Soil & Tillage Research 148 (2015), 40-45

Efficiency of inorganic and organic mulching materials for soil evaporation control

Zribi W., Aragüés R., Medina E., Faci J.M.*

Soil and Irrigation Department (EEAD-CSIC Associated Unit), Agrifood Research and Technology Center of Aragon, CITA, DGA. Ave. Montañana 930, 50059 Zaragoza, Spain.

* Corresponding author E-mail: jfaci@cita-aragon.es

Abstract

Soil evaporation is an important component of the water balance in irrigated agriculture. Mulching can be an effective technique to reduce soil evaporation but its efficiency depends on meteorological conditions and the characteristics of the different mulching materials. The objective of this work was to assess the effectiveness of inorganic (plastic) and organic (pine bark, vine pruning residues, geotextile and wheat straw) mulching materials for soil evaporation control during the energy-limited and falling-rate evaporation stages. Soil evaporation rates (ER) were quantified through consecutive weighings of initially wet soils placed in trays in the laboratory and in microlysimeters in the field. ER depended on meteorological and experimental conditions, stage of evaporation and type of mulching material. In the falling-rate stage, ERs decreased linearly ($p < 0.001$) with decreases in GWC, and for long drying periods the ERs were low and similar among treatments, implying that soil mulching will be ineffective for soil evaporation control in low-frequency irrigation systems. In the energy-limited stage, all mulching materials decreased the ERs in relation to the bare soil, but the plastic, vine residues and pine bark materials had lower ERs than the rest of mulching materials. These materials will be therefore recommended for soil evaporation control in high-frequency irrigation systems where the soil surface remains wet most of the time.

Key words: microlysimeter; geotextile; pine bark: wheat straw; plastic film; vine residues.

1. Introduction

Soil evaporation is the process whereby liquid water is converted to water vapour and removed from the soil surface. Soil evaporation is determined solely by meteorologic conditions (i.e., solar radiation, air temperature, air humidity and wind speed) when the amount of water available for evaporation at the soil surface is unlimited. During this “energy-limited stage”, soil evaporation is constant and occurs at its maximum rate limited only by meteorologic conditions. As the upper soil dries out, the decreasing hydraulic conductivity cannot be compensated by an increasing hydraulic gradient and water cannot be transported to the soil surface at the required rate to supply the potential demand. As a consequence, the evaporation rate is reduced in proportion to the water available at the soil surface (“falling-rate stage”) (Idso et al., 1974; Allen et al., 1998).

Soil evaporation is a very important component of the water balance in natural and cultivated systems. It is estimated that 50-70% of the annual precipitation returns to the atmosphere without any benefit to biomass production (Jalota and Prihar, 1990). The reduction of soil evaporation is essential to increase the water use efficiency of agricultural crops. The use of mulching materials is an efficient way to reduce the exchange of water vapour between the soil surface and the atmosphere. Consequently, the evaporation of water from a mulched soil decreases relative to a bare soil, and more water is available for beneficial crop transpiration (Sarkar et al., 2007; Hou et al., 2010).

The type, amount or thickness of the mulching materials, and the atmospheric evaporative demand determine the rate of soil drying (Tolk et al., 1999). Mulching with impervious materials such as plastic films minimizes the evaporation of water from the soil surface, but prevents the entry of rainfall into the root zone of crops. In contrast, mulching with porous materials allows the entry of rainfall, but soil evaporation increases over that of impervious materials. Therefore, the benefits of the different types of mulching materials for water conservation are weather-dependent and rely on the balance between the water entering the soil from rainfall and irrigation, and the water leaving the soil by evaporation and transpiration.

Soil mulching is a well-established technique for increasing the profitability of crops, and the effectiveness of inorganic and organic mulches for soil evaporation control has been documented for numerous annual crops (Unger and Parker, 1976; Todd et al., 1991; Tolk et al., 1999; Ghosh et al., 2006; Awoodoyin et al., 2007). Particularly, in the last decade in China soil mulching with plastic film and different straw materials has been used to reduce soil evaporation, improve crop water use efficiency and minimize salt build-up in the root zone of crops (Huang et al., 2005; Deng et al., 2006; Xie et al., 2006; Dong et al., 2009; Yuan et al., 2009; Hou et al., 2010; Wang et al., 2014). However, most of these and other works were focused on the response of crops to soil mulching rather than on quantifying soil evaporation as affected by the different mulching materials.

Besides the benefits for water conservation, soil mulching is an efficient alternative to traditional methods of weed control because it prevents contamination of soil and groundwater by pesticides. Other advantages include protection against surface runoff and erosion, acceleration of crop maturity and, in general, an increase in the economic productivity of horticultural crops. The use of opaque materials such as black polyethylene films prevents light penetration, reduces the germination of weed seeds (Walsh et al., 1996) and provides a physical barrier to the emergence of weeds (Teasdale, 2003) and to gas exchange. Plastic films have been used widely as mulching materials and are used on a large scale in horticultural crops because in combination with high-frequency drip irrigation systems they substantially reduce the evaporation from the wetted surface and improve application irrigation efficiency. Soil mulching has shown positive effects on yield, fruit quality and earliness of harvest due to soil heating, an advantage of great interest in the marketing of early horticultural crops (Moreno and Moreno, 2008).

