# Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments

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# Straw mulch as a sustainable solution to decrease runoff and erosion in glyphosate-treated clementine plantations in Eastern Spain. An assessment using rainfall simulation experiments

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## Abstract

In many Mediterranean areas, citrus orchards exhibit high soil loss rates because of the expansion of drip irrigation that allows cultivation on sloping terrain and the widespread use of glyphosate. To mitigate these non-sustainable soil losses, straw mulch could be applied as an efficient solution but this has been poorly studied. Therefore, the main goal of this paper was to assess the use of straw mulch as a tool to reduce soil losses in clementine plantations, which can be considered representative of a typical Mediterranean citrus orchard. A total of 40 rainfall simulation experiments were carried out on 20 pairs of neighbouring bare and mulched plots. Each experiment involved applying 38.8 mm of rain at a constant rate over one hour to a circular plot of 0.28 $m^2$. The results showed that a cover of 50% of straw (60 g $m^{-2}$) was able to delay the time to ponding from 32 to 52 s and the time to runoff initiation from 57 to 129 s. Also, the mulching reduced the runoff coefficient from 65.6 to 50.5 %. The effect on sediment transport was even more pronounced, as the straw mulch reduced the sediment concentration from 16.7 g $l^{-1}$ to 3.6 g $l^{-1}$ and the soil erosion rates from 439 g to 73 g. Our results indicated that mulching can be used as a useful management practice to control soil erosion rates due to the immediate effect on high soil detachment rate and runoff initiation reduction in conventional clementine orchards on sloping land, by slowing down runoff initiation and by reducing runoff generation and, especially, sediment losses. We concluded that straw mulch is also a sustainable solution in glyphosate-treated citrus plantations.

**Keywords:** Clementine; erosion; runoff generation; straw mulch; detachment; rainfall simulation.

## 1. INTRODUCTION

Desertification, and specifically, soil erosion is a big concern for the humankind as it threatens land use sustainability (García-Ruiz et al., 2013, 2015). Soil and water losses are especially prominent in arid and semiarid areas such as the Mediterranean territories (Vanmaercke et al., 2011). Mediterranean soils are highly affected by the intensification of agricultural production and non-sustainable agricultural practices (Kairis et al., 2013; Ben Salem et al., 2018). Moreover, the conditions under which farmers need to make a living are increasingly difficult due to climate change (Martínez-Valderrama et al., 2016). In order to develop an agricultural system that is more productive and economically viable, Mediterranean farmers are applying an increasing amount of pesticides and fertilizers, and increasingly using mechanized production systems which may enhance land and water degradation (Gómez et al., 2014). One of the clearest examples of modern productive agricultural systems is the drip irrigated mechanized glyphosate treated citrus plantations. It is perceived as icons of novel agriculture, although they are unsustainable from an environmental point of view (Cerdà et al., 2018a).

It is important to remark that Spain is worldwide well-known for high-quality citrus production (Picazo-Tadeo and Reig-Martínez, 2006). In the Valencian region (Eastern Spain), during the last three decades, the citrus production has expanded into the hillslopes thanks to the introduction of drip irrigation technology (Bono, 2010). Also, from surveys carried out by native farmers, we discovered that one of the motivations for this expansion is apparently the occurrence of frost in the valley bottoms (Cerdà et al., 2018b). Frost is found in the lowlands because of thermic inversion during high-pressure meteorological conditions in winter. The expansion has raised concerns about enhanced erosion rates on the hillslopes. However, scientific evidence for this is lacking in recent research on citrus plantations.

The acceleration of soil erosion rates in Mediterranean fields is a consequence of the combination of the sloping terrain, bare soils due to herbicide applications, and because of the compaction of the soil surface layer that results in low infiltration rates (Gómez et al., 2004). For example, in Asian citrus plantations, soil degradation was also found as a result of a drastic increase in production, although measurements are limited and need to be updated (Xu et al., 2012). China is a country that represents a clear example where the effects of the new citrus plantation with intense use of agrichemicals have caused non-sustainable soil erosion rates, which have been observed under field conditions (Liu et al., 2012; Li et al., 2014).

During the last twenty years, there has been a strong demand for clementines from northern European countries, incentivised Spanish by a premium price in the market (Moll and Igual, 2006). The increase in clementine production resulted in an increase in the use of herbicides to sustain the production, in particular, glyphosate has become the standard practice in the Valencian region. (Cerdà et al., 2018b). The use of herbicides (glyphosate) caused an increase in bare soils in the sloping terrain in the Valencia region (see figure 1), which leads to high soil erosion rates after heavy storms.

Soils are a key resource that offers goods and services to humanity. A healthy soil is a cornerstone of our biophysical system that is vital to reach the Sustainable Development Goals (Likar et al., 2015; Keesstra et al., 2016). This set of Goals, that is aimed to be met in 2030, can only be reached through good management of the biophysical, the socio-economic and policy environment. The first requirement, therefore, is a healthy biophysical environment in which the soil forms the basis. Thus, to achieve sustainability, new management strategies for agricultural production are needed that take economically sustainable production as a primary goal without damaging soil fertility and the services soils offer (Calleja-Cervantes et al., 2015). For that, the implementation of low-cost solutions may contribute to maintaining a healthy soil and avoid impacts in other regions or in other spheres of the Earth such as the atmosphere (i.e. air pollution) or hydrosphere (i.e. aquifer recharge).

An efficient natural solution for non-unsustainable soil erosion rates in agricultural lands (Verheijen et al., 2009) is the use of catch crops, which are fast-growing crops that are sown between the rows or perennial sod crops in autumn or early winter (Finch et al., 2014; Jat et al., 2018). Catch crops can reduce soil losses due to rain and wind and increase soil water and nutrient-holding capacity (Kort et al., 2008). However, many farmers in the studied region reject their use due to the cost and due to the perception, that they will lose their reputation as good farmers because the community sees catch crops as weeds.

