IRIS - Archivio Istituzionale dell'Università degli Studi di Sassari

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

note finali coverpage

(Article begins on next page)

10 April 2024

**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**

Keesstra, S.D.[1,2], Rodrigo-Comino, J.[3,4*], Novara, A.[5], Giménez-Morera, A.[6], Pulido, M.[7], Di Prima, S.[8], Cerdà, A.[9]


[1]Soil, Water and Land Use Team, Wageningen Environmental Research, Wageningen UR, 6708PB Wageningen, The Netherlands saskia.keesstra@wur.nl
[2]Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan 2308, Australia.
[3]Instituto de Geomorfología y Suelos, Department of Geography, Málaga University, Campus of Teatinos s/n, 29071 Málaga, Spain. rodrigo-comino@uma.es
[4]Department of Physical Geography, Trier University, D-54286 Trier, Germany
[5]Dipartimento di Scienze Agrarie e Forestali, University of Palermo Italy, agata.novara@unipa.it
[6]Universitat Politècnica de València, Department of Economy and Social Sciences, Camino de Vera s/n, 46022, Valencia, Spain. angimo1@doctor.upv.es
[7]GeoEnvironmental Research Group, University of Extremadura, Faculty of Philosophy and Letters, Avda. de la Universidad s/n, 10071 Cáceres, Spain. mapulidof@unex.es
[8]Université de Lyon; UMR5023 Ecologie des Hydrosystèmes Naturels et Anthropisés, CNRS, ENTPE, Université Lyon 1, 3 rue Maurice Audin, 69518 Vaulx-en-Velin, France. simoedg@gmail.com
[9]Soil Erosion and Degradation Research Group. Department of Geography, Valencia University, Blasco Ibàñez, 28, 46010 Valencia, Spain. artemio.cerda@uv.es


*Contact author: Jesús Rodrigo Comino. rodrigo-comino@uma.es

26  **Abstract**

27  In many Mediterranean areas, citrus orchards exhibit high soil loss rates because of the

28  expansion of drip irrigation that allows cultivation on sloping terrain and the widespread use

29  of glyphosate. To mitigate these non-sustainable soil losses, straw mulch could be applied as

30  an efficient solution but this has been poorly studied. Therefore, the main goal of this paper

31  was to assess the use of straw mulch as a tool to reduce soil losses in clementine

32  plantations, which can be considered representative of a typical Mediterranean citrus

33  orchard. A total of 40 rainfall simulation experiments were carried out on 20 pairs of

34  neighbouring bare and mulched plots. Each experiment involved applying 38.8 mm of rain at

35  a constant rate over one hour to a circular plot of 0.28 m$^2$. The results showed that a cover

36  of 50% of straw (60 g m$^{-2}$) was able to delay the time to ponding from 32 to 52 s and the

37  time to runoff initiation from 57 to 129 s. Also, the mulching reduced the runoff coefficient

38  from 65.6 to 50.5 %. The effect on sediment transport was even more pronounced, as the

39  straw mulch reduced the sediment concentration from 16.7 g l$^{-1}$ to 3.6 g l$^{-1}$ and the soil

40  erosion rates from 439 g to 73 g. Our results indicated that mulching can be used as a useful

41  management practice to control soil erosion rates due to the immediate effect on high soil

42  detachment rate and runoff initiation reduction in conventional clementine orchards on

43  sloping land, by slowing down runoff initiation and by reducing runoff generation and,

44  especially, sediment losses. We concluded that straw mulch is also a sustainable solution in

45  glyphosate-treated citrus plantations.

46

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

48  simulation.

49

50

## 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

73  winter. The expansion has raised concerns about enhanced erosion rates on the hillslopes.

74  However, scientific evidence for this is lacking in recent research on citrus plantations.

75  The acceleration of soil erosion rates in Mediterranean fields is a consequence of the

76  combination of the sloping terrain, bare soils due to herbicide applications, and because of

77  the compaction of the soil surface layer that results in low infiltration rates (Gómez et al.,

78  2004). For example, in Asian citrus plantations, soil degradation was also found as a result of

79  a drastic increase in production, although measurements are limited and need to be updated

80  (Xu et al., 2012). China is a country that represents a clear example where the effects of the

81  new citrus plantation with intense use of agrichemicals have caused non-sustainable soil

82  erosion rates, which have been observed under field conditions (Liu et al., 2012; Li et al.,

83  2014).

