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Use of clay dispersed in water for decreasing soil water repellency

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Abstract

In this study we examined the efficiency of a kaolinitic clayey soil to mitigate water repellency of a sandy soil with olive trees. The clayey material was applied both in dry (incorporated onto the top soil) and wet form (after dispersion in irrigation water) on different study plots, while control plots were used for comparison. The study was conducted under field conditions and both treatments (wet and dry clay) were applied at a rate of 1 kg/m^2, followed by a series of wetting and drying cycles. The results of the study verify that clay application is beneficial to mitigate soil water repellency. Dry application however displayed lower efficiency within the first week of application, which was subsequently increased during the following wetting and drying cycles. On the contrary, wet clay was efficient immediately after application, indicating that the rate limiting step in the overall process is clay dispersion. Based on the findings of this study a portable equipment was designed for field application of clay suspensions.

Keywords: reclamation; kaolinite; clay suspension; water repellency; soil hydrophobicity.

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Highlights and Graphical Abstract

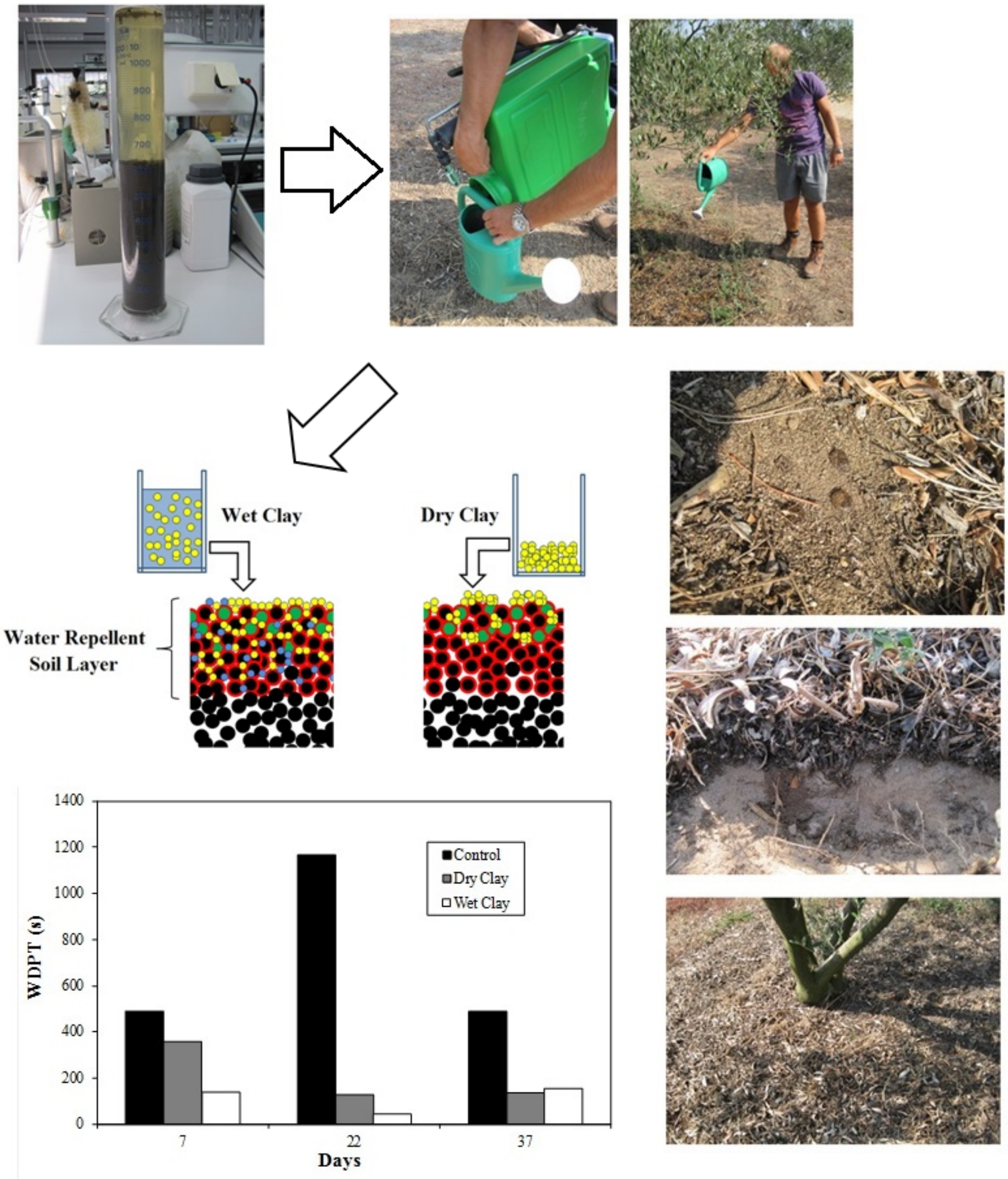
- Clay was applied at a rate of 1kg m^{-2} to a water repellent sandy soil