In agriculture lands, another strategy to control unsustainable soil losses is the use of straw mulch. Prosdocimi et al. (2016a) found that there is a sudden decrease in sediment delivery in vineyards, once the straw mulch is applied to the ploughed soils. In Portugal, the chipped material was successfully used as forest mulch because of the low prices (Prats et al., 2012; 2014). These implementations of the use of straw mulch in large-scale projects imply that it could also have a potential for the industrialized hillslope citrus farming under glyphosate treatment in the Valencia area. Other previous research showed that straw mulch apart from reducing soil loss also increased infiltration (Mannering and Meyer, 1963). Straw mulch is effective to reduce soil erosion, both immediately after applying (Döring et al., 2005; Bhatt et al., 2006; Gholami et al., 2013). Recently, the use of straw mulch was also applied to rangelands affected by forest fires (Vega et al., 2014).

This work aimed to i) quantify soil detachment and runoff initiation under conventional clementine cultivation on hillslopes in the Valencia region; and ii) assess the impact of straw mulch as a conservation measure to control the water and sediment losses. Both research questions were addressed through rainfall simulation experiments carried out in the field.

## 2. Case Study area and monitoring sites

An experimental plot cultivated with clementine trees was selected to quantify initial soil and water losses in Eastern Spain (Valencia Province, Canals Municipality). The research site is located on a sloping terrain (10 %), at 38$^{o}$ 57’ 27’’N; 0$^{o}$ 36’ 32, 230 m a.s.l. (Figure 2a). Mean annual rainfall is 550 mm and the average mean temperature 16.5$^{o}$C (Elías Castillo. and Ruiz Beltrán, 1979). The clementine orchard is located on a pediment on Cretaceous limestones that developed *Eutric Regosols* (IUSS Working Group WRB, 2014). Soil texture is silty clay and herbicide (glyphosate) was applied 3 to 4 times per year.

## *3. Materials and methods*

### *3.1. Experimental design and sample collection*

A straw application of 750 kg ha$^{-1}$ was applied in the study area. Plant and rock fragment cover, local slopes and soil roughness were measured prior to the rainfall experiments. Plant and rock fragment covers were determined by measuring the presence (1) or absence (0) of plants and rocks in 100 points regularly distributed at each 0.28 m$^{2}$ plot. Together with the straw cover, all were summarized and considered as total cover (%). Local slopes were measured using a digital clinometer. The roughness of the soil surface was determined within the plot with a 1 m long chain and measured twice, from the upper part to the bottom of the plot. The chain was carefully placed on the irregular soil surface and the roughness coefficient (m $m^{-1}$) was estimated (Saleh, 1993). Forty rainfall simulation experiments (2 types of management –without and with straw mulch- × 20 plots) homogeneously covering all the situations (close to the trees, the ridges, in the inter-row and row areas, etc.) were conducted in order to reduce noise or variance in the data. They were carried out at 38.8 mm $h^{-1}$ rainfall intensity for one hour on circular paired plots (0.28 $m^2$; Fig. 2b and 2c). Ring plots are widely used in the soil scientific community because they are able to concentrate soil losses and runoff to the outlet in order to improve the sampling inside the plot, avoiding the entrance of sediment detachment from other surrounding areas (Iserloh et al., 2012). The simulated thunderstorms represent a rainfall event with an average return period of 2 years in the study area (Elías Castillo and Ruiz Beltrán, 1971). In order to allow comparisons among plots, all experiments were carried out during the Mediterranean dry summer when the soil moisture is low (July) and any effect after a storm can modify previous soil conditions. At each plot, runoff flow was collected at 1-min intervals and the water volume was measured. Runoff coefficients were calculated as the percentage of rainfall water leaving the circular plot. During rainfall simulation experiments, time to ponding (time required for 50% of the surface to be ponded; Tp, s), time to runoff initiation (Tr, s) and time required by runoff to reach the outlet (Tro, s) were recorded. Time to ponding was determined when ponds were found and Tr when those ponds were connected by the runoff. Tr-Tp, Tro-Tr, and Tro-Tp were calculated and they indicate how the ponding is transformed into runoff and how much the runoff in the soil surface last to reach the plot outlet.

### *3.3. Laboratory analyses*

Soil samples (three repetitions) were collected using 100 cm$^3$ rings for the first 6 cm soil layer to determine the bulk density. Soil water content (%) was volumetrically calculated on a weight basis after drying the samples (105$^{o}$C, 24 h). Soil organic matter was determined by the Walkley-Black method (Walkley and Black, 1934). Runoff samples were air-dried and sediment yield was calculated on a weight basis in order to calculate soil loss per area and time (Mg ha$^{-1}$ h$^{-1}$).

### *3.4. Data analyses*

General descriptive statistics were calculated for the plot characteristics (average, standard deviation, maximum and minimum values, the coefficient of variation, Skewness, and Kurtosis) and hydrological responses (average, standard deviation, maximum and minimum values). Soil erosion results (runoff coefficient, sediment concentration, and soil loss) were depicted in box plots adding the mean (dash lines) and median values, and the results between 5th and 95th percentiles. Hydrological responses were summarized in a table.

Differences among managements (control and straw) in hydrological response and soil erosion results were compared. To check the normal distribution of data, the Shapiro-Wilk test was conducted. To assess the significant differences among treatments, an ANOVA-one way was conducted. If the normality test failed, a Mann–Whitney U test was used to find differences among treatments. Finally, the Spearman’s rank correlation coefficient was computed to assess the possible influence of environmental plot variables on hydrological responses and soil erosion results. SigmaPlot 12.0 (Systat) was used to perform all the statistical analysis.

## 4. RESULTS

### *4.1. Treatment effectiveness in terms of the targeted and non-targeted variable on soil properties*

In table 1, plot characteristics are summarized. The slope angle of the plots ranged from 7 to 16% with an average of 10.4 (C) and 10.2% (S). Rock fragment cover was 12.5 and 14.6% and plant cover 4.2 and 4.1% for the control and straw plots, respectively. The straw cover (applied after the soil surface measurements and soil sampling) showed the unique difference between control (0.0%) and straw plots (50.1%). Soil properties also showed no statistically significant differences. Bulk density was 1.33 and 1.34 g cm$^{-3}$, and the soil organic matter was 1.28 and 1.29% on average for control and straw, respectively. Soil surface roughness was very low due to the lack of litter cover and the smooth surface relief as a consequence of the tractor passes and the use of herbicides (see figure 1). Soil water content was 5.5 and 5.0% and no significant differences were found. The control plots showed that on average 82% of the surface bare, meanwhile the straw-covered plots showed 44.5% bare soil surface.

