Evaporation losses from bare soils as influenced by cultivation techniques in semi-arid regions

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Abstract

The impact of cultivation techniques on the evaporation from bare soils was investigated in the laboratory. Two soil-types, which are important resources for rainfed cultivation of olives and almonds in semi-arid regions, were selected: a loamy sand soil and a stony (loam) soil. Evaporation from the soil surface is an important loss of soil moisture in these farming systems since a large percentage of the soil is kept bare in order to maximise the water availability for the tree crop. For the loamy sand soil the impacts of a straw mulch and treatment of the topsoil with olive mill effluent (OME) were tested. For the stony soil the effects of different rock fragment contents and distribution within the soil profile were tested. After thoroughly wetting with simulated rainfall and allowing the soil moisture to redistribute, the columns were subjected to evaporation for 46 days. Cumulative evaporation depth of soils treated with OME was 28% lower than that of the control soil. A similar reduction, be it lower (16%) was observed for the soil with a high rock fragment content by volume (Rv = 0.35 m³ m⁻³). The straw mulch and rock fragment mulch did not have an impact on the cumulative evaporation depth after 46 days. Furthermore, the time required to reach half of the total evaporation losses (d₀.₅) increased from 9 days for the control soil (loamy sand) to 24 days for the soil impregnated with OME and to 15 days for the straw mulch treatment. The same trend was observed for the stony soils: an increase in d₀.₅ from 4 days for the control soil (Rv = 0.19 m³ m⁻³) to 7 days for the soil with Rv = 0.35 m³ m⁻³ and to 8 days for the rock fragment mulch. These experiments show that the changes in water retention capacity of the topsoil by treatment with a hydrophobic substance (OME) or an increase in rock fragment content have a
longer lasting effect on the reduction of evaporation losses, and result in a higher and more evenly distributed soil moisture content. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Evaporation losses; Cultivation techniques; Topsoils treated with olive mill effluent; Stony soils; Semi-arid regions

1. Introduction

Evaporation from bare soils results in a considerable loss of moisture and has a direct impact on crop yield in rainfed agriculture of arid and semi-arid regions. Under annual field crops the soil surface remains bare for many weeks when the moisture content of the upper soil layer can be of critical importance during periods of seed germination and seedling establishment as well as during the subsequent growth of the young crop. In orchards, a typical component of agriculture in the Mediterranean region, the soil surface between the trees is kept bare by frequent tillage and is continuously subjected to evaporation. The very wide spacing between the trees allows a maximum catchment and soil volume to collect and store the sparse rainfall for individual trees (spacing between the trees extends to 24 m; Ennabli, 1993).

In the U.S. Midwest up to 50% of the maize evapotranspiration is lost by evaporation during a normal growing season (Peters, 1960). Research conducted in Tunisia for two decades demonstrated that evaporation from bare soils accounted for 75% of the annual precipitation (Riou, 1977). Under similar climatic conditions, this water loss was evaluated to be 30–61% of the annual precipitation for various rainfed winter wheat-based production systems (Stewart and Burnett, 1987). By means of an evaporation simulation model, Floret et al. (1982) estimated that in the south Tunisian steppe region where the soil surface cover of perennial grasses (Stipa spp.) is about 30%, half of the available soil moisture is lost by evaporation from bare soil. In Syria, where soil nutrient deficiency often severely limits crop growth, as much as 75% of the soil moisture is lost by evaporation from the soil surface under barley (Cooper et al., 1987). Since these evaporation losses are very important, their reduction will strongly contribute to soil moisture conservation for crop production. This is even more urgent in arid and semi-arid regions, characterised by highly variable and often chronically deficient rainfall. Many of the countries in these regions will have to take up an important challenge at the beginning of the next century: increasing food production in order to realise food security for a growing population while optimising the use of limited water resources (FAO, 1994). In addition, climate change will affect rainfall depth and its reliability which will increase the threat of desertification.