- Clay treatment was capable to decrease soil hydrophobicity

- Treatment efficiency was improved when clay was initially dispersed in water

- Conventional dry application required subsequent wetting and drying cycles

- A portable equipment was designed for clay preparation and application



1. Introduction

Soil water repellency (hydrophobicity) reduces the affinity of soils to water in such a way that infiltration is delayed for minutes, hours, days or even weeks (Doerr et al., 2000). As a consequence, infiltration is reduced that can lead to a significant increase in overland flow and erosion on slopes. Formation of preferential pathways through the soil can also be developed, which can accelerate leaching of agrichemicals, thus there is an increased groundwater pollution risk. For agriculture, the formation of preferential pathways is potential to lead to decreased nutrient availability for plant growth, causing decreased agricultural production. It can also lead to reduced seed germination and plant growth and reduced irrigation efficiency (Doerr et al., 2000).

The improvement of water repellent soils has thus been the subject of recent research and relevant review articles have been published on the topic (McKissock et al., 2000; Muller and Deurer, 2011). Clay consist a widely used additive for reducing hydrophobicity in sandy soils. Published studies from Australia, reported a two-fold increase in crop yields and long-term beneficial effects through clay amendment (Cann, 2000; McKissock et al., 2002). Clay is usually applied in dry form on the top soil and subsequently incorporated to a depth of 5-10 cm. This is followed by a wetting and drying cycle, which enables the clay to disperse and therefore increase its effectiveness.

The ability of clay to decrease soil water repellency is not attributed to surface active properties since clay dispersion in water does not decrease the surface tension (Schramm and Hepler, 1994), rather than to the process of "masking" of hydrophobic surfaces, accompanied with the exposure of hydrophilic clay surfaces (Muller and Deurer, 2011). The type of clay mineral plays an important role on the efficiency of the overall process. Previous studies showed that kaolinite display optimum performance for soil water repellency mitigation, which was attributed to its high surface area, dispersibility and hydrophilicity (Cann, 2000; Dlapa et al., 2004). Clay hydrophilicity results in high adhesion forces between water and the mineral surface, while the oxides and hydroxides of the clay minerals display significant sorption to hydrophobic organic matter (Ghosh and Keinath, 1994; Bantignies et al., 1997). According to Kaiser and Zech (2000) the sorption capacity of clay was sharply decreased, when the samples were chemically treated to remove aluminum and iron oxides and hydroxides. Other mechanisms by which dissolved organic matter is adsorbed onto clay mineral surfaces have been reported by Shen (1999).

An important factor determining the application of clay treatment for soil water repellency mitigation, is the cost involved (purchase, transportation, application). The latter depends strongly on the availability but also on the quantity of clay required for a specific application. Previous studies showed that clay incorporation at 1-2% w/w was beneficial to decrease soil water repellency (McKissock et al., 2002; McKissock et al., 2000; Dlapa et al., 2004). The overall quantity, however, depends on the total depth of the water repellent soil layer. According to Cann (2000), clay was amended at a rate of 50 up to 100 tn ha^{-1} (which corresponds to 5-10 kg m^{-2}), and the beneficial effects were sustained over long periods of time (>6 year). Therefore, emphasis should be given to develop modified or new application techniques that decrease the quantity of clay required for a specific application, while simultaneously increase its effectiveness.

In an attempt to increase the efficiency of clay for soil water repellency mitigation, we proposed the use of wet clay, instead of the conventional dry mode of application. In this study we examined under field conditions the application of a kaolinitic clayey soil for amelioration of a highly hydrophobic sandy soil with olive trees. The clayey material was applied in wet (after mixing with tap water) and dry form (through incorporation onto the top soil), followed by a series of wetting and drying cycles. Soil samples were obtained at regular time intervals and the degree of soil water repellency was determined. Based on the results of this study the overall mechanism for the improved performance of wet clay technology was identified.

2. Materials and Methods

2.1. Study site

The study site has been described in detail in Diamantis et al (2013). It consists of a water repellent sandy soil with olive trees and grass cover. The soil is classified as Entisol/ Psamment and it is of sandy nature in the upper 20 cm, while it becomes coarser at increasing depth. The soil ~90 cm perimetrically of each olive tree was used for the study (see Electronic Supplementary Material).