### *4.2. Treatment effectiveness in terms of principal soil threat for soil erosion results*

#### *4.2.1. Runoff generation*

Soil hydrological responses are presented in figures 3 and 4, and statistical differences in table 2. Average time to ponding was found to be 32 and 52 s for control and straw plots. The runoff initiation was measured after 59 and 128 s, and the runoff initiation reached the plot outlet after 98 and 194 s. Those numbers showed that the runoff generation was faster in the control plots than in the straw covered plots. Some numbers also showed the impact of straw cover on runoff generation. The mean time from the ponding until the runoff initiation was 27 s on the control plots, meanwhile at the straw plots the average runoff was

76 s delayed from the ponding time. Another key parameter that identifies the contrasting response of the straw-covered plots is the fact that the mean runoff reached the outlet of the plot after 67 s since the runoff initiation, meanwhile, on the control plots, the runoff was found after 39 s. From the mean ponding time to the runoff outlet, the control plots show 66 s on average and the straw plots 142 s.

#### *4.2.2. Runoff discharge*

Runoff amounted to 26.3 l out of 40 l of rainfall in the control plots (Fig. 5a). In the straw plots, the runoff discharge amounted to 20.2 l. This is a runoff coefficient of 65.6 and 50.5% respectively for control and straw plots. The variability of the runoff was similar in both sets of plots. The runoff discharge ranged from 22.8 to 28.5 l in the control plots and from 16.1 to 22.5 l at the straw plots. The differences between control and straw plots were statistically significant for the runoff discharge parameters.

#### *4.2.3. Sediment concentration*

The sediment concentration was highly affected by the straw application (Fig. 5b). The twenty bare plots generated runoff with 16.7 g $l^{-1}$ of sediment, meanwhile, the straw-covered plots contributed with 3.6 g $l^{-1}$. The values ranged from 12.3 to 20.1 g $l^{-1}$ at the control plots, and from 2.3 to 4.8 g $l^{-1}$ at the straw mulch covered plots. Statistically significant differences were found.

#### *4.2.4. Soil erosion*

The total sediment detached from the 0.28 $m^2$ plots was calculated: 439 g and 73 g for the control and straw plots, respectively (Fig. 5c). That means soil erosion rates of 15.7 and 2.6

Mg ha$^{-1}$ h$^{-1}$, respectively. The sediment yield ranged from 314 to 559 g and from 44.3 and 104.2 g for the control and straw covered plots. Soil erosion ranged from 11.2 and 20 Mg ha$^{-1}$ h$^{-1}$, and from 1.6 and 3.7 Mg ha$^{-1}$ h$^{-1}$ for the control and straw covered plots. Statistically significant differences were found for soil erosion, runoff discharge, and sediment concentration.

### *4.3. Straw as a key factor*

After conducting a Spearman rank´s correlation coefficient, the straw was found to be the key factor that explained the differences between the paired plots either for the runoff generation as for the runoff discharge, sediment concentration and soil erosion (Table 3). All the other parameters measured did not show any influence on the changes within the two-paired set of plots. It was also found that soil erosion is highly dependent on the sediment concentration, which is the factor that was most affected by the use of the straw mulch.

## 5. DISCUSSION

### 5.1. Treatment effectiveness in terms of principal soil threats

There was a clear impact of the application of straw mulch on highly degraded soils from clementine plantations due to the role of straw played as a protective cover. Figure 6 shows the distribution of the soil erosion, sediment concentration and runoff for the two sets of twenty plots: with and without straw mulch. In general, the studied plots showed a low cover of plants and rock fragments. However, the applied straw mulch made the difference related to the soil erosion, sediment concentration, and runoff discharge. The mulched plots showed much lower runoff discharge, sediment concentration, and soil erosion. Straw mulch influenced five runoff-erosion processes at the pedon scale: splash erosion, rainfall interception, ponding, infiltration and flow connectivity.

## 5.2. Changes in biophysical processes

### *5.2.1. Soil processes at the pedon scale*

There was a clear contrast between mulched and bare plots in splash erosion due to the role straw plays in the reduction of the raindrop impact. The reduced raindrop impact decreases the detachment effect on the soil floor when the straw is present (Bisal, 1960). There is a need of more research on splash erosion, and this research should address to find new and sustainable management strategies that have the objective to lessen raindrop impact (Sadeghi et al., 2017). Straw acts as a protective cover against the raindrop impact and this reduces soil erosion rates such as Gholami et al (2013) measured. This verifies previous research (Poesen et al., 1986) developed under the field, laboratory and modelling approaches that show that soil surface cover is the key factor determining splash erosion and thereby that affects sediment delivery at the pedon scale (Angulo-Martínez et al., 2012). The mulched plots showed more cover (an increase of 50%). The straw increased the time to ponding, and the time the ponded surfaces took to generate overflow was also much longer (Fig. 3). This was entirely or partly due to the fact that the straw intercepted some of the rainfall, which delayed the wetting of the soil surface. Furthermore, the straw creates a rougher surface, creating more potential ponding surfaces. The interception by straw could be one of the causes of the delay in runoff initiation and as a consequence of the decrease in total runoff. The role of interception in the rainfall-runoff response is well-known in forest hydrology where the role litter can play in the interception process was already found by Helvey and Patric (1965) who showed that there is a clear control of the biomass and the storage and drainage capacity of the litter (see also Pitman, 1989). The effect of the amount and cover of straw and other mulch effects is a key topic that must be investigated in detail.