However, some practical problems may arise in soil mulching. Plastic films may rip and deteriorate with time in open meteorological conditions and must be reinstalled. Also the remains of plastic materials have to be properly removed from the field at the end of the crop growing cycle to avoid soil contamination, although the introduction of photo- and biodegradable plastic materials has greatly reduced this problem. Organic mulches have to be renewed periodically to maintain their effects because they decompose with time (Haynes, 1980). In general, soil mulching implies a high economic cost factor since the materials are not often available within the farm and have to be purchased elsewhere, transported to the site and installed on the plots. These aspects have restricted the use of mulching in most cases to high-value commercial crops (McCraw and Motes, 2009).

Many mulching experiments measuring its effectiveness in reducing soil evaporation were conducted in cropped soils and therefore their results are affected by the difficulties to separate soil evaporation from crop transpiration. The objective of the present work was to determine the evaporation losses from uncropped soils subject to different types of inorganic (plastic) and organic (pine bark, vine pruning residues, geotextile and wheat straw) soil mulching materials with the aim to assess their efficiency for soil evaporation control.

2. Materials and methods

Soil evaporation was measured or estimated with different inorganic and organic mulching materials in laboratory (Experiment 1) and field (Experiments 2) conditions. In experiment 1, the top layer (0-10 cm) of a clayey soil located in the experimental farm of the Agrifood Research and Technology Center of Aragon (CITA) was used. The soil of experiment 2, located in the AFFRUCAS (Association of fruit growers of the County of Caspe) farm, has an average depth of 1.5 m and is classified as calcic haploxerept, fine loamy, mixed, thermic (Soil Survey Staff, 2006).

The field capacity (FC) and permanent wilting point (PWP) determinations were performed in the CITA laboratory with a pressure plate apparatus at pressures of 33 and 1500 kPa, respectively, according to Klute (1986). Disturbed soil samples were taken at several locations in each experiment with a 50 mm diameter auger. The particle size composition and the values of FC and PWP of the soils used in the two experiments are presented in Table 1 (means of three replications).

2.1. Experiment 1 (soil trays)

Soil evaporation from a saturated soil placed in plastic trays closed at the bottom and covered with different mulching materials was measured by weighing periodically the trays with a 0.1 g precision balance. The trays were located in a room maintained at constant air temperature (28ºC) and air relative humidity (60%). The trays (29 cm length, 19 cm width and 5 cm height) were filled with 1000 g of air-dry soil. Based on a measured saturation percentage of the soil of 56 g per 100 g, the required amount of water was evenly added to each tray to bring it to saturation. The gravimetric values of FC and PWP of the soil were 27.5 g per 100 g and 18.7 g per 100 g, respectively (Table 1). Thereafter, the mulching materials were placed over the saturated soil in direct contact with it. The trays were weighed the first day of the trial just after the installation of the mulching materials over the saturated soil. The weight was measured three days after the beginning of the experiment and daily thereafter at 09:00 am. The positions of the eighteen trays on the bedplate were changed randomly every day.

Besides the control or bare soil, the following mulching materials were examined: black polyethylene (PE) film of 0.1 mm thickness with a specific weight of 0.09 g cm^{-3} (plastic); natural fibers of jute geotextile (*Corchorus capsularis)* with a thickness of 5.5 mm and a specific weight of 0.10 g cm^{-3} (Ponpun Viscosa Yute-6.5 of 650 g m^{-2}; Bontrech Co., Zaragoza, Spain) (geotextile); wheat chopped straw with 5 cm thickness and a specific weight of 0.08 g cm^{-3} (wheat straw); vine pruning residue with 5 cm thickness and a specific weight of 0.09 g cm^{-3} (vine residues); pine bark (chunks of 3 cm average diameter) with a thickness of 5 cm and a specific weight of 0.17 g cm^{-3} (pine bark).

The statistical design was at random with three replications per treatment.

2.2. Experiment 2 (microlysimeters)

Soil evaporation was measured by weighing periodically 36 microlysimeters (ML) installed in a nectarine orchard located in the AFRUCCAS experimental farm (county of Caspe, Zaragoza, Spain, 41º 18´ 57´´ N, 0º 4´ 57´´ E, 157 m elevation above sea level). Gravimetric values of FC and PWP of the soil layer 0-20 cm were 26.0 g per 100 g and 11.0 g per 100 g, respectively (Table 1). The climate was characterized using the daily data gathered in an automated agrometeorological station located close to the AFRUCCAS experimental farm.