84  During the last twenty years, there has been a strong demand for clementines from northern

85  European countries, incentivised Spanish by a premium price in the market (Moll and Igual,

86  2006). The increase in clementine production resulted in an increase in the use of herbicides

87  to sustain the production, in particular, glyphosate has become the standard practice in the

88  Valencian region. (Cerdà et al., 2018b). The use of herbicides (glyphosate) caused an

89  increase in bare soils in the sloping terrain in the Valencia region (see figure 1), which leads

90  to high soil erosion rates after heavy storms.

91  Soils are a key resource that offers goods and services to humanity. A healthy soil is a

92  cornerstone of our biophysical system that is vital to reach the Sustainable Development

93  Goals (Likar et al., 2015; Keesstra et al., 2016). This set of Goals, that is aimed to be met in

94  2030, can only be reached through good management of the biophysical, the socio-

95  economic and policy environment. The first requirement, therefore, is a healthy biophysical

96  environment in which the soil forms the basis. Thus, to achieve sustainability, new

97    management strategies for agricultural production are needed that take economically

98    sustainable production as a primary goal without damaging soil fertility and the services soils

99    offer (Calleja-Cervantes et al., 2015). For that, the implementation of low-cost solutions may

100    contribute to maintaining a healthy soil and avoid impacts in other regions or in other

101    spheres of the Earth such as the atmosphere (i.e. air pollution) or hydrosphere (i.e. aquifer

102    recharge).

103    An efficient natural solution for non-unsustainable soil erosion rates in agricultural lands

104    (Verheijen et al., 2009) is the use of catch crops, which are fast-growing crops that are sown

105    between the rows or perennial sod crops in autumn or early winter (Finch et al., 2014; Jat et

106    al., 2018). Catch crops can reduce soil losses due to rain and wind and increase soil water

107    and nutrient-holding capacity (Kort et al., 2008). However, many farmers in the studied

108    region reject their use due to the cost and due to the perception, that they will lose their

109    reputation as good farmers because the community sees catch crops as weeds.

110    In agriculture lands, another strategy to control unsustainable soil losses is the use of straw

111    mulch. Prosdocimi et al. (2016a) found that there is a sudden decrease in sediment delivery

112    in vineyards, once the straw mulch is applied to the ploughed soils. In Portugal, the chipped

113    material was successfully used as forest mulch because of the low prices (Prats et al., 2012;

114    2014). These implementations of the use of straw mulch in large-scale projects imply that it

115    could also have a potential for the industrialized hillslope citrus farming under glyphosate

116    treatment in the Valencia area. Other previous research showed that straw mulch apart

117    from reducing soil loss also increased infiltration (Mannering and Meyer, 1963). Straw mulch

118    is effective to reduce soil erosion, both immediately after applying (Döring et al., 2005; Bhatt

119    et al., 2006; Gholami et al., 2013). Recently, the use of straw mulch was also applied to

120    rangelands affected by forest fires (Vega et al., 2014).

121  This work aimed to i) quantify soil detachment and runoff initiation under conventional

122  clementine cultivation on hillslopes in the Valencia region; and ii) assess the impact of straw

123  mulch as a conservation measure to control the water and sediment losses. Both research

124  questions were addressed through rainfall simulation experiments carried out in the field.

125

126  **2. Case Study area and monitoring sites**

127  An experimental plot cultivated with clementine trees was selected to quantify initial soil

128  and water losses in Eastern Spain (Valencia Province, Canals Municipality). The research site

129  is located on a sloping terrain (10 %), at $38^o$ 57' 27''N; $0^o$ 36' 32, 230 m a.s.l. (Figure 2a).