### *5.2.2. Infiltration runoff impacts on sediment yield*

The straw cover reduces overland flow speed and this can increase infiltration, and therefore may reduce the amount of runoff. Similar effects were found for emerging vegetation (James et al., 2004), in wetlands (Kadlec, 1990) and in vegetated channels (Carollo et al., 2002). The effect of vegetation stems was also researched and found to be an important factor in overland flow hydraulics changes (Zhao et al., 2016) and explains the impact of vegetation on the resistance to overland flow in grasslands and shrublands, if the shrubs are covering the soil surface, as occurs also with the straw mulch.

## 5.3. Covered soils using natural products, why should they be preferred

The soils studied in the clementine's orchards on bare surfaces are poor in organic matter, which results in high soil and water losses. There is a need to stop further degradation and, in many cases, to restore soil quality and the associated soil functions. Straw mulch is a natural product that enhances the soil functions in the long term and has an immediate effect on soil erosion and can be an option to achieve these goals. In a recent review of nature-based solutions in land management (Keesstra et al., 2018), it was explained that there are two types of Nature Based Solutions: soil and landscape solutions. The use of straw mulch can be seen as a soil solution; it immediately reduces the erosion and water loss, as was explained in this study. It will also generate higher water availability for the plants due to higher infiltration. The straw will also increase the soil organic matter, improve the soil physical properties, soil moisture and temperature levels (Ramakrishna et al., 2006;

Mulumba and Lal, 2008). It was also found to have a positive effect on nitrogen management (Verma and Bhagat, 1992; Döring et al., 2005), and on the soil microbial biomass (Tu et al., 2006).

In addition, straw mulch is an agricultural, local and natural product which needs to be shown as an efficient solution that can enable farmers to achieve sustainable management. However, more work is needed in order to convince farmers to implement this type of management. Recent research carried out in the same region in rainfed agricultural lands demonstrated that the farmers might be willing to adopt this kind of management interventions if these were subsidized (Cerdà et al., 2018a; 2018b). The same kind opinions were found with other Spanish farmers, such as olive orchards (Sastre et al., 2016) or vineyards (Marques et al., 2015), where farmers also perceived mulch and cover crops as dirt. Even though the farmers know these kinds of strategies are beneficial to counteract erosion, the perception of it being dirty as well as the pressure from their fellow farmers seems to hinder the widespread adoption of these measures.

## 6. CONCLUSIONS

The use of straw mulch was very efficient to reduce soil and water losses under simulated rainfall on intensively managed clementine plantations with intense use of agrichemicals. The mulching reduced overland flow amounts, sediment concentration and soil losses with a factor of 1.3, 4.63 and 6, respectively. These reductions and changes could be attributed to the impacts of straw mulch on splash erosion and overland flow velocity. Our research furthermore demonstrated that straw mulching produced a clear delay in runoff initiation and runoff amount due to the straw. Therefore, we conclude that mulching would seem a feasible solution to use local agricultural residues to mitigate non-sustainable soil and water losses found in conventional clementine orchards in the Mediterranean belt.

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Figure 3. Scatter plots between time to runoff initiation minus time to ponding (Tr-Tp), time to runoff outlet minus time to generation (Tro-Tr), and time to runoff outlet minus time to ponding (Tro-Tp).

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## Highlights

- Citrus plantations with bare soils show high erosion rates: 15.7 Mg $ha^{-1}$ $h^{-1}$
- Runoff rates in citrus plantations reach as much as 67 % of the simulated rainfall
- Straw mulch reduces runoff from 65.6% to 50.7% and erosion rates up to 2.6 Mg $ha^{-1}$ $h^{-1}$
- Sediment concentration can be reduced from 16.7 to 3.6 g $l^{-1}$
- Straw mulch is an efficient solution that disconnects water and sediment flows

Table 1. Plot characteristics

| n = 20 for each treatment | Slope (%) | | R.f. (%) | | B.D. (g cm$^{-3}$) | | SOM (%) | | R (mm mm$^{-1}$) | | SWC (%) | | Vc (%) | | Straw (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | S | C | S | C | S | C | S | C | S | C | S | C | S | C | S |
| Mean<br>SD | 10.4<br>±2.2 | 10.2<br>±2.2 | 12.5<br>±3.1 | 14.6<br>±3.1 | 1.33<br>±0.15 | 1.34<br>±0.16 | 1.3<br>±0.2 | 1.3<br>±0.2 | 1.05<br>±0.02 | 1.04<br>±0.02 | 5.5<br>±0.7 | 5.0<br>±0.7 | 4.2<br>±1.7 | 4.1<br>±1.9 | 0 | 50.1<br>±4.9 |
| Max | 16.0 | 15.0 | 19.0 | 19.0 | 1.56 | 1.65 | 1.7 | 1.7 | 1.09 | 1.08 | 7.0 | 6.0 | 7.0 | 8.0 | 0 | 59 |
| Min | 8.0 | 7.0 | 7.0 | 8.0 | 1.09 | 1.15 | 1.0 | 1.0 | 1.02 | 1.01 | 4.7 | 3.7 | 1.0 | 1.0 | 0 | 42 |
| Kurt | 1.0 | -0.2 | -0.2 | -0.2 | -1.1 | -1.3 | -1.5 | -0.7 | -0.5 | 0.9 | -0.8 | -1.0 | -0.2 | -0.6 | 0 | 0.1 |
| Skew | 1.1 | 0.7 | 0.0 | -0.4 | 0.1 | 0.4 | 0.3 | 0.1 | 0.9 | 0.7 | 0.4 | -0.4 | -0.5 | 0.2 | 0 | -0.8 |
| Diff. | p<0.72 | | p<0.033 | | p<0.914 | | p<0.933 | | p<0.456 | | p<0.027 | | p<0.932 | | p<0.001 | |

C: Control plot without straw; S: Plot covered by straw; SD: Standard deviation; Diff. Statistical differences; R.f.: Rock fragment cover; B.D.: Bulk density; SOM: Soil organic matter; R: Roughness; SWC: Soil water content; V.C.: Vegetation cover.