Management techniques commonly called ‘mulching’ are mostly based on the modification of the soil surface conditions. Mulching enhances the formation of thin air-dry layer on the top bare soil, which hampers capillary rise and slows the evaporation process. Such a well-developed air-dry surface layer can either be achieved by frequent tillage, commonly called dry farming (Willis and Bond, 1971; Jalota and Prihar, 1990a; Mwendera, 1992) or by the application of a soil cover (e.g. straw, sand, gravel or plastic film). The role of various types of soil cover in reducing evaporation has been widely
studied: crop residue mulches (Bond and Willis, 1969; Unger and Parker, 1976; Smika, 1983; Tanaka, 1985; Jalota and Prihar, 1990b; Gicheru, 1994; Mellouli, 1996), plastic film (e.g. El Amami and Haffani, 1974), sand mulches (Modaihsh et al., 1985; Bousnina, 1993) and rock fragment mulches (Corey and Kemper, 1968; Groenevelt et al., 1989; Kemper et al., 1994; van Wesemael et al., 1996). However, these mulches are labour-intensive to apply and maintain (Gale et al., 1993) and increasingly crop residues have become a valuable food supply for livestock.

Other techniques to reduce evaporation from bare soils are based on modification of the hydrodynamics of the topsoil (i.e. to force water to penetrate deep into the soil profile). Both the aggregate stability of the topsoil and its rock fragment content are important factors in this respect. The increase in structural stability of the topsoil assists in the rapid development of a dry mulch layer and can be achieved by mixing the topsoil with a hydrophobic compound either of synthetic origin (e.g. soil conditioners, Hillel and Berliner, 1974; Al-Jaloud, 1988; Verplancke et al., 1990) or of natural origin, for example, Olive Mill Effluents (OME; Mellouli, 1996; Mellouli et al., 1998). OME, better known in Tunisia as ‘margines’, that is, liquor from olive oil extraction processes, are characterised by their fertility properties (e.g. Fiestas Ros de Ursinos, 1986), as well as by their adhesive and hydrophobic behaviour (e.g. Friaâ et al., 1986). Mellouli (1996) has shown that OME has a beneficial influence on soil aggregation, soil structure stability and hydrodynamic properties of a sandy soil, for example, liquid–soil contact angle (water repellency) and saturated hydraulic conductivity were increased. Furthermore, unsaturated hydraulic conductivity and water retention at the pressure potential range corresponding to the available water capacity can be reduced by the application of OME.

The main impact of the rock fragment content in stony soils on evaporation is attributed to the reduction of the water holding capacity and deeper penetration of water in stony soils compared to non-stony soils (Ravina and Magier, 1984; Kosmas et al., 1993; Poesen and Lavee, 1994; van Wesemael et al., 1995, 1996). Stony soils are quite common in semi-arid regions. They cover more than 60% of the land in the Mediterranean (Poesen and Lavee, 1994). Frequent tillage of, in particular, orchards leads to the development of a spatial pattern of stoniness on hillslopes (Poesen et al., 1997). Denudation creates very stony soils on the convexities whereas kinetic sieving and the downward transport of rock fragments by the tines of the chisel ploughs result in a rock fragment mulch at the foot of the slopes.

The overall objective of this paper is to investigate the impact of different cultivation practices with regard to water conservation in two soils which are important resources for dryland farming where a large proportion of the soil remains bare: (i) a loamy sand soil typical for a large proportion of the olive plantations in the coastal plains on the southern fringes of the Mediterranean and (ii) a stony soil typical for many areas of rainfed agriculture in the uplands which are increasingly used for tree crops such as almonds and olives (Fig. 1). The specific research questions are:

1. Whether physical modifications of the upper few centimetres of a loamy sand, by incorporating OME will create a stable and hydrophobic mulch and will have a favourable effect on the soil water balance by reducing the evaporation.
Fig. 1. Two typical examples of farming systems where a large proportion of the soil is bare throughout the year. (a) olive groves near Sfax (Tunisia) with a loamy sand soil and an annual precipitation of 190 mm and (b) almond plantations in the Guadalentin basin (south-east Spain) on stony soils with an annual precipitation of 280 mm.
2. Whether modification of moisture retention capacity in loamy soils by the increase of rock fragment content (resulting from intensive cultivation on hillslopes) will force rain water to penetrate deeper in the profile where it should be saved from the evaporation process.