The MLs were installed in three replicated mulching treatments (bare soil, and geotextile and pine bark with a 10 cm thickness) at two positions (tree rows and emitter laterals) completely shaded by the trees. Two MLs were installed in each position. Thus, each treatment had 12 MLs. The cylindrical MLs were made of white polyethylene with 80 mm outside diameter, 76 mm inside diameter and 100 mm height. In the upper part of the ML a wire handle was incorporated to facilitate its periodic extraction from the holes made in each position.

The MLs were filled with undisturbed soil by inserting them in some wetted areas close to the experimental area one day after an irrigation event. Therefore, the initial gravimetric soil water content was slightly above field capacity in all MLs (average of 29.6 g per 100 g as compared to a value of 26.0 g per 100 g at field capacity). After filling, the bottoms of the MLs were sealed with black polyethylene film. The MLs were weighed just before installation. Afterwards, the MLs were extracted and weighed with a portable balance (0.01 g precision) at around 10:30 am at different date intervals. After each weighing, the MLs were located again in their previous positions. This process was followed in two periods: 27 June-7 July and 26 July-25 August 2011.

To facilitate the extractions of the MLs in the geotextile treatment, an opening of 10 cm by 20 cm was made on each ML location and the geotextile was placed over the ML without direct contact with the wetted soil. In the pine bark treatment a 30 cm by 30 cm metallic screen was placed above each ML and the pine bark chunks were located over it without direct contact with the wetted soil.

The orchard was irrigated daily with a drip system with two laterals per tree row located at 0.5 m from the rows with 1 m spaced self-compensating emitters with a discharge of 4 L h^{-1}. Each tree was in the center of 1 m square with four emitters located in the corners. All mulching treatments received the same amount of irrigation. The seasonal irrigation water applied in 2011 was 677 mm and the annual rainfall was 347 mm. The irrigation water applied did not affect the soil moisture inside the MLs since the top of the ML wall was positioned about 1 cm above the soil surface to avoid the entrance of irrigation water. The evaporation was monitored during two drying cycles starting with the ML at around field capacity in each drying cycle.

2.3. Statistical analysis

The results were analyzed using analysis of variance (ANOVA) and General Linear Model (GLM) procedure of the SAS 9.1 software (SAS Institute, 2004). The means were separated using the Tukey's multiple comparison test at $p = 0.05$.

3. Results

3.1. Experiment 1 (soil trays)

The cumulative soil evaporation increased linearly (i.e., constant evaporation rate) in all mulching treatments until day four since the start of the drying cycle (Fig. 1). Following this energy-limited stage, the evaporation rate declined with time in those treatments with highest evaporation rates (bare soil, geotextile and vine residues treatments) because of the increasingly limited amount of water at the soil surface (falling-rate stage). The cumulative evaporation deviated from the linear relation on day 5 in the bare soil, day 6 in the geotextile and day 7 in the vine residue (Fig. 1). The cumulative soil evaporation was different among treatments, with values at the end of the experiment (day 7) highest (above 7 mm) in the bare soil, geotextile, vine residues and wheat straw treatments, intermediate (5.5 mm) in the pine bark treatment and lowest (2.2 mm) in the plastic treatment (Fig. 1). Although low, evaporation in the plastic treatment was important, indicating that the trays were not completely sealed or that the 0.1 mm thickness polyethylene film allowed the transfer of some water vapour through it.

The average daily soil evaporation rates (ER) for the first four days of the drying cycle (energy-limited stage) were different ($p < 0.05$) among all the mulching treatments, with a lowest value of 0.32 mm day^{-1} in the plastic treatment and a highest value of 1.64 mm day^{-1} in the bare soil (Table 2). For the 4-6 days period (energy-limited or falling-rate stages depending on treatments) the three treatments with highest cumulative evaporation amounts and lower residual soil water contents (bare soil, geotextile and vine pruning residues) decreased their ERs. At the end of the experiment (6-7 days period), the ERs of these treatments further decreased to values that were similar ($p > 0.05$) to the ER of the plastic treatment because the low amount of soil water remaining in these treatments was the limiting factor for soil evaporation.

The relative effectiveness of the different mulching treatments for soil evaporation control in the energy-limited stage was based on the results obtained for the period 0-4 days, when evaporation rates were independent of soil water content (i.e., linear increases of cumulative evaporation, Fig. 1). Table 2 shows the percent relative soil evaporation rates of the five mulching treatments in relation to the bare soil evaporation rate of 1.64 mm day^{-1}. The plastic treatment had the lowest relative ER (19%), although it was higher than expected for a material considered impermeable to vapour transfer. The next most efficient mulching material for soil evaporation control was pine bark (relative ER = 45%), followed by wheat straw (66%) and vine pruning residues (77%). The geotextile material in contact with the wetted soil had the lowest efficiency for soil evaporation control (relative ER = 89%), presumably because its pores adsorbed part of the soil water by capillarity, and this water was then readily transferred as water vapour to the atmosphere. Based on these results, the mulching materials in contact with the wetted soil had the following order of effectiveness (high to low) for soil evaporation control: plastic > pine bark > wheat straw > vine residues > geotextile > bare soil.