2.2. Treatment application

The clayey soil was obtained from a local agricultural field and used for ameliorating soil water repellency. It was characterized by a LS Particle Size Analyzer (Beckman Coulter) and X-Ray Diffraction (Philips Analytical C-Ray) (Figure 1). Based on the results from previous studies (McKissock et al., 2002; McKissock et al., 2000; Dlapa et al., 2004), the applied dosage of the clayey soil was selected equal to 1 kg m^{-2} which corresponded to ~1% w/w, considering that the treatment was targeted on the surface (0-5 cm) highly water repellent soil layer.

Wet clay was prepared by dispersing 2.5 kg of clayey soil into 18 liters of tap water, followed by mixing by hand for a few seconds and subsequently left overnight to soak. The wet clay containers were transported to the field where it was mixed thoroughly again. Then it was allowed for 2 min to separate the sand fraction (> 60 μm), and the supernatant was applied to the experimental trees by the use of a watering can (see Electronic Supplementary Material). By this procedure, sand particles were separated and mostly silt and clay was applied onto the study soil.

Each treatment, including the control, was replicated three times. TDR sensors connected to data loggers were installed at two (2) study trees, one (1) for the control and one (1) for wet clay treatment. After treatment application a total of six (6) wetting and drying cycles were performed by the flooding method, with each study plot receiving ~70 L of irrigation water.

2.3. Soil sampling and characterization

Soil sampling was performed using cylinders of 5 cm height and 5 cm diameter (100 cm^3). It was accomplished at 0-5 cm, which consisted the highly water repellent soil layer of the site under consideration. A total of eight (8) replicate samples were obtained from each tree and sampling campaign. The samples were obtained perimetrically of each tree within the area where the treatment was applied. The soil samples were emptied in plastic bags and sealed until transported to the laboratory. The field moist samples were weighted and the Water Drop Penetration Time (WDPT) was determined immediately (field moist WDPT). The samples were consequently air-dried for a period of approximately 7 days, until the weight was stabilized. During the drying period the content of the bags was mixed manually. After drying, the WDPT was measured again. From the difference between the initial and the final weight of the samples, the air-dry moisture content was calculated.

Composite samples were prepared in the laboratory to determine the soil organic matter content. This was done by mixing the samples taken from each treatment tree, prior to removal of vegetation and large particles (> 1.7 mm). A total of three (3) replicate samples were analyzed from each tree and treatment based on the weight loss after ignition at 550 ^{o}C for 15 min.

2.4. Continuous soil moisture monitoring

At each experimental tree four (4) TDR sensors (ECH2O-5, Decagon) were installed vertically at an effective depth of 5-10 cm, in order to monitor soil moisture content (see Electronic Supplementary Material). The sensors were inserted according to the instructions of the manufacturer. The data were collected using a decagon Em5 data logger. Calibration of the TDR sensors was performed in the lab using the same soil and the calibration curve was determined as MC (%) = 6.396 (mvolt) + 411.84 (R^2=0.974). For calibration, the method recommended by the manufacturer was used. Sensors were not installed at depth deeper than 5-10 cm, in order (a) to not disturb the root zone of the olive trees and the experimental soil in general, and d) because the main objective of the study was to examine the effect of clay application on mitigating water repellency of the surface soil layer.

3. Results and discussion

3.1. Clay properties

The clayey soil was characterized by dark brown color and a clay (< 2 μm) and fine silt content (2-16 μm particle size) equal to 16 and 63.5% respectively. Therefore, the majority of the soil particles (79.5%) ranged within fine silt to clay, which is considered as the most important predictive factor for its ability to reduce soil water repellency (McKissock et al., 2000). Based on the XRD analysis the clayey sample was mainly composed of kaolinite, which constituted for more than 60% of the <2 μm particle fraction. According to McKissock et al. (2000), the proportion of kaolin in the clay fraction contributes to the prediction of clay effectiveness, since the mineral displays a significant attraction to hydrophobic surfaces and organic compounds (Zbik and Horn, 2003; Bantignies et al., 1997). Ward and Oades (1993) showed that kaolin crystals remained spread out covering the surfaces of sand grains, masking the hydrophobic surface of an artificial water repellent soil.