2. Methods

Laboratory experiments were conducted in order to simulate two conditions that are common in rainfed agriculture within semi-arid Mediterranean landscapes: loamy sand soils and stony soils (Figs. 1 and 2).

2.1. Loamy sand soil

The soil used in this experiment is a loamy sand containing 7.9% clay, 16.2% silt and 75.9% sand, with an organic matter content of 1.7%. The OME used in the treatment of the soil has the following characteristics: pH(H₂O) = 5.0; electrical conductivity: 10 mS cm⁻¹; density: 1.034 Mg m⁻³; dry matter content: 10.5%; mineral composition: 1%; organic matter: 9.5%. Three soil containers (length × width × height: 48.5 cm × 48.5 cm × 50 cm), having a drainage system, were filled for 45 cm from the bottom with the soil compacted to a bulk density of 1.4 Mg m⁻³. The uppermost 5 cm of these containers were treated in the following way (Fig. 2):

1. Surface layer of untreated aggregates (0–8 mm) simulating the natural mulch situation (control);
2. Similar to the ‘Control’ except for a surface cover of straw. Straw was applied at the optimal rate of 450 g m⁻² (Bond and Willis, 1969; Smika, 1983);
3. Surface layer of aggregates (0–8 mm) impregnated with OME at a concentration of 1% of active material on dry soil basis as suggested by Mellouli (1996).

The soils were first exposed for 3 h to a rainfall intensity of 20 mm h⁻¹ by means of a rainfall simulator in order to investigate how the different surface conditions affect water infiltration and redistribution (Kamphorst, 1987; Fig. 2). Then the surfaces of the containers were covered during 3 days to allow redistribution of soil moisture. The containers were subsequently subjected to evaporation for 46 days (corresponding to a cumulative potential evaporation (Ep) of 460 mm) in a controlled environment simulating the evaporation conditions of Mediterranean regions (Potential evaporation rate e_p = 9.9 ± 1.8 mm day⁻¹, temperature fluctuated between 20–30°C and relative humidity between 50–85%). Moisture content was measured by means of Time Domain Reflectometry (TDR). Two-rod probes were inserted horizontally in the containers at 2.5 cm depth in the surface layer and at 3 cm interval from 6.5 cm depth. Drainage was not observed and therefore evaporation was determined by change in soil moisture storage. Soil moisture storage is defined by the analytical integral, from the soil surface to a certain depth z, of the smooth moisture content profile, \( \Theta(z) \). Since no analytical integral is available, the storage was obtained by a numerical (trapezoidal) method.
2.2. Stony soil

The treatments were selected to represent a common scenario induced by tillage of shallow, stony soils: a stony control soil with a rock fragment content by volume (Rv) of 0.19 m$^3$ m$^{-3}$ that can evolve either to a non-stony soil with a rock fragment ‘mulch’ on top by kinetic sieving of the rock fragments in case of shallow tillage (Oostwoud
Wijdenes et al., 1997; Poesen et al., 1997) or to a skeletal soil with an increased rock fragment content (e.g. \( R_v = 0.35 \text{ m}^3 \text{ m}^{-3} \)) by breaking up the bedrock and bringing the rock fragments to the surface (Fig. 2). Soil columns with a diameter of 19 cm and a height of 20 cm were filled with an aggregated silt loam soil containing rock fragment contents by volume (\( R_v \)) of 0.19 and 0.35 \( \text{ m}^3 \text{ m}^{-3} \). In addition, a 5 cm thick layer of rock fragments was applied to a similar silt loam soil (Fig. 2). Each treatment was duplicated. The fine earth material consisted of well-structured, homogeneous silt loam (13% clay, 78% silt, 9% sand and 0.4% organic matter). Its dry aggregate size distribution was close to that of a fine seedbed: 14% of the aggregates was smaller than 2 mm, 46% was between 2 and 11.2 mm, 30% was between 11.2 and 31.5 mm and 10% was larger than 31.5 mm. Well-rounded river gravel (mainly flint and quartzites) were sieved and only the fraction between 1.7 and 2.7 cm was used. The soil moisture content of the fine earth equalled 0.18 kg kg\(^{-1}\).