130  Mean annual rainfall is 550 mm and the average mean temperature $16.5^oC$ (Elías Castillo.

131  and Ruiz Beltrán, 1979). The clementine orchard is located on a pediment on Cretaceous

132  limestones that developed *Eutric Regosols* (IUSS Working Group WRB, 2014). Soil texture is

133  silty clay and herbicide (glyphosate) was applied 3 to 4 times per year.

134

135  *3. Materials and methods*

136  *3.1. Experimental design and sample collection*

137  A straw application of 750 kg ha$^{-1}$ was applied in the study area. Plant and rock fragment

138  cover, local slopes and soil roughness were measured prior to the rainfall experiments. Plant

139  and rock fragment covers were determined by measuring the presence (1) or absence (0) of

140  plants and rocks in 100 points regularly distributed at each 0.28 m$^2$ plot. Together with the

141  straw cover, all were summarized and considered as total cover (%). Local slopes were

142  measured using a digital clinometer. The roughness of the soil surface was determined

143  within the plot with a 1 m long chain and measured twice, from the upper part to the

144  bottom of the plot. The chain was carefully placed on the irregular soil surface and the

6

145   roughness coefficient (m m$^{-1}$) was estimated (Saleh, 1993). Forty rainfall simulation

146   experiments (2 types of management –without and with straw mulch- × 20 plots)

147   homogeneously covering all the situations (close to the trees, the ridges, in the inter-row

148   and row areas, etc.) were conducted in order to reduce noise or variance in the data. They

149   were carried out at 38.8 mm h$^{-1}$ rainfall intensity for one hour on circular paired plots (0.28

150   m$^2$; Fig. 2b and 2c). Ring plots are widely used in the soil scientific community because they

151   are able to concentrate soil losses and runoff to the outlet in order to improve the sampling

152   inside the plot, avoiding the entrance of sediment detachment from other surrounding areas

153   (Iserloh et al., 2012). The simulated thunderstorms represent a rainfall event with an

154   average return period of 2 years in the study area (Elías Castillo and Ruiz Beltrán, 1971). In

155   order to allow comparisons among plots, all experiments were carried out during the

156   Mediterranean dry summer when the soil moisture is low (July) and any effect after a storm

157   can modify previous soil conditions. At each plot, runoff flow was collected at 1-min intervals

158   and the water volume was measured. Runoff coefficients were calculated as the percentage

159   of rainfall water leaving the circular plot. During rainfall simulation experiments, time to

160   ponding (time required for 50% of the surface to be ponded; Tp, s), time to runoff initiation

161   (Tr, s) and time required by runoff to reach the outlet (Tro, s) were recorded. Time to

162   ponding was determined when ponds were found and Tr when those ponds were connected

163   by the runoff. Tr-Tp, Tro-Tr, and Tro-Tp were calculated and they indicate how the ponding is

164   transformed into runoff and how much the runoff in the soil surface last to reach the plot

165   outlet.

166

167   ***3.3. Laboratory analyses***

168  Soil samples (three repetitions) were collected using 100 cm$^3$ rings for the first 6 cm soil

169  layer to determine the bulk density. Soil water content (%) was volumetrically calculated on

170  a weight basis after drying the samples (105$^o$C, 24 h). Soil organic matter was determined by

171  the Walkley-Black method (Walkley and Black, 1934). Runoff samples were air-dried and

172  sediment yield was calculated on a weight basis in order to calculate soil loss per area and

173  time (Mg ha$^{-1}$ h$^{-1}$).

174

175  **3.4. Data analyses**

176  General descriptive statistics were calculated for the plot characteristics (average, standard

177  deviation, maximum and minimum values, the coefficient of variation, Skewness, and

178  Kurtosis) and hydrological responses (average, standard deviation, maximum and minimum

179  values). Soil erosion results (runoff coefficient, sediment concentration, and soil loss) were

180  depicted in box plots adding the mean (dash lines) and median values, and the results

181  between 5th and 95th percentiles. Hydrological responses were summarized in a table.