The clayey soil examined was highly hydrophilic (wettable), since both the WDPT was consistently less than 5 s, while an immediate dispersion of the bulk soil in water was achieved after shaking by hand for a few seconds (see Electronic Supplementary Material). Similarly, Znik and Smart (2002) examined the wettability of kaolinite using a simple dispersion test with deionized water. The authors concluded that kaolinite is hydrophilic and is easily dispersed in water, while no remaining particles or foam were observable at the air-water interface (Zbik and Smart, 2002). These findings are consistent with our observations, with the exception of some vegetation residues floating on the water-air interface. Considering the data above, an improved performance of the selected clayey soil to decrease soil water repellency was expected.

3.2. Effect of wet and dry clay application on soil water repellency mitigation

In Figure 2 the average air-dry WDPT for the control, the dry clay and wet clay treated plots during the study period, as well as the evolution of soil moisture content in the 5-10 cm soil layer for the control and wet clay treated plots are presented. The soil moisture data (Figure 2a) illustrate the subsequent wetting and drying cycles employed after treatment application. From the results provided in Figure 2b it is evident that both dry and wet clay were beneficial in decreasing soil water repellency of the surface soil layer, compared to the control soil. Wet clay treatment showed a considerable increase of soil wettability within the first week of application (~ 38% of the samples were classified as wettable), which was not the case when it was applied in dry form (~ 12% wettable samples). The dry clay treatment however, displayed a gradual increase in soil wettability with time, which was attributed to the subsequent wetting and drying cycles (Figure 2a). Therefore, it can be concluded that the rate limiting step in the overall reclamation process is clay dispersion, which is difficult to occur by a single wetting cycle, when clay is incorporated dry into the soil matrix. Similarly, in laboratory as well as field studies, repeated wetting and drying cycles were beneficial to enhance the effectiveness of clay treatment (Cann, 2000; McKissock et al., 2002; Lichner et al., 2006). Soil wetting enables clay to disperse, thus it is subsequently mixed with the soil grains and their hydrophobic organic coatings and bonds form between them.

In Figure 3 the actual WDPT for the control, the dry clay and wet clay treated plots as a function of the air-dry soil moisture content are presented. The results verify the general rule that soil water repellency is decreasing with increasing soil moisture content, and that there is a critical soil water content above which the soil becomes hydrophilic (Doerr et al., 2000). During this study, the air-dry soil moisture content of the soil samples obtained from the field, varied from 0.5 up to 14% (see Figure 2a). Accordingly, the WDPT displayed high variability from more than 1 h (extremely water repellent) to less than 5 s (wettable samples). The untreated control soil was highly water repellent with 57% of the samples exhibiting WDPT > 60 s and only 17% being wettable. In this case, the critical soil water content ranged between 11-13%, while it was decreased to 7-8 and 6-7% when dry and wet clay respectively were added. The observed decrease in critical soil water content is of major significance since the clay treated soil can remain relatively dry without the risk to develop high degree of hydrophobicity. Similarly, the critical soil water content of a grass-covered dune sand varied between 18-23% for the surface soil layer (Dekker et al., 2001).

In Figure 4, the air-dry WDPT is presented as a function of the organic matter content of the control, the dry clay and wet clay composite samples. By considering the data from the untreated control soil, it is evident that soil water repellency display a linear increase with increasing organic matter content (R^2 = 0.82). The organic matter present onto the sandy soil, consisted mainly of composted animal manure, degraded olive tree residuals (leaves, fruits, etc) and natural grass residues (see Electronic Supplementary Material). Analyzing the data from the clay treated plots it is evident that soil water repellency remained low despite the increasing values of soil organic matter content. Indeed, in wet clay treatment, the lower degree of WDPT (13-25 s) was determined on soil samples having an organic matter content of 9.5-10%. Concluding, the use of clay does not remove hydrophobic organic compounds rather than masking/ coating them. This masking process, between the hydrophobic organic matter and the clay minerals seem to be irreversible, as repeated water flooding (wetting and drying cycles), did not resulted in clay flushing and treatment efficiency minimization. Furthermore, as demonstrated by the study of Ghosh and Keinath (1994), even a mixture of surfactants were unable to mobilize the clay (kaolinite) sorbed hydrophobic organic contaminants, due to sorption irreversibility.

Based on the results present above, the beneficial effects of wet clay application to decrease soil water repellency are attributed to the following:

- Since clay is mixed with water, the release of silt and clay minerals from the soil aggregates is achieved. Sand particles are separated and can be recovered for other purposes.