Table 2. Hydrological parameters related to the runoff generation

| n = 20 for each treatment | Tp (s) | | Tr (s) | | Tro (s) | | Tr-Tp (s) | | Tro-Tr (s) | | Tro-Tp (s) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | S | C | S | C | S | C | S | C | S | C | S |
| Mean | 32 | 51.7 | 59 | 127.5 | 98.1 | 194 | 27.1 | 75.8 | 39.1 | 66.5 | 66.1 | 142.3 |
| SD | ±5.3 | ±6.2 | ±4.3 | ±4.3 | ±11.1 | ±8.6 | ±13.3 | ±5.5 | ±15.1 | ±5.4 | ±9.2 | ±16.2 |
| Max | 41 | 61 | 69 | 149 | 115 | 220 | 38 | 104 | 49 | 76 | 81 | 175 |
| Min | 24 | 42 | 53 | 110 | 85 | 175 | 14 | 51 | 32 | 57 | 46 | 117 |
| Diff. | P<0.001* | | P<0.001 | | P<0.001 | | P<0.001 | | P<0.001 | | P<0.001* | |

SD: Standard deviation; Max: Maximum; Min: Minimum; Diff.; Statistical differences; *Saphiro-Wilk did not pass, Mann–Whitney U test. Tp: Time to ponding; Tr: Time to runoff generation; Tro: Time to runoff in outlet; Tr-Tp: Time to runoff generation minus time to ponding; Tr-Tro: Time to runoff in outlet minus time to runoff generation; Tro-Tp: Time to runoff in outlet minus time to ponding.

Table 3. Spearman´s rank correlation coefficient among environmental plot characteristics and hydrological response

| | Tp | Tr | Tro | Tr-Tp | Tro-Tr | Tro-Tp | Rc | SC | Se |
|---|---|---|---|---|---|---|---|---|---|
| Slope | 0.23 | -0.15 | -0.12 | -0.29 | -0.02 | -0.22 | -0.14 | 0.18 | 0.07 |
| R.f. | 0.32 | 0.26 | 0.25 | 0.26 | 0.21 | 0.22 | -0.22 | -0.26 | -0.23 |
| BD | -0.20 | 0.03 | -0.04 | 0.14 | -0.17 | 0.00 | 0.22 | 0.05 | 0.16 |
| SOM | 0.28 | -0.12 | -0.08 | -0.23 | 0.05 | -0.16 | -0.20 | -0.01 | -0.12 |
| R | -0.19 | -0.07 | -0.05 | -0.09 | -0.05 | -0.04 | 0.23 | 0.06 | 0.12 |
| SWC | -0.50 | -0.17 | -0.23 | -0.10 | -0.30 | -0.10 | 0.39 | 0.16 | 0.26 |
| V.C. | -0.21 | 0.14 | 0.16 | 0.17 | 0.06 | 0.21 | -0.03 | -0.04 | 0.00 |
| Straw | 0.77* | 0.83* | 0.83* | 0.83* | 0.81* | 0.83* | -0.85* | -0.80* | -0.81* |

*: $p<0.05$; R.f.: Rock fragments; BD: Bulk density; SOM: Soil organic carbon; R: Roughness; SWC: Soil water content; V.C.: Vegetation cover; Tp: Time to ponding; Tr: Time to runoff generation; Tr-Tp: Time to runoff generation minus time to ponding; Tro: Time to runoff in outlet minus time to runoff generation; Tr-Tro: Time to runoff in outlet minus time to runoff generation; Rc: Runoff coefficient; SC: Sediment concentration; Se: Soil erosion