3. 2. Experiment 2 (microlysimeters)

During drying cycle #1 (length of 10 days) the average daily values of wind speed, air temperature and air relative humidity were 2.9 m s^{-1}, 25.2 ºC and 46%, respectively. A rainfall of 4.4 mm was recorded at day 8, and the cycle was halted at day 10 because of a rainfall of 11.4 mm recorded three days later. During drying cycle #2 (length of 30 days) the average daily values of wind speed, air temperature and air relative humidity were 2.8 m s^{-1}, 26.5 ºC and 54%, respectively. Rainfall during this cycle was negligible (0.4 mm). Except for rainfall, the meteorological conditions in both cycles were therefore similar.

The cumulative soil evaporation increased steadily in the three mulching treatments during the energy-limited stage and leveled-off during the falling-rate stage as the soil inside the ML dried out (Fig. 2). The behavior of soil evaporation during the first 10 days was similar in both drying cycles, but with lower cumulative evaporations in cycle #1 than in cycle #2. In the first periods of both cycles the cumulative evaporation was highest in the bare soil, intermediate in the pine bark and lowest in the geotextile treatment. At later periods of cycle #2, the cumulative evaporation of the three mulching treatments tended to equalize and leveled off at values of about 26 to 31 mm at day 30 (Fig. 2) because the soil inside the ML was very dry (average GWC = 9.5 g per 100 g) and hydraulic conductivity was the limiting factor for soil evaporation.

The average daily soil evaporation rates were relatively high and different ($p < 0.05$) among the three mulching treatments at the beginning of the drying cycles (until day 3 in cycle #1 and day 7 in cycle #2, Table 3) when the soil was wet (energy-limited stage). At these dates the evaporation rates were highest in the bare soil (3.8-3.0 mm day^{-1}), intermediate in the pine bark treatment (2.2-1.9 mm day^{-1}) and lowest in the geotextile treatment (1.4 mm day^{-1}). Thus, relative to the bare soil the evaporation rates decreased by about 40% and 60% in the pine bark and geotextile treatments, respectively. Afterwards, the soil evaporation rates decreased significantly (falling-rate stage) and were similar ($p > 0.05$) among treatments. The increases in evaporation at the end of cycle #1 were due to the 4.4 mm rainfall recorded in this period. At the end of cycle #2 (days 29-30) the soil inside the MLs was very dry and the soil evaporation rates in the three mulching treatments were similar ($p > 0.05$) and almost negligible (0.2 mm day^{-1} or lower).

Soil evaporation and soil water content were positively and linearly correlated ($p < 0.001$) in the three mulching treatments (Fig. 3). These relationships are linear because most observations pertain to the falling-rate stage of soil evaporation (i.e., GWC below field capacity). At low GWC, the soil evaporation rates were very low and similar among the three treatments because the limiting factor for evaporation was the insufficient volume of water in the ML. As GWC increased, soil evaporation rates deviated among treatments and became highest in the bare soil, intermediate in the pine bark treatment and lowest in the geotextile treatment. Accordingly, the slopes of the corresponding linear equations were different ($p < 0.05$) and indicate that, relative to the bare soil, the increases in the rate of soil evaporation per unit increase in GWC were reduced by 54% and 71% in the pine bark and geotextile treatments, respectively. Therefore, although the experimental area was shaded by the canopy of the nectarine trees, soil mulching proved to be very beneficial for soil evaporation control.

4. Discussion

To facilitate comparisons among experiments 1 and 2, Table 4 summarizes for each mulching treatment the most consistent results obtained in terms of daily soil evaporation rates (ER). Unique, absolute ER values for each mulching treatment could not be specified because of differences among experiments, length of drying cycles and soil water contents (i.e., energy-limited and falling-rate stages). However, the relative efficiencies of the tested treatments for soil evaporation control proved to be generally consistent among experiments, with the exceptions given below. Thus, during stage 1 (energy-limited stage) the plastic, vine residues and pine bark materials were most efficient, and the bare soil and the geotextile material were least efficient for soil evaporation control. In contrast, during stage 2 (falling-rate stage) the ER values were low and similar (p > 0.05) for all mulching treatments (ER-2 in experiment 2 for bare soil, geotextile and pine bark, and ER_{6-7} in experiment 1 for bare soil, geotextile, vine residues and plastic).

Experiment 1 discriminated better the ERs in stage 1 among mulching treatments because it was tightly controlled and the standard errors were very low (Fig. 1). However, this indoor experiment was not subject to some climatological variables such as wind that could be relevant under field conditions. The results in experiment 2 were probably the most consistent because water percolation was not allowed outside the microlysimeters and because they were located in real field conditions, but only three mulching treatments were analyzed because of the high labor required in this experiment.