- The silt and clay suspension can be uniformly distributed onto the hydrophobic soil. Uniform clay application is not easy to accomplish when clay is applied in dry form and especially at low dosage.
- The suspension penetrates into the soil matrix, while infiltration is delayed due to silt and clay particles thus potential leaching of the applied treatment (due to preferential flow) is partially controlled. Subsequently, the suspension is diffused into the soil, dead spaces and pores (Hunter and Alexander, 1963).
- The clay minerals are adsorbed onto hydrophobic organic compounds present inside the soil matrix or coating sand grains. The clay is exposing its hydrophilic surface and accordingly the grains become wettable.
- Desorption of the clay does not occur by flooding irrigation, thus the process is considered irreversible.

3.3. Proposed equipment for wet clay application

Based on the findings above we designed a portable equipment for wet clay applications (Figure 5). The equipment is compact and can be used for reclamation of small fields or scaled-up for larger areas. It consists of a water tank equipped with a slow mixer and an air diffuser for aerating the clay/water mixture. The tank is designed in such way to separate sand particles by gravity and simultaneously maintain the silt and clay content in suspension. The mixture can be thus applied onto water repellent soils either by gravity or by using a drainage pump and a distributor. A container of 1 m^3 water capacity, supplemented with 100 kg of clay can be efficiently used for the amelioration of approximately 100 m^2 of agricultural field, which is the total reclamation area in the olive orchard under consideration.

4. Conclusions

Wet clay was beneficial to decrease soil water repellency of a highly hydrophobic sandy soil immediately after application. This was not the case when it was applied dry, although subsequent wetting and drying cycles increased its efficiency similarly to the wet mode of application. The beneficial effects of wet clay were attributed to the dispersion of clay particles and the ability to apply the suspension uniformly over the water repellent soil.

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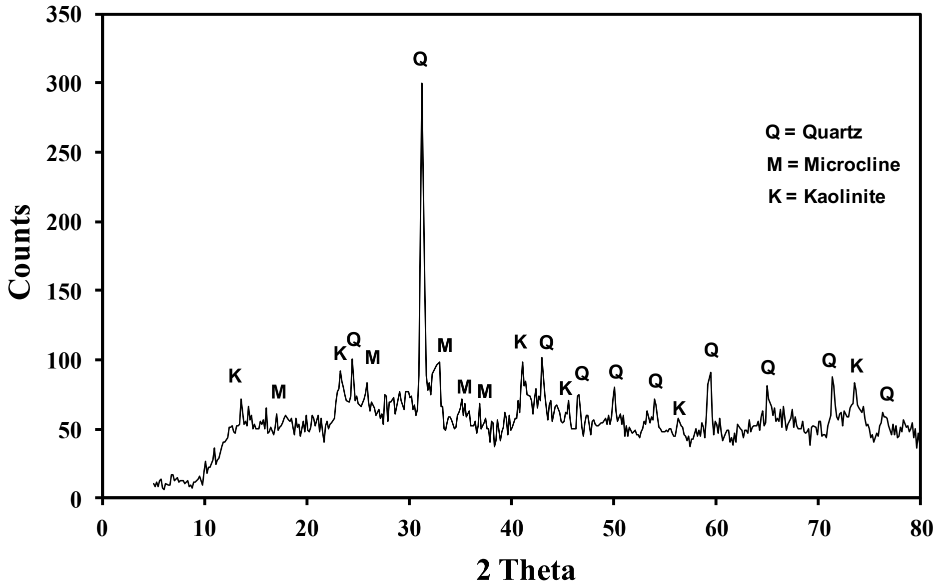
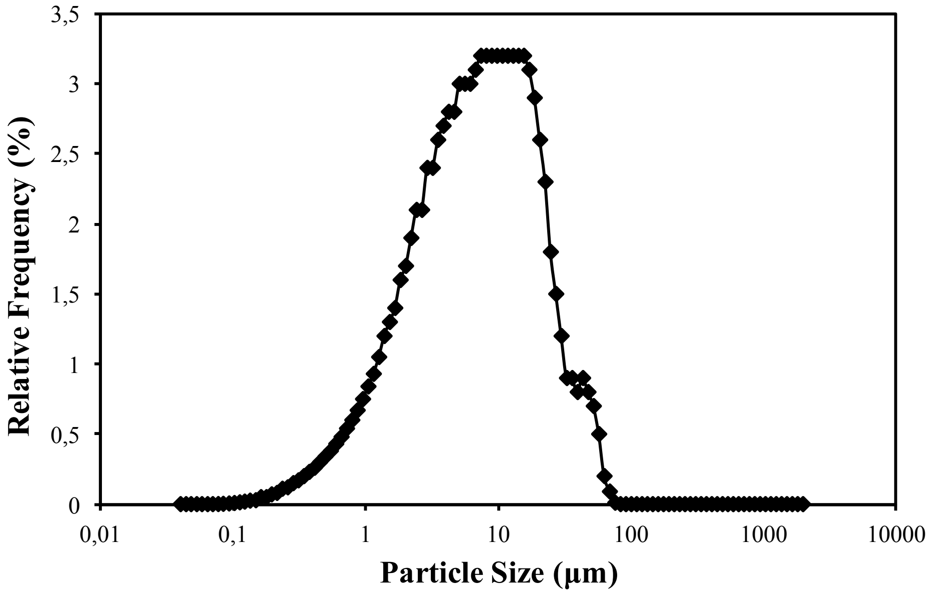
Figures