**Figure 1**

Figure 2

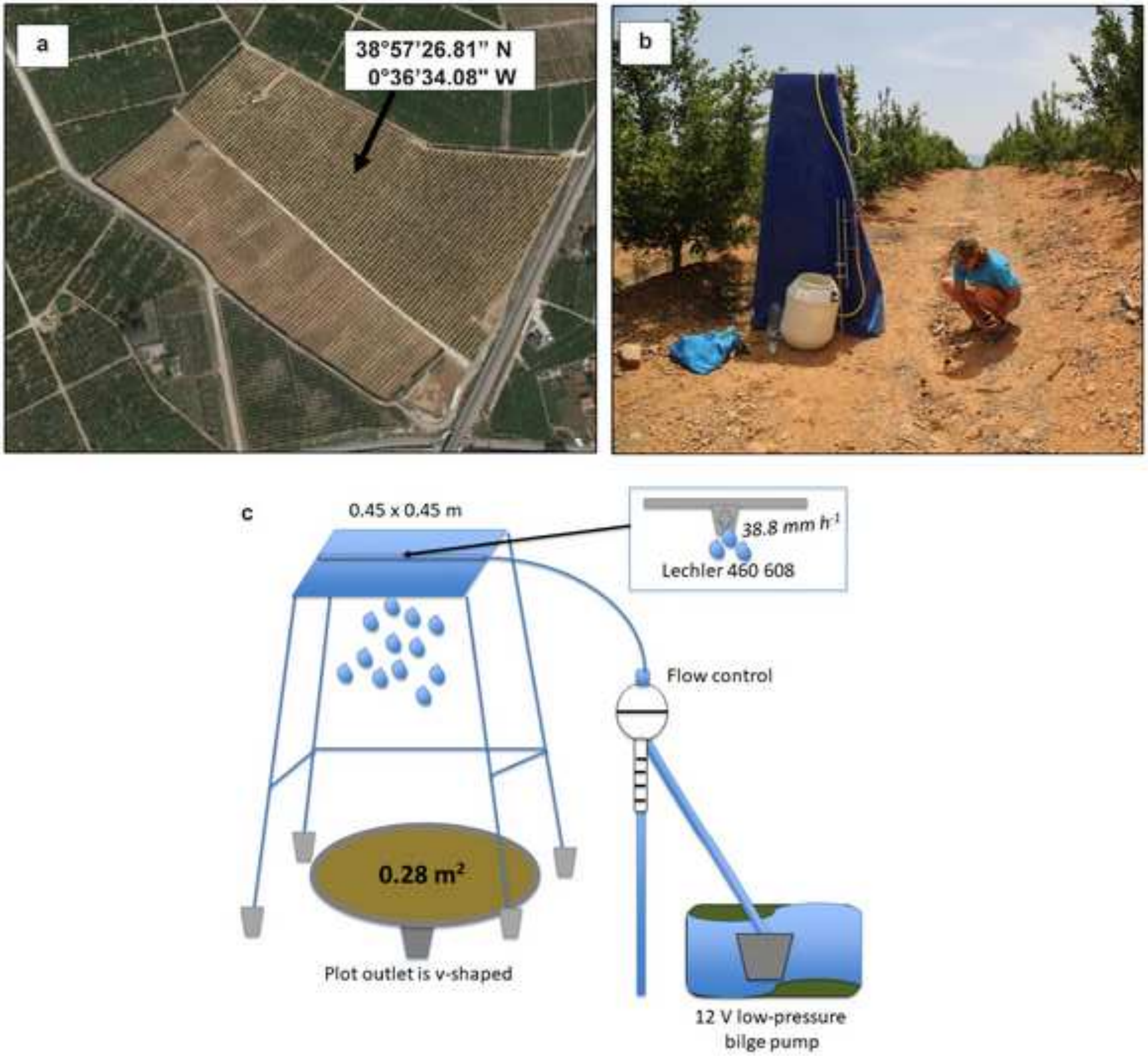

a
38°57'26.81" N
0°36'34.08" W
b
c
0.45 x 0.45 m
38.8 mm h-1
Lechler 460 608
Flow control
0.28 m²
Plot outlet is v-shaped
12 V low-pressure
bilge pump

Figure 3

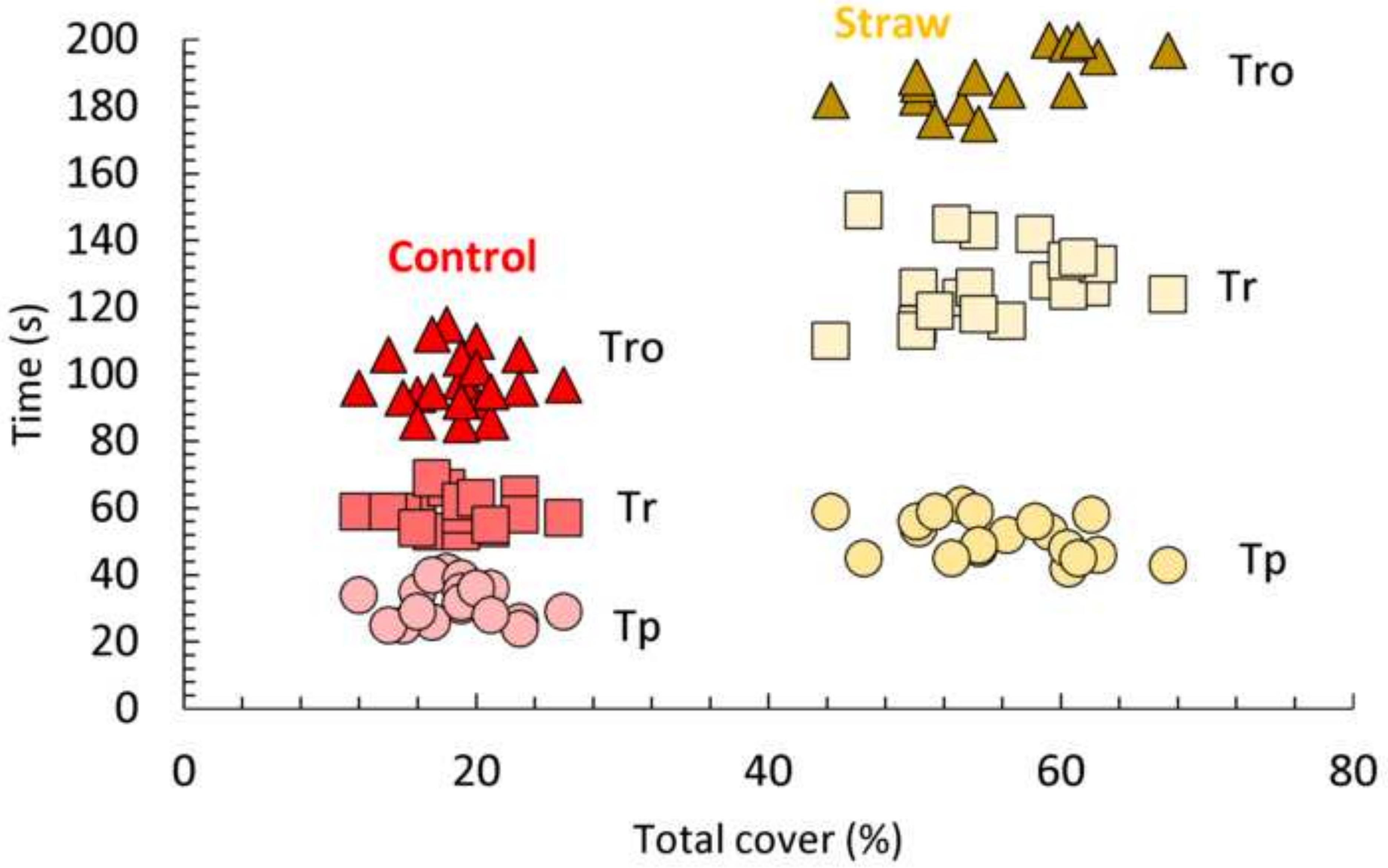

Straw
Control
Tro
Tr
Tp
Tro
Tr
Tp
Time (s)
0
20
40
60
80
100
120
140
160
180
200
Total cover (%)
0
20
40
60
80