Contrasting results were obtained in the geotextile treatment between experiments 1 (very high ER, equal to 89% of bare soil in stage 1) and 2 (low ER, equal to 41% of bare soil in stage 1). Moreover, the geotextile was less efficient for soil evaporation control than the pine bark in experiment 1, but more efficient in experiment 2 (Table 4, stage 1 in both experiments). One reason for this apparent discrepancy could be that the mulching materials were in contact with the wetted soil in experiment 1 but not in experiment 2. It was speculated that the finer and uniform pores of the geotextile in contact with the wetted soil were able to adsorb by capillarity the water present at the soil surface that was thereafter readily transferred as water vapor to the atmosphere, whereas the larger and patchy pores of the pine bark were less able to adsorb the soil water by capillarity.

Our results confirm those of other works reporting the efficiency of different mulching materials for soil evaporation control. Thus, Fuchs and Hadas (2011) indicated that retardation of evaporation depended on the nature of the mulching material; Yuan et al. (2009) found that the porous materials slowed the transport of vapor to the atmosphere but did not completely prevent soil evaporation; Todd et al. (1991) concluded that the straw mulching in a maize plot reduced the evaporation as compared to the bare soil, and that this reduction was lower at low (rainfed) than at high (irrigation) soil water contents; and Aragüés et al. (2014) showed in a grapevine orchard that plastic and grapevine pruning residues were more efficient for soil salinity control than the bare soil because of their reduced soil evaporation.

Overall, the results obtained in experiment 1 indicate that the black PE film was the most effective material for soil evaporation control during the energy-limited stage. Similar results were obtained in other studies under cropped soils. Ghosh et al. (2006) found in a peanut crop that the reduction of soil evaporation was higher with plastic than with wheat straw cover except in the rainy months; Maurya and Lal (1981) also concluded from a study with a maize crop that in the dry period the reduction of soil evaporation was higher with plastic than with rice straw cover; Kumar and Dey (2011) showed in a strawberry crop that plastic and cereal straw cover significantly reduced soil evaporation as compared to the bare soil, while cumulative evaporation was higher with plastic than with cereal straw; and Awoodoyin et al. (2007) established the efficiency for soil evaporation control of different mulching materials in a tomato crop that followed the order black plastic > bark materials > weed residues > bare soil.

After the plastic material, the next mulching material most effective for soil evaporation control was the pine bark (experiment 1, stage 1). Although the ER was higher with this material than with plastic, it would allow the infiltration of rainfall whereas the plastic is impermeable to rainfall. Therefore, pine bark and other porous materials such as wheat straw and vine residues could be more beneficial than plastic in terms of root zone water storage in areas where rainfall is relevant. These porous materials could be also more effective than plastic for soil salinity control, as indicated by Aragüés et al. (2014) in a grapevine orchard with a precipitation of 109 mm that infiltrated through the vine residues mulch but was intercepted by the plastic mulch.

For long drying cycles and relatively low soil water contents (falling-rate stage), differences in ERs among treatments were small (Table 4). Similar results were obtained by Unger and Parker (1976) and Xie et al. (2006), with ERs almost identical in all the tested mulching treatments for long periods of evaporation and the subsequent drying of soils. Thus, soil mulching would be most beneficial in high-frequency irrigation systems were the soil surface remains wet most of the time, whereas it would be less beneficial in low-frequency irrigation systems where the soil surface dries out between irrigations.

5. Conclusions

Soil evaporation depended on meteorological and experimental conditions, stage of evaporation (energy-limited or falling-rate stages) and type of mulching materials. Soil evaporation increased linearly with increases in soil water content in the falling-rate stage, but these increases were much lower in the mulched than in the bare soil because of the lower energy available for evaporation at the mulched soil surface.

All mulching materials decreased soil evaporation in the energy-limited stage in relation to the bare soil, but the decreases and their significance varied among the two experiments. In experiment 1 (soil trays), the average daily soil evaporation rates (ER) were different ($p < 0.05$) among all mulching treatments, with highest ER decreases in plastic and pine bark, and lowest ER decreases in geotextile and vine residues with a 5 cm thickness. In experiment 2 (microlysimeters) where, in contrast with experiment 1, the mulching materials were not in contact with the wetted soil, the geotextile was more beneficial than the pine bark for soil evaporation control.

During the falling-rate stage where evaporation is controlled by soil water content, the evaporation rates were low and similar among treatments, suggesting that soil mulching will be inefficient for soil evaporation control in low-frequency irrigation systems where the soil remains dry most of the time. During the energy-limited stage, the plastic and pine bark materials in contact with the wetted soil were most effective for evaporation control. These materials will be therefore recommended in high-frequency irrigation systems because of the high and almost continuous wetting of the soil surface in these systems. Only in cases were the mulching materials would not be in contact with the wetted soil, the geotextile will be recommended over the pine bark for soil evaporation control.

Acknowledgments

This work was financed by the CSD2006-00067 project (CONSOLIDER-INGENIO 2010). The authors would like to thank the field and laboratory technicians of the Soils and Irrigation Department (CITA), J. L. Espada and the personnel of the AFRUCCAS experimental for providing technical support.

References

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper No. 56. Rome, Italy, 300 pp.