Rainfall (30 mm) was applied to the columns with a rainfall simulator (intensity: 35 mm/h; Poesen et al., 1990). The columns were covered with a fine PVC mesh to reduce degradation of the soil surface. The bottoms of the columns were perforated to drain excess moisture. The columns were covered with a plastic sheet for 2 days in order to drain excess moisture and to start the experiment with equilibrated moisture conditions. Thereafter, the bottom of the columns was closed, the plastic cover was removed, the columns were weighed and placed on a drying table with two fans blowing across. After weighing the columns daily, they were replaced in a different position. Maximum and minimum temperature and relative humidity were monitored on a daily basis. Three similar columns filled with water were used to measure potential evaporation (\( E_p \)). Potential evaporation varied around a mean of 7.7 mm day\(^{-1}\) (5.6–10.1 mm day\(^{-1}\)) due to variations in mean temperature 20.1°C (16–28°C) and relative humidity (Rh) 77.8% (58–95%).

3. Results and discussion

3.1. Loamy sand soil

The initial soil moisture distribution with depth was more or less equal in all containers (Fig. 3(a)). At the start of the evaporation experiment (3 days after infiltration) the amount of soil moisture in the three columns was equal although a more evenly distributed moisture profile was obtained in the case of the OME treatment (Table 1; Fig. 3(b)). This can be attributed to the fact that the aggregates, present at the soil surface, have acquired hydrophobic and adhesive properties due to their treatment with OME. Aggregate stability increases due to OME treatment while the aggregates themselves do not take up moisture which leads to a higher infiltration rate and a deeper penetration of rain water in the soil through the large cavities between the stable aggregates (Mellouli, 1996; Mellouli et al., 1998). These processes lead to a decrease in water retention in the upper 20 cm of the soil profile and a more homogeneous distribution of the water content within the entire profile.
Fig. 3. Soil moisture distribution profiles of the columns used for the experiment with loamy sand soil: (a) Initial soil moisture content profiles, (b) soil moisture profiles after 60 mm rainfall and redistribution of soil moisture for 3 days, and (c) soil moisture content profiles after 46 days of evaporation.
After 46 days, reduction of the cumulative evaporation of the OME treatment compared to the control treatment amounted to 27.9%. The straw mulch did not seem to be effective since the evaporation reduction was limited to 4.5% of the control (Table 1).

The cumulative evaporation of the different soil columns as a function of the cumulative potential evaporation ($E_p$), the environmental evaporative demand, is plotted in Fig. 4(a). Two phases in the evaporation process can be clearly distinguished: a first phase with a more or less constant evaporation rate which is energy-limited and a second phase with a decreasing evaporation rate which is soil moisture content limited (e.g. Black et al., 1969). The OME topsoil is the most efficient in reducing evaporation losses and affects both the first and second phase (Fig. 4(a)). Where straw was applied as a mulch, the whole system reacted as a two-layered mulch. The application of straw is very efficient in the first stage of evaporation but has no effect in the second phase and after 46 days the effect is negligible since the length of the first phase is extended. The restriction of the efficiency of mulches to the constant rate stage was already observed by Corey and Kemper (1968) and Groenevelt et al. (1989).

The evaporation retarding effect of the two treatments on water conservation can be observed from the potential evaporation required to lose about one-half of the total cumulative evaporation of the control treatment ($E_{p,0.5}$). The $E_{p,0.5}$ equals 74 mm (reached in 9 days) for the control experiment, 134 mm (reached in 15 days) for the straw mulch and 232 mm (reached in 24 days) for the OME topsoil (Table 1; Fig. 4(a)).

The presence of a topsoil treated with OME has a beneficial effect on the soil moisture content distribution after 46 days of evaporation (Fig. 3(c)). A homogeneous moisture content along the entire soil column at a higher level than that of the control or straw experiment were observed. Such a higher moisture content within the plough layer is important for germination and the development of young plants. A homogeneous distribution of water and its conservation over the upper 50 cm of the profile is also beneficial for the development of some deep rooting crops.