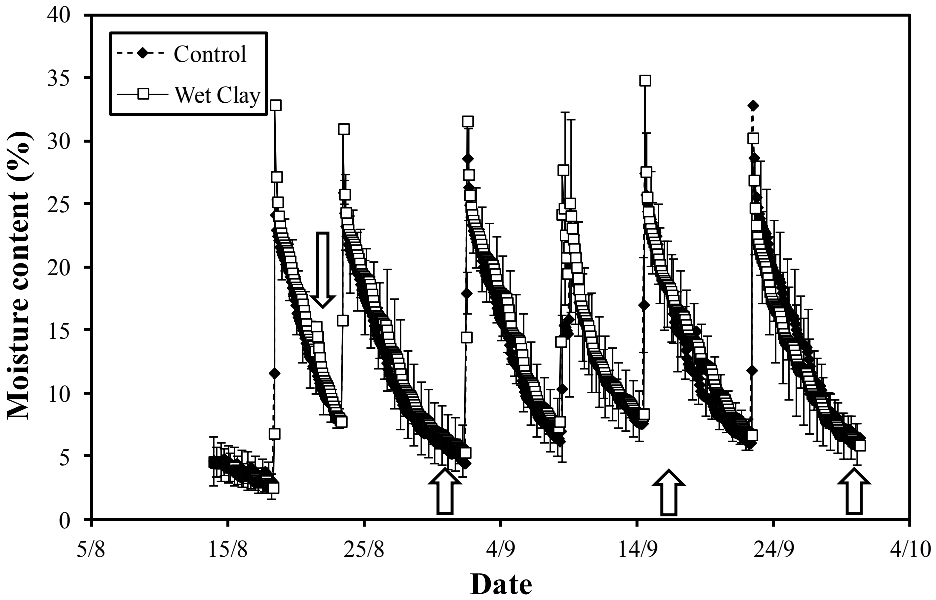


(a)



(b)

Figure 1. Physical and mineralogical properties of the clayey soil used for the amelioration of soil water repellency.



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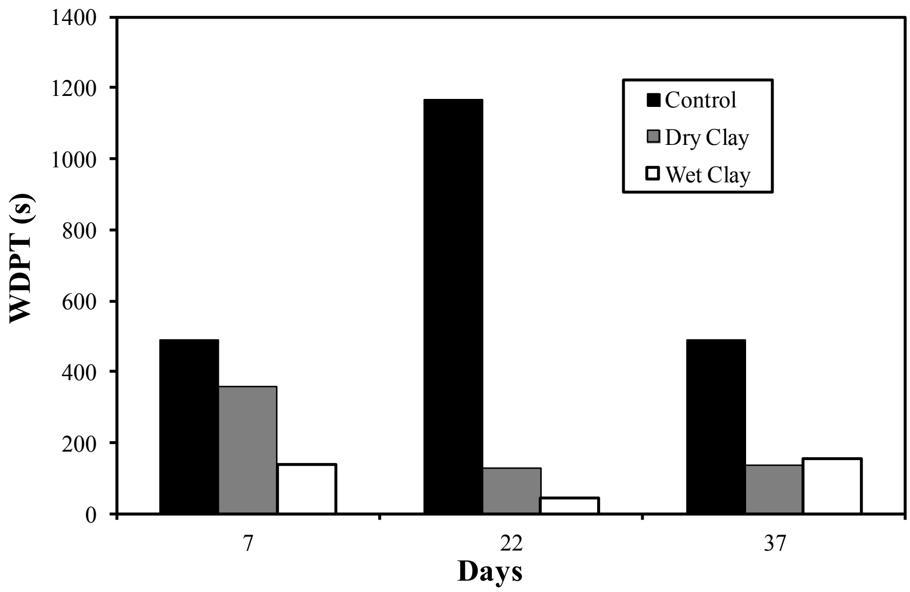
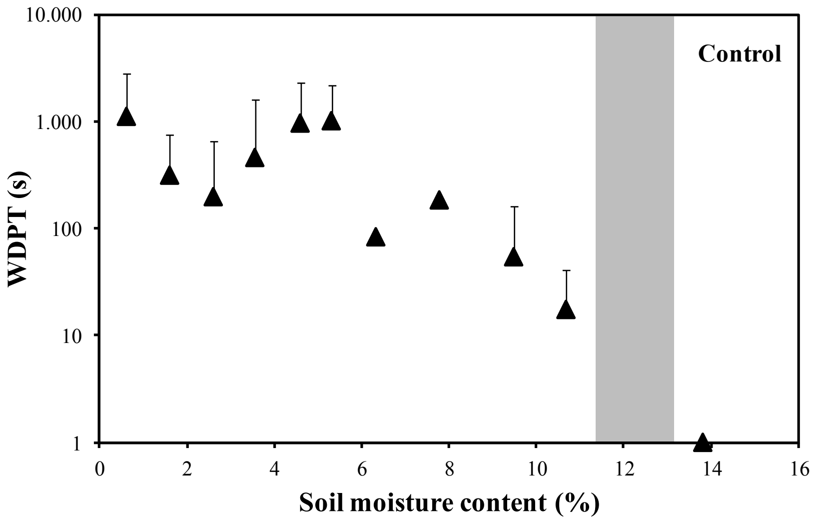


