperature, ground, and sieved (6 mm). Before coring, tuff was removed from sampling area to avoid mixing of cores with surface tuff. The five cores from each pot were combined into a single sample, homogenized, and stored in sealed plastic bags at 4 °C until they were analyzed. Fully matured leaves were detached from the middle of new shoots and analyzed for the nutrients N, P, K, Ca, Mg, and Na according to the recommended methods of AOAC (2000).

Statistical analysis

The data were statistically analyzed by Statistical Analysis Software (SAS) package (SAS 2004) for each season followed by Fisher's least significant difference (LSD, $p=0.05$) procedure for treatment means comparison.

Results

The effect of natural volcanic tuff as a mulching on plant growth and soil chemistry was determined under different water stress levels (75%, 65%, 55%, and 45%). The effect of irrigation regimes and mulching was determined through many indicators, namely plant growth, plant water relation, leaf water potential, and soil chemistry.

Plant growth

For both types of soil (S1 and S2), water stress showed a high impact on the plant height (Fig. 1), number of branches (Fig. 2), trunk diameter (Fig. 3), shoot length (Fig. 4), shoot diameter, and number of leaves (Fig. 5) where the plant growth decreased significantly with water stress. In contrast, mulching with volcanic tuff provided significant improvement in plant growth for all water regimes. In comparison with S1W1 (control soil, 75% of field capacity), S1W4 (control soil, 45% of field capacity) showed a significant reduction in the number of branches, trunk diameter, shoot length, shoot diameter, number of leaves, and plant weight up to 32%, 27%, 38%, 33%, 48%, and 30%, respectively, indicating a high impact of water stress on the plant growth. In case of mulching soil with volcanic tuff, S2W4 showed a less reduction with 23, 18, 32, 25, 43, and 21% for the same parameters, respectively, in comparison with S1W4. This result revealed that mulching with volcanic tuff could be used to minimize the negative impact of draught and decrease the destructive effect of water stress. Regardless of irrigation level, plant height, number of branches, trunk diameter, shoots length, shoot diameter, number of leaves,

Fig. 1 Interactive effect of volcanic tuff and irrigation regime on height of olive tree through the 4 years

Fig. 2 Interactive effect of volcanic tuff and irrigation regime on number of branches of olive tree through the 5 years

and plant weight for soil covered with volcanic tuff were significantly greater than those of plants grown in silty clay soil without mulching after the fifth growing season. Mulching treatment increased number of leaves by 2.85%, 7.91%, 14.22%, and 14.5%, number of branches (8.2%, 16.9%, 14%, and 18.3%), plant height (0.3%, 0.4%, 0.9%,

and 0.6%), plant weight (10.73%, 18.62%, 9.63%, and 13.7%), trunk diameter (9%, 9.4%, 13.9%, and 12.5%), shoot length (3%, 11.4%, 13.9%, and 14.8%), and shoot diameter (11.1%, 12.5%, 8.6%, and 12.5%) for W1, W2, W3, and W4, respectively. It can be concluded that for all irrigation regimes, mulching increased the morphological

Fig. 3 Interactive effect of volcanic tuff and irrigation regime on trunk diameter of olive tree through the 5 years

Fig. 4 Interactive effect of volcanic tuff and irrigation regime on shoot length of olive tree through the 5 years

performance but its effects were more pronounced under high water stress.

Plant water relations

Relative water content (RWC) and leaf water potential are significant indicators of water status in plants in terms of the physiological consequence of cellular water deficit

Fig. 5 Interactive effect of volcanic tuff and irrigation regime on shoot diameter and number of leaves for olive tree through the 5 years

Fig. 6 Interactive effect of volcanic tuff and irrigation regime on relative water content and leaf water potential of olive tree through the 5 years

which reveals the equilibrium between water supply to the leaf tissue and transpiration rate. A relative water content in the leaves was much greater under higher irrigation (W1) and decreased significantly under severe water stress (24%) (Fig. 6). Mulching treatment had a significant effect on RWC, which surpassed that for without mulching by 14%. Among the different irrigation levels, relative water content increased slightly (9%) with mulching under adequate moisture content (S2W1) but increased considerably (20%) under deficient irrigation (S2W4). Also, this result buttressed the higher impact of volcanic mulching at higher water stress.

Leaf water potential

Leaf water potential was significantly affected by water availability (Fig. 6). Under control soil (S1), leaf water

potential with sufficient irrigation (W1) was significantly greater than other treatments of irrigation and decreased rapidly by 19.4%, 40%, and 52% after subjecting the plants to water stress W2, W3, and W4, respectively. The leaf water potential of plants grown in mulched soil was significantly greater than those of untreated soil by 19.3% (W1) to 32.7% (W4) with an average value of 16%.

Effect of tuff mulching on soil minerals

At the end of the investigational period, in December 2016, total cations, CaCO_3 , pH, Na, Mg, Ca, SAR, ESP, OM, EC, N, and K contents of the soil were determined. Total cations, Na, Ca, ESP, EC, N, K and SAR contents increased in soil covered with volcanic tuff significantly

Fig. 7 Effect of volcanic tuff on nutrient contents of soil

compared to control one by 22%, 39%, 24%, 48%, 25%, 43%, 18 and 33%, respectively (Fig. 7). In comparison with the control soil, there was no significant effect of tuff mulching on CaCO₃, pH, Mg, and OM of the soil.