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Loamy sand soils</th>
<th>Stony soils</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Straw</td>
</tr>
<tr>
<td>Initial moisture (mm)</td>
<td>115.6</td>
<td>117.4</td>
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<tr>
<td>Final moisture (mm)</td>
<td>57.9</td>
<td>62.3</td>
</tr>
<tr>
<td>$E_{46}$ (mm)</td>
<td>57.7</td>
<td>55.1</td>
</tr>
<tr>
<td>$\Delta E_{46}/E_{46\text{control}}$ (%)</td>
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<td>4.5</td>
</tr>
<tr>
<td>$E_{p,0.5}$ (mm)</td>
<td>74</td>
<td>134</td>
</tr>
<tr>
<td>$d_{0.5}$ (days)</td>
<td>9</td>
<td>15</td>
</tr>
</tbody>
</table>

- OME, Treatment with olive mill effluent.
- $E_{46}$, Cumulative evaporation at the end of the experiment (46 days).
- $\Delta E_{46}/E_{46\text{control}}$, Relative efficiency in $E_{46}$ reduction compared to the control experiment.
- $E_{p,0.5}$ Potential evaporation at the time when half of the $E_{46}$ is lost from the control experiment (30 mm for loamy sand soils and 22 mm for stony soils).
- $d_{0.5}$ Length of period to reach $E_{p,0.5}$. 

3.2. Stony soil

The soil in the cylinders has compacted somewhat due to the impact of the raindrops resulting in a soil depth of 15.9 cm for Rv 0.19 m³ m⁻³, 16.9 cm for Rv 0.35 m³ m⁻³ and 17.0 cm for the rock fragment mulch (Fig. 2). The difference in initial soil moisture

Fig. 4. Effect of different treatments on cumulative evaporation (E) as a function of evaporative demand (Ep) for (a) the loamy sand soil and for (b) the stony soil.
content between the three treatments can be explained by the decrease in water holding capacity due to an increased volume taken up by rock fragments and a higher macroporosity of soils containing rock fragments (Childs and Flint, 1990; van Wesemael et al., 1995). The volume of the column taken up by rock fragments is similar for control (Rv = 0.19 m³ m⁻³) and the rock fragment mulch. This is reflected in similar initial soil moisture contents (Table 1). The column with the highest rock fragment content (Rv = 0.35 m³ m⁻³) has the lowest water-holding capacity and therefore the lowest moisture content at the start of the evaporation experiment.

After 46 days, the cumulative evaporation of the column with Rv = 0.35 m³ m⁻³ is 16% less than the control. The rock fragment mulch did not seem to be effective since the evaporation reduction was limited to 1.9% of the control (Table 1). The column with a higher rock fragment (Rv = 0.35 m³ m⁻³) shows a shorter constant rate stage evaporation and a lower evaporation rate thereafter compared to the control experiment (Rv = 0.19 m³ m⁻³; Fig. 4(b)). This decrease in the evaporation rate can be explained by the reduced water-holding capacity of stony soils resulting in drainage of excess moisture. The rock fragment mulch results in a lower evaporation rate during the constant rate stage, although the constant rate stage lasts longer and the final cumulative evaporation is similar to that of the control experiment.

Similar to the experiment with the loamy sand soils, the evaporation retarding effect of the various treatments on water conservation can be observed from the potential evaporation required to lose about half of the total cumulative evaporation of the control treatment (Eₚ₀.₅). The Eₚ₀.₅ equals 34 mm (reached in 4 days) for the control experiment, 62 mm (reached in 8 days) for the rock fragment mulch and 55 mm (reached in 7 days) for the Rv = 0.35 m³ m⁻³ (Table 1).

4. The role of cultivation practices in reducing evaporation losses

Most efforts to prevent moisture loss by evaporation from bare soils have been directed towards modification of the soil surface conditions. The experiments in this paper have shown that straw and gravel applied on top of the soil act as two-layered mulches. However, their efficiency is short-lived, mainly restricted to the constant rate stage of the evaporation process (e.g. Groenevelt et al., 1989). However, these mulches tend to lengthen the constant rate stage and therefore on the longer term, cumulative evaporation is similar to that from the control experiments. These mulches are therefore best applied in situations where crops are very sensitive to drying during the initial evaporation phase (e.g. germination of young plants or irrigated crops). The high level of labour and investments involved in the application and maintenance of these mulches as well as the scarcity of crop residues in semi-arid regions limits their extensive use (Gale et al., 1993).