182  Differences among managements (control and straw) in hydrological response and soil

183  erosion results were compared. To check the normal distribution of data, the Shapiro-Wilk

184  test was conducted. To assess the significant differences among treatments, an ANOVA-one

185  way was conducted. If the normality test failed, a Mann–Whitney U test was used to find

186  differences among treatments. Finally, the Spearman's rank correlation coefficient was

187  computed to assess the possible influence of environmental plot variables on hydrological

188  responses and soil erosion results. SigmaPlot 12.0 (Systat) was used to perform all the

189  statistical analysis.

190

191  **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

216  76 s delayed from the ponding time. Another key parameter that identifies the contrasting

217  response of the straw-covered plots is the fact that the mean runoff reached the outlet of

218  the plot after 67 s since the runoff initiation, meanwhile, on the control plots, the runoff was

219  found after 39 s. From the mean ponding time to the runoff outlet, the control plots show 66

220  s on average and the straw plots 142 s.

221

222  ### *4.2.2. Runoff discharge*

223  Runoff amounted to 26.3 l out of 40 l of rainfall in the control plots (Fig. 5a). In the straw

224  plots, the runoff discharge amounted to 20.2 l. This is a runoff coefficient of 65.6 and 50.5%

225  respectively for control and straw plots. The variability of the runoff was similar in both sets

226  of plots. The runoff discharge ranged from 22.8 to 28.5 l in the control plots and from 16.1 to

227  22.5 l at the straw plots. The differences between control and straw plots were statistically

228  significant for the runoff discharge parameters.

229

230  ### *4.2.3. Sediment concentration*

231  The sediment concentration was highly affected by the straw application (Fig. 5b). The

232  twenty bare plots generated runoff with 16.7 g $l^{-1}$ of sediment, meanwhile, the straw-

233  covered plots contributed with 3.6 g $l^{-1}$. The values ranged from 12.3 to 20.1 g $l^{-1}$ at the

234  control plots, and from 2.3 to 4.8 g $l^{-1}$ at the straw mulch covered plots. Statistically

235  significant differences were found.

236

237  ### *4.2.4. Soil erosion*

238  The total sediment detached from the 0.28 m$^2$ plots was calculated: 439 g and 73 g for the

239  control and straw plots, respectively (Fig. 5c). That means soil erosion rates of 15.7 and 2.6

240   Mg ha$^{-1}$ h$^{-1}$, respectively. The sediment yield ranged from 314 to 559 g and from 44.3 and

241   104.2 g for the control and straw covered plots. Soil erosion ranged from 11.2 and 20 Mg ha$^{-}$

242   $^{1}$ h$^{-1}$, and from 1.6 and 3.7 Mg ha$^{-1}$ h$^{-1}$ for the control and straw covered plots. Statistically

243   significant differences were found for soil erosion, runoff discharge, and sediment

244   concentration.

245

246   *4.3. Straw as a key factor*

247   After conducting a Spearman rank´s correlation coefficient, the straw was found to be the

248   key factor that explained the differences between the paired plots either for the runoff

249   generation as for the runoff discharge, sediment concentration and soil erosion (Table 3). All

250   the other parameters measured did not show any influence on the changes within the two-

251   paired set of plots. It was also found that soil erosion is highly dependent on the sediment

252   concentration, which is the factor that was most affected by the use of the straw mulch.

253

254   **5. DISCUSSION**

255   **5.1. Treatment effectiveness in terms of principal soil threats**

256   There was a clear impact of the application of straw mulch on highly degraded soils from

257   clementine plantations due to the role of straw played as a protective cover. Figure 6 shows

258   the distribution of the soil erosion, sediment concentration and runoff for the two sets of

259   twenty plots: with and without straw mulch. In general, the studied plots showed a low

260   cover of plants and rock fragments. However, the applied straw mulch made the difference

261   related to the soil erosion, sediment concentration, and runoff discharge. The mulched plots

262   showed much lower runoff discharge, sediment concentration, and soil erosion. Straw mulch

263 influenced five runoff-erosion processes at the pedon scale: splash erosion, rainfall

264 interception, ponding, infiltration and flow connectivity.