Effect of tuff mulching on leaves minerals

The content of nitrogen, phosphorus, and sodium inside the leaves was significantly increased ($p \leq 0.01$) by 27%, 60%, and 126%, respectively, for the tree grown in mulched soil (Fig. 8). In contrast, insignificant effects of soil mulching on leaves calcium, potassium, and magnesium content were observed as compared to the control treatment. Calcium and magnesium content in leaves grown in mulched soil is higher than that in leaves grown in silty clay soil by 2% and 18%, respectively, but this increase is statistically insignificant.

Discussion

It was found that both water stress and mulching with volcanic tuff affected the morphological and physiological components significantly. Water stress was pronounced by a reduction in leaf water potential and relative water content.

A reduction in relative water content under water stress has been designated in numerous plants (Singh and Singh 1995). This reduction will reduce physiological activities inside the plant such as stomata conductance, which decreases the availability of carbon dioxide for the plant (Lafitte 2002), plant turgor, total water potential, and cell enlargement and growth. A reduction in vegetative growth such as number of leaves, shoot elongation, individual leaf size, leaf longevity, trunk diameter, and plant height by water stress is an important cause of reduced crop yield through a reduction in photosynthesis (Kramer 1983; Palese et al. 2010). Plant growth and development depend on cell division, enlargement, and differentiation which are decreased by water stress (Manivannan et al. 2007). A reduction in cell division and enlargement, photosynthesis, and canopy structure due to the low turgor pressure as a result of water stress is the main reason for reducing plant height and fresh weight (El Madidi et al. 2005; Beemarao et al. 2007; Manivannan et al. 2007).

Natural tuff is extensively applied as soil amendment material in agriculture for improving the absorption and preservation of nutrients and water, especially under adverse weather conditions (Coppola et al. 2002; Alelishvili et al. 2002; Al-Busaidi et al. 2011; Zahedi et al. 2011; Rădulescu 2013).

Fig. 8 Effect of volcanic tuff on nutrient contents of leaves

In this study, a positive effect of volcanic tuff as a mulching on plant height, number of branches, trunk diameter, shoots length, shoot diameter, and number of leaves was determined. The application of volcanic tuff to the soil resulted in double effect on water content: Firstly, it reduced the evaporation rate and secondly it worked as water storage (Mumpton 1999; Micu et al. 2005). This action decreased temperature fluctuation and increased the available water for plant. The increase in soil water resulted in an increase in relative water content and leaf water potential inside the leaves.

This study is also in agreement with Azarpour et al. (2011) who revealed the significant effect of volcanic materials (zeolite) on yield and yield component of cowpea. The highest outcomes were observed from zeolite application of 5 t ha⁻¹. Similar trends about the progressive effects of volcanic tuff like materials (zeolite) on diverse crops were originated by Gül et al. (2005) and Ozbahce et al. (2015).

After volcanic tuff application, relative water content and leaf water potential were increased inside the leaves.

This increment was reflected in plant height, number of branches, trunk diameter, shoot length, shoot diameter and number of leaves for plants grown under all moisture levels by increasing these morphological traits. The positive effect of volcanic tuff on various morphological components in this study and previous studies may be due to higher available water saving and high adsorption capacities (Mumpton 1999; Micu et al. 2005) which indicated from high relative water content and leaf water potential results, in addition to enhancement of calcium, magnesium, nitrogen, and phosphorus uptake. Tejedor et al. (2003) found that the soil mulching with volcanic materials has a great efficiency for soil water conservation provided eight times more water in the surface layer and twice at depth of 1 m. Volcanic tuff is a relatively abundant mineral resource. Numerous studies stated that volcanic tuff applications increased most nutrient contents (N, P, K, Mn, Cu, and Zn) in many crops. It was reported a significant effect of soil amendment on crops by increasing yield as a result of supply available water and nutrients to growing plants. A comparable phenomenon

was distinguished by Gül et al. (2005) and Ozbahce et al. (2015) who reported an increase in plant growth and nutrient contents in plant tissues as a result of soil amendment with zeolite. Previous study compared between phosphate concentrations in soil covered with tuff material and without covering. The results indicated that tuff materials significantly increase solution phosphate concentration compared with phosphate without tuff additions (Ming and Allen 2001; Ramesh and Reddy 2011).

Conclusion

This study aimed to evaluate the impact of using volcanic tuff as a soil mulching on the morphological and physiological parameters of plants. Five-year monitoring period of olive trees indicated that soil treatment with volcanic tuff has a positive impact on plant height, number of branches, trunk diameter, shoots length, shoot diameter, number of leaves, and plant weight as well as relative water content (RWC) and leaf water potential which are probably the most appropriate measures of plant water status in terms of the physiological consequence of cellular water deficit. Covering the soil with volcanic tuff increased both the relative water content and leaf water potential, and the impact was more pronounced in case of water stress. The results of the present study suggest that volcanic tuff affected the uptake of some macro- and micronutrients by olive plants. Volcanic tuff increases the content of total cations, Na, Ca, ESP, EC, N, and K. This result buttressed the usefulness of using tuff as a natural low-cost material in agricultural applications, which may enhance plant growth, improve soil properties, and absorb the negative impact of water stress.

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