(b)

Figure 2. Evolution of (a) soil moisture content of the control and wet clay treatment plots and (b) average air-dry WDPT of the control, dry clay and wet clay treatment plots during the study period.



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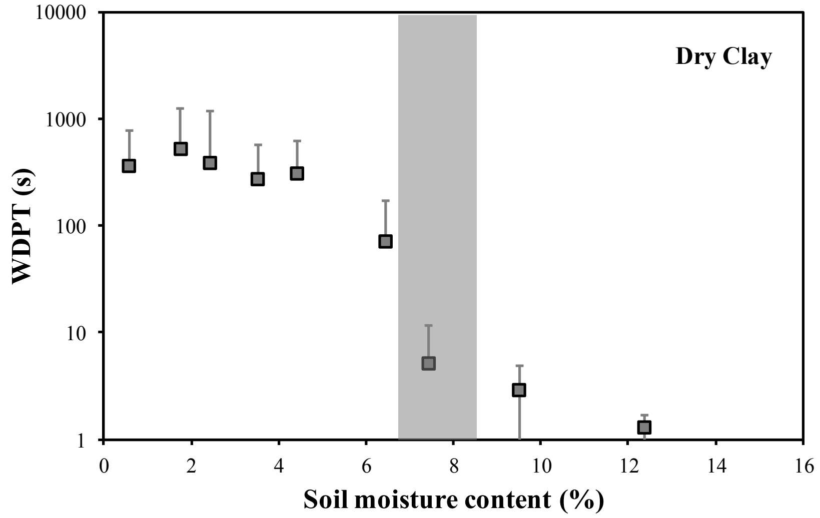
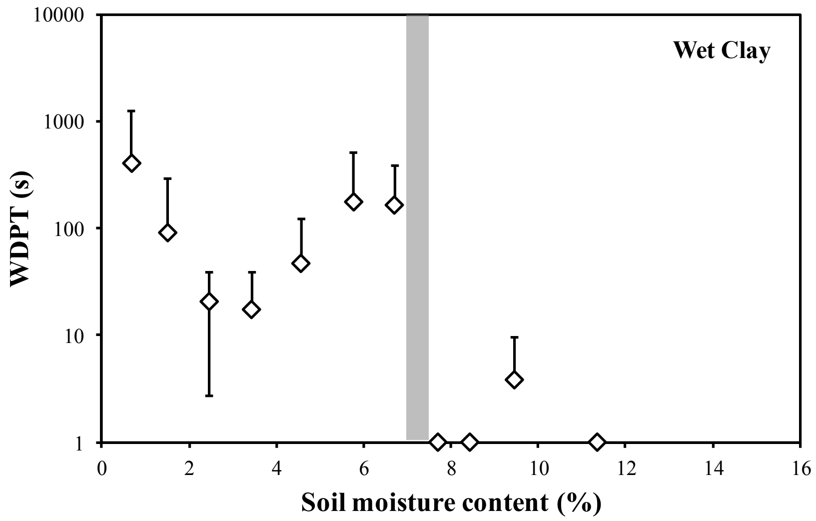


(b)



(c)

Figure 3. Effect of soil moisture content on soil water repellency for the control, the dry clay and wet clay treated plots. The grey zone illustrates the critical soil water content.