**Figure 4**

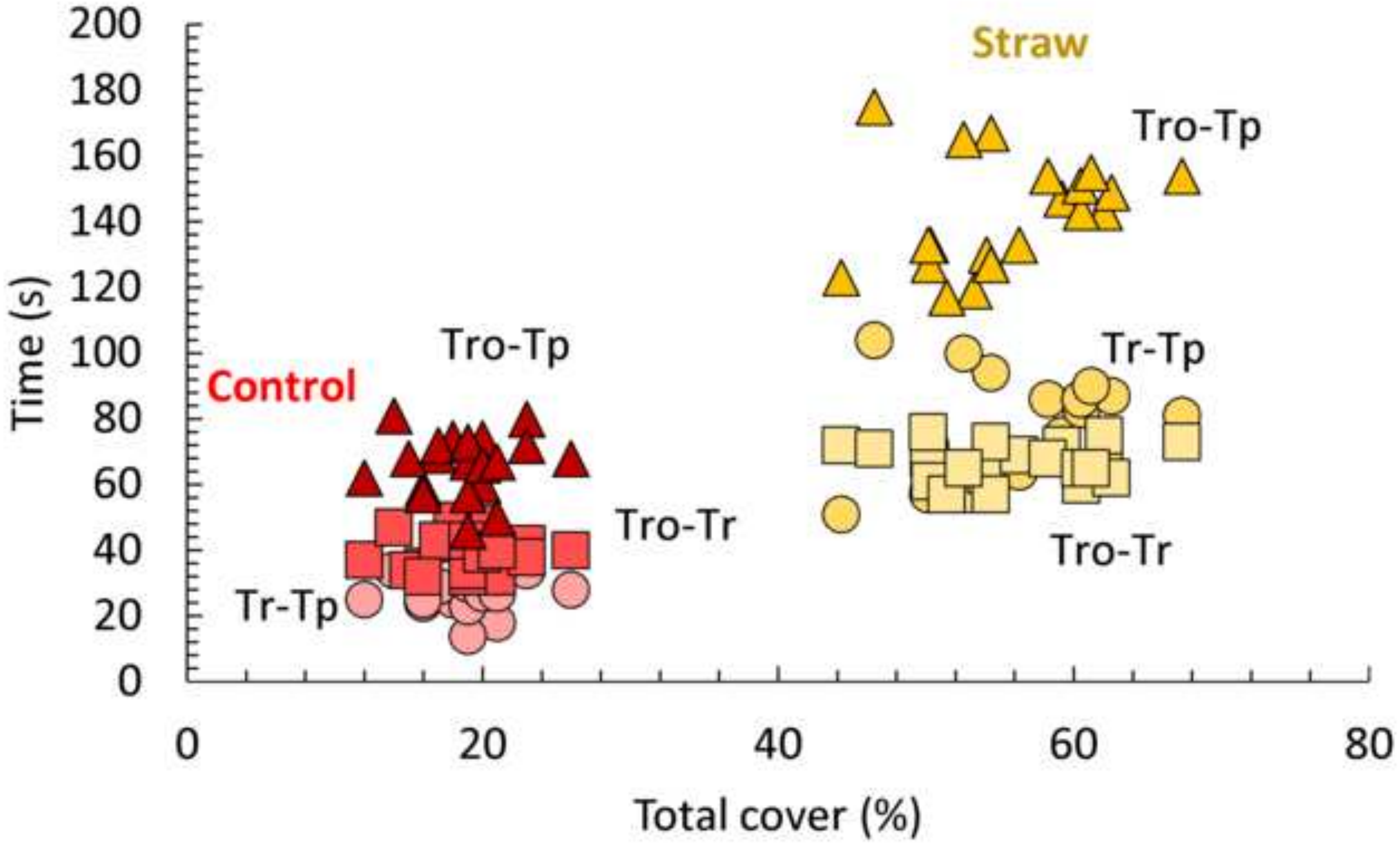

Straw
Tro-Tp
Tr-Tp
Tro-Tr
Control
Tro-Tp
Tro-Tr
Tr-Tp
Time (s)
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
Total cover (%)