The experiments in this paper show that the modification of the hydrodynamic properties of the plough layer has a longer lasting effect on water conservation compared to surface mulching and is therefore more relevant to rainfed agriculture in semi-arid regions. The impregnation of the loamy sand soil with hydrophobic substances such as OME at a concentration of 1% of active material on a dry soil basis increases their
aggregate stability and reduces their unsaturated hydraulic conductivity (Mellouli, 1996). Treating the upper 5 cm of soil columns with OME resulted after 46 days of evaporation in a homogeneous distribution of water and its conservation over the upper 50 cm. In particular, tree crop plantations could benefit from such conservation of water over a prolonged period, since a large proportion of the surface is kept bare between the trees and the water availability for each tree is stored in a large volume of soil (e.g. Ennabli, 1993). Disposal of OME in the sewage system poses considerable problems because of its high organic matter and polyphenol content. However, trials in Spain and France with the spreading of OME at a rate of not more than 100 m$^3$ ha$^{-1}$ have proven that the polyphenols can be broken down rapidly and that the high nutrient content of OME can partly replace fertilisers (Fiestas Ros de Ursinos, 1986). The magnitude of the evaporation reduction obtained with OME in the laboratory experiments suggests an additional advantage of the spreading of OME in olive plantations.

On hillslopes with thin soils, rock fragments tend to move to the surface by tillage with chisel ploughs (Oostwoud Wijdenes et al., 1997; Poesen et al., 1997). Frequent tillage on slopes will lead to the creation of two types of soil profiles: (a) a rock fragment mulch, if the tillage depth does not exceed the soil depth or (b) a profile with a high rock fragment content if the tines of the chisel plough break up the bedrock (Fig. 2). Poesen et al. (1997) demonstrated that these two types of soil profiles will generally occur in different landscape positions dictated by slope characteristics that determine the intensity of tillage erosion. The thin stony soils will occur on the convexities and the deeper soils with a rock fragment mulch will prevail at the foot of the slopes. From the results of the laboratory experiments, it is possible to predict the consequences of this spatial distribution of soil types for water conservation. The thin stony soils on the convexities will behave similarly to the column with Rv = 0.35 m$^3$ m$^{-3}$ and will only retain small amounts of soil moisture. Water conservation will be efficient even in the longer term by reduced evaporation and redistribution of soil moisture downslope to the deeper soils on the footslopes and in valley bottoms. These soils are covered by a rock fragment mulch that to some extent protects soil moisture from evaporation losses at least during the initial phase. Intensive cultivation with a tine-like implement (e.g. in south-east Spain two-to-three times per year, Poesen et al., 1997) will thus cause a clear distinction between runoff generating areas (shallow stony soils) where water losses are limited due to low soil moisture retention and water receiving footslopes and valley bottoms with a tillage-induced rock fragment mulch that protects against evaporation.

The results are in agreement with the calculations of Riou (1977), who indicated that soil water retention characteristics are crucial in the availability of water for the plants in semi-arid regions. Field experiments are required to assess the costs and benefits of cultivation techniques such as the incorporation of OME or the increase of rock fragments’ content by frequent tillage.

5. Conclusions

The water-use efficiency of tree crops such as almonds and olives in semi-arid environments depends to a large extent upon the evaporation rates from the bare soil in
between the widely spaced trees. The expansion of rainfed tree crops in Mediterranean environments has stimulated this research into the impacts of the modification of surface and subsurface characteristics on evaporation losses. The results of laboratory experiments indicate that the effects of surface treatments (a straw mulch for a loamy sand soil and a rock fragment mulch for a stony soil) are relatively short-lived, whereas after 46 days ($E_p = 10 \text{ mm/day}$) sub-surface treatments (impregnation with OME for the loamy soil and increase of rock fragment content of the stony soil) significantly reduce evaporation losses. These results indicate that cultivation techniques should aim to reduce the water holding capacity in the topsoil. This can either be achieved by treatment with a hydrophobic substance (OME), or it will result from frequent tillage of stony soils on hillslopes whereby the stone content increases by breaking up the bedrock and kinetic sieving. Field experiments into the impacts of the water-holding capacity on water-use efficiency are in progress.

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**References**