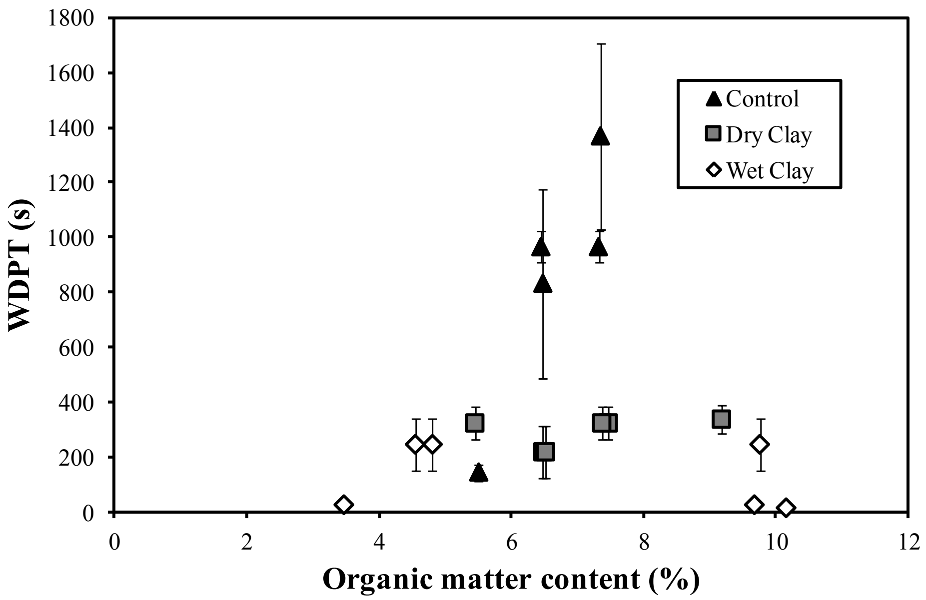


Figure 4. Variation of the air-dry WDPT as a function of the soil organic matter content for the control, the dry clay and wet clay treated plots.

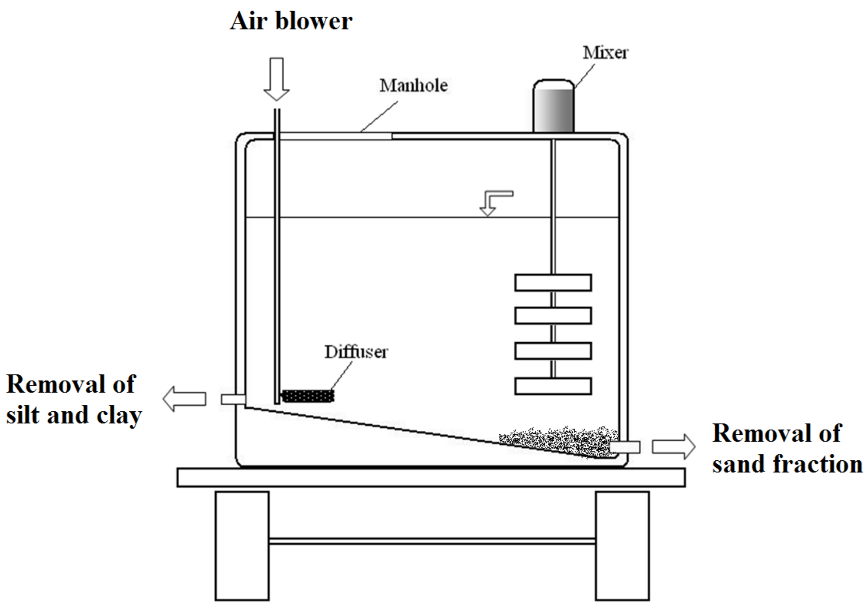


Figure 5. Proposed equipment for clay dispersion and field application

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Electronic Supplementary Material – Photographic diary

Laboratory clay dispersion tests using tap water. The clayey soil displayed high wettability. Some organic matter was floating on the water-air interface.

Determination of soil water repellency of the selected study plots

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Soil water repellency and preferentially flow phenomena in the study site.

Wet clay application using a watering can.

TDR calibration and installation

Soil sampling campaign using stainless steel cyclinders

Soil water repellency measurements in the laboratory. Composted animal manure and olive tree residuals are evident inside the soil matrix.

Preparation of the composite samples for the determination of soil organic matter content

Wetting cycle (irrigation) applied on the field