Aragüés, R., Medina, E.T. & Claveria, I. 2014. Effectiveness of inorganic and organic mulching for soil salinity and sodicity control in a grapevine orchard drip-irrigated with moderately saline waters. *Spanish J. Agric. Res.* **12**, 501-508.

Awoodoyin, R.O., Ogbeide, F.L. & Oluwole, O. 2007. Effects of three mulch types on the growth and yield of tomato (Lycopersicon esculentum Mill.) and weed suppression in Ibdan; Rainforest-savanna transition zone of Nigeria. *Tropical Agric. Res. Ext.***10**, 53-60.

Deng, X.P., Shan, L., Zhang, H. & Turner, N.C. 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manage*. **80**, 23-40.

Dong, H., Li, W., Tang, W. & Zhang, D. 2009. Early plastic mulching increases stand establishment and lint yield of cotton in saline fields. *Field Crops Res.* **111**, 269-275.

Fuchs, M. & Hadas, A. 2011. Mulch resistance to water vapor transport. *Agric. Water Manage.* **98**, 990-998.

Ghosh, P.K., Dayal, D., Bandyopadhyay, K.K. & Mohanty, M. 2006. Evaluation of straw and polythene mulch for enhancing productivity of irrigated summer groundnut. *Field Crops Res.* **99**, 76-86.

Haynes, R.J. 1980. Influence of soil management practice on the orchard agro-ecosystem. *Agro-Ecosystems* **6**, 3-30.

Hou, X.Y., Wang, F.X., Han, J.J., Kang, S.Z. & Fena, S.H. 2010. Duration of plastic mulch for potato growth under drip irrigation in an arid region of Northwest China. *Agric. For. Meteorol.* **150**, 115-121.

Huang, Y.L., Chen, L.D., Fu, B.J., Huang, Z.L. & Gong, J. 2005. The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. *Agric. Water Manage.* **72**, 209-222.

Idso, S.B., Reginato, R.J., Jackson, R.D., Kimball, B.A. & Nakayama, F.S. 1974. The three stages of drying of a field soil. *Soil Sci. Soc. Amer. Proc.* **38**, 831-837.

Jalota, S.K. & Prihar, S.S. 1990. Bare-soil evaporation in relation to tillage. In: B.A. Steward, Editor, Advances in Soil Science, Spring-Verlag. (eds), New York, pp. 187-216.

Klute, A. 1986. Methods of Soil Analysis, Part 1 (Physical and Mineralogical Methods), Agronomy 9 (second ed.), Amer. Soc. Agron., Chapter 36, 901-926.

Kumar, S. & Dey, P. 2011. Effects of different mulches and irrigation methods on root growth, nutrient uptake, water-use efficiency and yield of strawberry. *Sci. Hortic.* **127**, 318-324.

Maurya, P.R. & Lal, R. 1981. Effect of different mulch materials on soil and on root growth and yield of maize and cowpea. *Field Crops Res.* **4**, 33-45.

McCraw, D. & Motes, E.J. 2009. Use of plastic mulch and row covers in vegetable production. http://pods.dasnr.okstate.edu/docushare/dsweb/Get/Document-1099.

Moreno, M.M. & Moreno, A. 2008. Effect of different biodegradable and polyethylene mulches on soil properties and production in a tomato crop. *Sci. Hortic.* **116**, 256-263.

Sarkar, S., Pramanik, M. & Goswami, S.B. 2007. Soil temperature, water use and yield of yellow sarson (Brassica napus, var glauca) in relation to tillage intensity and mulch management under rainfed lowland ecosystem in eastern India. *Soil Tillage Res.* **93**, 94–101.

SAS Institute Inc. 2004. SAS/STAT user's guide release 9.0. Statistical Analysis Institute, Cary, NC., USA.

Soil Survey Staff. 2006. Keys to Soil Taxonomy. United States Department of Agriculture. Washington D.C.

Teasdale, J. 2003. Principles and practices of using cover crops in weed management systems In: Weed management for developing countries. FAO plant production and protection paper. Addendum 1. Rome, Italy.

Todd, R.W., Klocke, N.L., Hergert, G.W. & Parkhurs, A.M. 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. *Trans. ASAE* **34**, 461-466.

Tolk, J. A., Howell, T. A. & Evett, S. R. 1999. Effect of mulch, irrigation and soil type on water use and yield of maize. *Soil Tillage Res.* **50**, 137-147.

Unger, P.W. & Parker, J.J. 1976. Evaporation reduction from soil with wheat, sorghum, and cotton residues. *Soil Sci. Soc. Am. J.* **40**, 938-942.

Walsh, B.D., Salmins, S., Buszard, D.J. & MacKenzie, A.F. 1996. Impact of soil management systems on organic dwarf apple orchards and soil aggregate stability, bulk density, temperature and water content. *Can. J. Soil Sci.* **96**, 203-209.