**Figure 5**

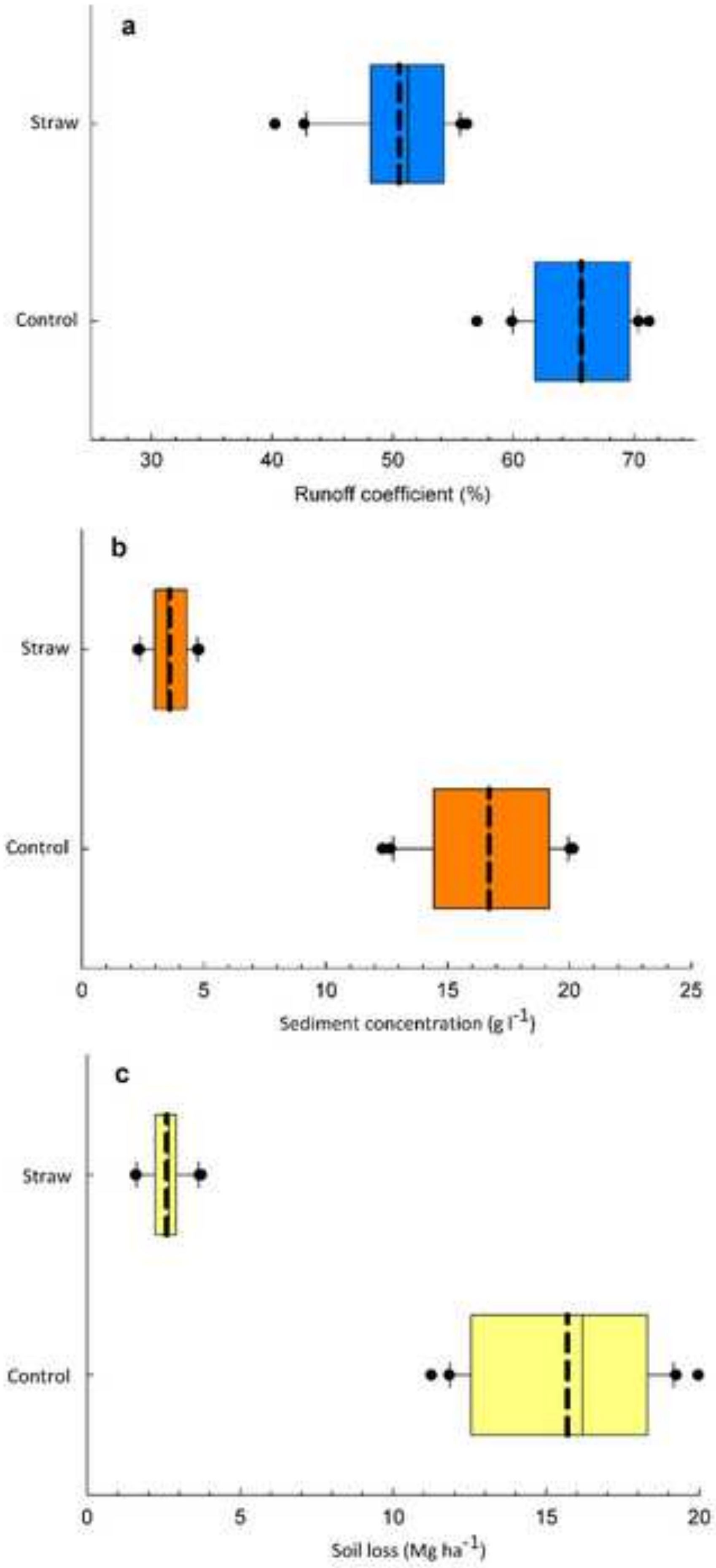
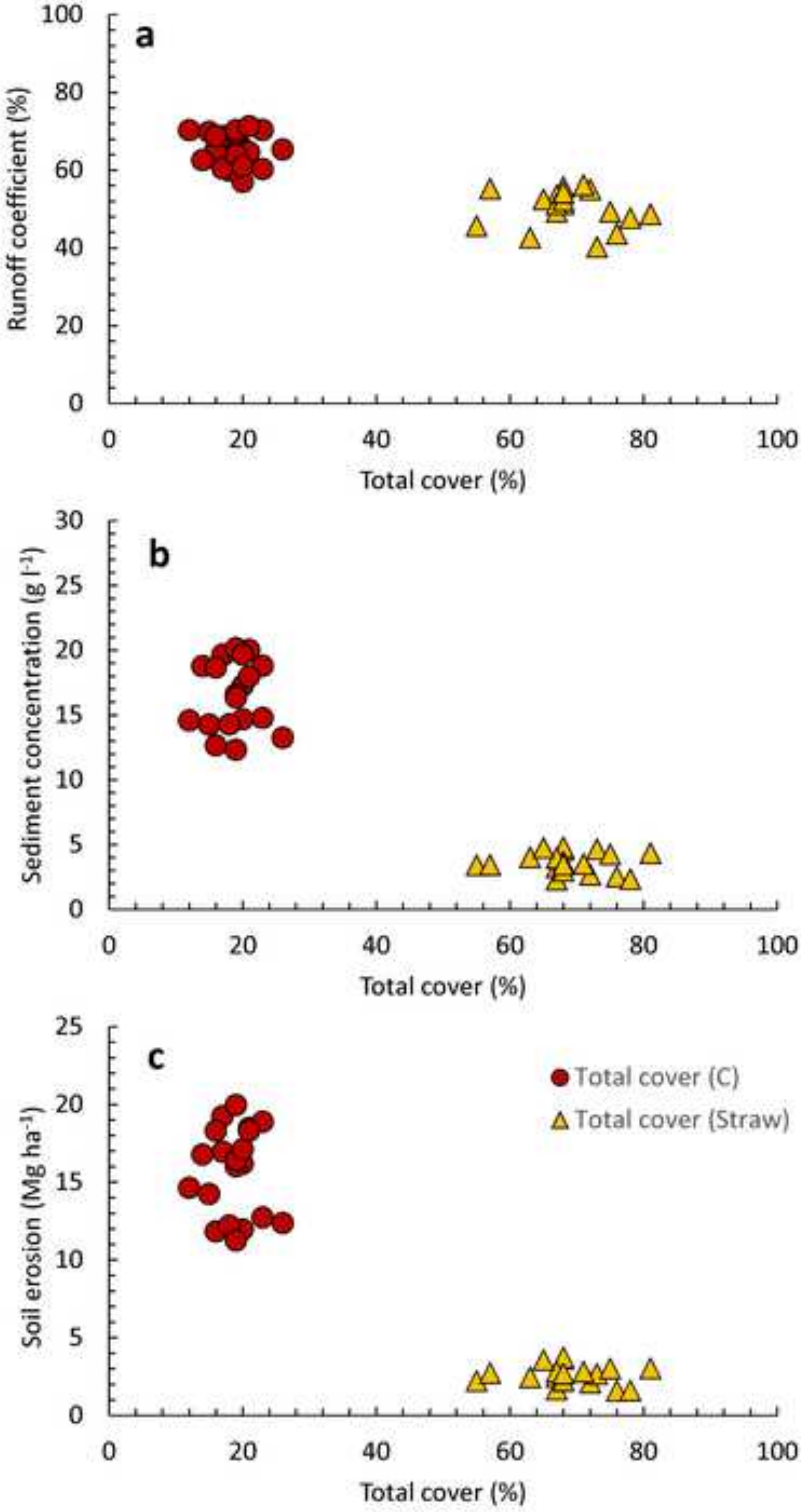

a
Straw
Control
30
40
50
60
70
Runoff coefficient (%)
b
Straw
Control
0
5
10
15
20
25
Sediment concentration (g l$^{-1}$)
c
Straw
Control
0
5
10
15
20
Soil loss (Mg ha$^{-1}$)

Figure 6


a
Runoff coefficient (%)
100
80
60
40
20
0
0
20
40
60
80
100
Total cover (%)
b
Sediment concentration (g l⁻¹)
30
25
20
15
10
5
0
0
20
40
60
80
100
Total cover (%)
c
Soil erosion (Mg ha⁻¹)
25
20
15
10
5
0
● Total cover (C)
△ Total cover (Straw)
0
20
40
60
80
100
Total cover (%)