Wang, Z., Jin, M., Simunek, J. & van Genuchten, Th. 2014. Evaluation of mulched drip irrigation for cotton in arid Northwest China. *Irrig. Sci.* **32**, 15-27.

Xie, Z., Wang, Y., Jiang, Y. & Wei, X. 2006. Evaporation and evapotranspiration in a watermelon field mulched with gravel of different sizes in northwest China. *Agric. Water Manage.* **81**, 173-184.

Yuan, C., Lei, T., Mao, L., Liu, H. & Wu, Y. 2009. Soil surface evaporation processes under mulches of different sized gravel. *Catena* **78**, 117-120.

Table 1. Soil texture and gravimetric water contents at field capacity (FC) and permanent wilting point (PWP) of the 0-10 cm soil depth in Experiment 1 (soil trays) and 0-20 cm soil depth in Experiment 2 (microlysimeters).

	Sand (%)	Silt (%)	Clay (%)	FC (g per 100 g)	PWP (g per 100 g)
Experiment 1	33	28	39	27.5	18.7
Experiment 2	25	50	25	26.0	11.0

Table 2. Experiment 1 (soil trays): average daily soil evaporation rates measured in each soil mulching treatment in different periods of the drying cycle. Within each column, values followed by different letters are significantly different (*p* < 0.05). For the period 0-4 days, the percent average daily soil evaporation rate in each soil mulching treatment relative to that in the bare soil is also shown in parenthesis.

Soil mulching treatment	Soil evaporation rate (mm day^{-1}) at period (initial day-final day):		
	0-4	4-6	6-7
Bare soil	1.64f (100%)	0.65b	0.10a
Geotextile	1.46e (89%)	0.96c	0.19a
Vine residues	1.27d (77%)	1.19d	0.38a
Wheat straw	1.08c (66%)	1.17d	1.00b
Pine bark	0.74b (45%)	0.85c	0.89b
Plastic	0.32a (19%)	0.27a	0.25a

Table 3. Experiment 2 (microlysimeters): average daily soil evaporation rates measured in each soil mulching treatment in several periods of the two irrigation-drying cycles. Within each column, values followed by different letters are significantly different (*p* < 0.05).

Soil mulching treatment	Soil evaporation rate (mm day^{-1}) in each irrigation-drying cycle at period (initial day-final day):										
	Cycle #1				Cycle #2						
	0-1	1-3	3-8	8-10	0-1	1-7	7-8	8-15	15-16	16-29	29-30
No. days	1	2	5	2	1	6	1	7	1	13	1
Bare soil	3.7c	3.8c	1.0a	1.9b	5.3c	3.0c	1.7a	0.9a	0.4a	0.3a	0.1a
Pine bark	1.6b	2.2b	0.8a	1.5b	2.7a	1.9b	1.6a	1.0a	0.7b	0.5a	0.2a
Geotextile	1.0a	1.4a	0.8a	0.9a	2.0a	1.3a	1.8a	1.0a	0.8b	0.6a	0.2a

Table 4. Average daily soil evaporation rates (ER) obtained in each soil mulching treatment in experiments 1 and 2. The percent values in each treatment relative to those in the bare soil are shown in parentheses. Within each column, values followed by different letters are significantly different ($p < 0.05$). Stages 1 or 2 for each experiment are given in the last row.

Soil mulching treatment	Experiment 1		Experiment 2	
	$^{a}ER_{0-4}$	$^{b}ER_{6-7}$	^{c}ER-1	^{d}ER-2
	------------------ (mm day^{-1}) -----------------			
Bare soil	1.6f (100%)	0.10a (100%)	3.4c (100%)	1.0a (100%)
Wheat straw	1.1c (66%)	1.0b (1000%)	---	---
Pine bark	0.74b (45%)	0.89b (890%)	2.1b (62%)	0.9a (90%)
Geotextile	1.5e (89%)	0.19a (190%)	1.4a (41%)	0.9a (90%)
Vine residues	1.3d (77%)	0.38a (380%)	---	---
Plastic	0.32a (19%)	0.25a (250%)	---	---
[e]Stage	1	1 or 2	1	2

[a] Average of period 0-4 days

[b] Average of period 6-7 days

[c] Average of stage 1 (periods 1-3 days of cycle #1 and 1-7 days of cycle #2)

[d] Average of stage 2 (periods 3-8 days of cycle #1 and 8-15 of cycle #2)

[e] Stage 1 = energy-limited stage (high soil water content in topsoil; evaporation limited only by energy availability at the soil surface)

[e] Stage 2 = falling-rate stage (limited soil water content in topsoil; evaporation reduced in proportion to the amount of water remaining in topsoil).

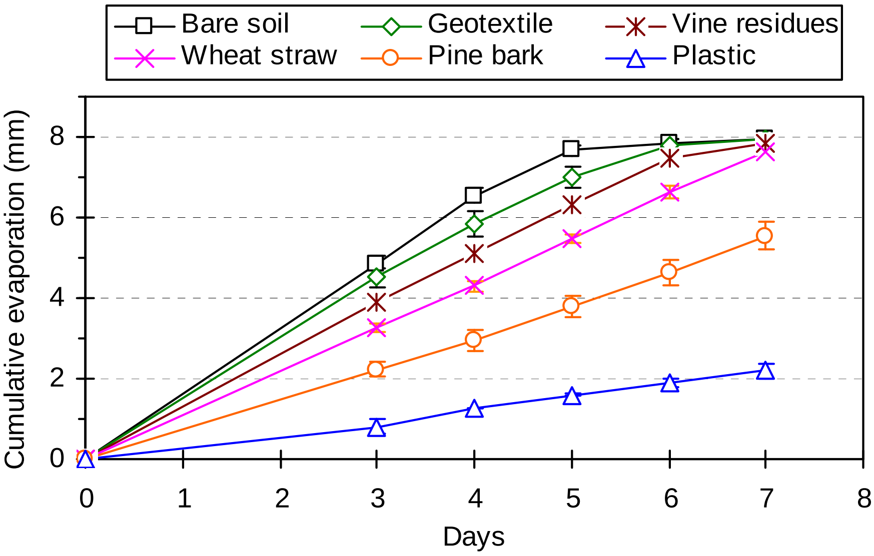

Fig. 1. Experiment 1 (soil trays): cumulative evaporation of the initially water-saturated soil measured in each soil mulching treatment during seven days at constant air temperature (28 ºC). Each point is the average of three replications (± SE).

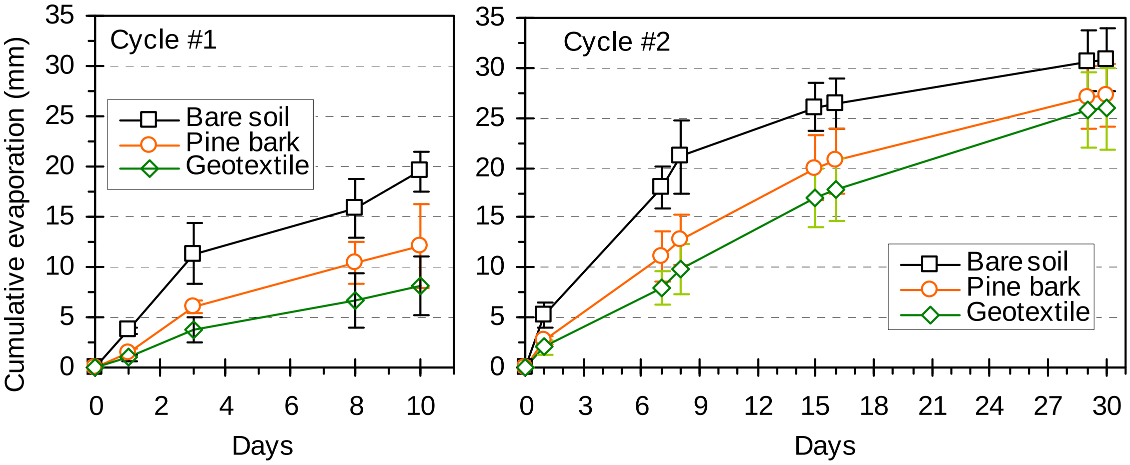

Fig. 2. Experiment 2 (microlysimeters): cumulative evaporation of the soil initially at field capacity (GWC = 26.0 %) measured in each soil mulching treatment in drying cycles #1 (10 days length) and #2 (30 days length). Each point is the average of 12 microlysimeters (± SE).

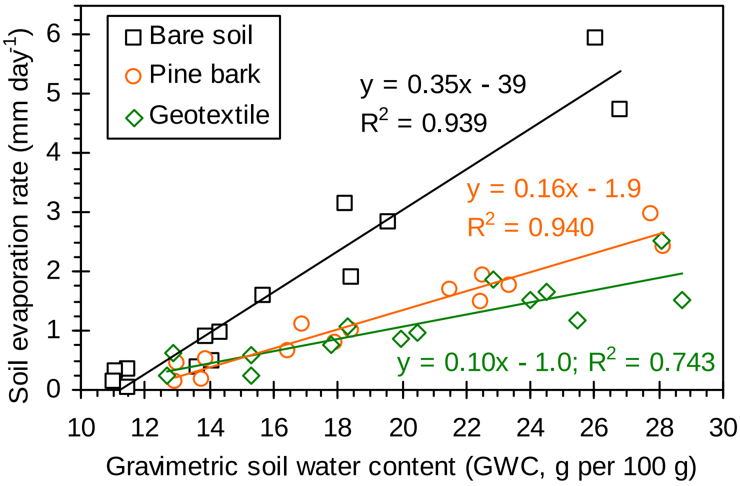

Fig. 3. Experiment 2 (microlysimeters): relationships and linear regression equations between soil evaporation rate and gravimetric soil water content measured in each soil mulching treatment in the two study irrigation-drying cycles. Each point is the average of 12 microlysimeters.