265

266 **5.2. Changes in biophysical processes**

267 *5.2.1. Soil processes at the pedon scale*

268 There was a clear contrast between mulched and bare plots in splash erosion due to the role

269 straw plays in the reduction of the raindrop impact. The reduced raindrop impact decreases

270 the detachment effect on the soil floor when the straw is present (Bisal, 1960). There is a

271 need of more research on splash erosion, and this research should address to find new and

272 sustainable management strategies that have the objective to lessen raindrop impact

273 (Sadeghi et al., 2017). Straw acts as a protective cover against the raindrop impact and this

274 reduces soil erosion rates such as Gholami et al (2013) measured. This verifies previous

275 research (Poesen et al., 1986) developed under the field, laboratory and modelling

276 approaches that show that soil surface cover is the key factor determining splash erosion

277 and thereby that affects sediment delivery at the pedon scale (Angulo-Martínez et al., 2012).

278 The mulched plots showed more cover (an increase of 50%). The straw increased the time to

279 ponding, and the time the ponded surfaces took to generate overflow was also much longer

280 (Fig. 3). This was entirely or partly due to the fact that the straw intercepted some of the

281 rainfall, which delayed the wetting of the soil surface. Furthermore, the straw creates a

282 rougher surface, creating more potential ponding surfaces. The interception by straw could

283 be one of the causes of the delay in runoff initiation and as a consequence of the decrease in

284 total runoff. The role of interception in the rainfall-runoff response is well-known in forest

285 hydrology where the role litter can play in the interception process was already found by

286 Helvey and Patric (1965) who showed that there is a clear control of the biomass and the

287 storage and drainage capacity of the litter (see also Pitman, 1989). The effect of the amount

288 and cover of straw and other mulch effects is a key topic that must be investigated in detail.

289

290 *5.2.2. Infiltration runoff impacts on sediment yield*

291 The straw cover reduces overland flow speed and this can increase infiltration, and therefore

292 may reduce the amount of runoff. Similar effects were found for emerging vegetation

293 (James et al., 2004), in wetlands (Kadlec, 1990) and in vegetated channels (Carollo et al.,

294 2002). The effect of vegetation stems was also researched and found to be an important

295 factor in overland flow hydraulics changes (Zhao et al., 2016) and explains the impact of

296 vegetation on the resistance to overland flow in grasslands and shrublands, if the shrubs are

297 covering the soil surface, as occurs also with the straw mulch.

298

299 **5.3. Covered soils using natural products, why should they be preferred**

300 The soils studied in the clementine's orchards on bare surfaces are poor in organic matter,

301 which results in high soil and water losses. There is a need to stop further degradation and,

302 in many cases, to restore soil quality and the associated soil functions. Straw mulch is a

303 natural product that enhances the soil functions in the long term and has an immediate

304 effect on soil erosion and can be an option to achieve these goals. In a recent review of

305 nature-based solutions in land management (Keesstra et al., 2018), it was explained that

306 there are two types of Nature Based Solutions: soil and landscape solutions. The use of straw

307 mulch can be seen as a soil solution; it immediately reduces the erosion and water loss, as

308 was explained in this study. It will also generate higher water availability for the plants due

309 to higher infiltration. The straw will also increase the soil organic matter, improve the soil

310 physical properties, soil moisture and temperature levels (Ramakrishna et al., 2006;

311    Mulumba and Lal, 2008). It was also found to have a positive effect on nitrogen management

312    (Verma and Bhagat, 1992; Döring et al., 2005), and on the soil microbial biomass (Tu et al.,

313    2006).

314    In addition, straw mulch is an agricultural, local and natural product which needs to be

315    shown as an efficient solution that can enable farmers to achieve sustainable management.

316    However, more work is needed in order to convince farmers to implement this type of

317    management. Recent research carried out in the same region in rainfed agricultural lands

318    demonstrated that the farmers might be willing to adopt this kind of management

319    interventions if these were subsidized (Cerdà et al., 2018a; 2018b). The same kind opinions

320    were found with other Spanish farmers, such as olive orchards (Sastre et al., 2016) or

321    vineyards (Marques et al., 2015), where farmers also perceived mulch and cover crops as

322    dirt. Even though the farmers know these kinds of strategies are beneficial to counteract

323    erosion, the perception of it being dirty as well as the pressure from their fellow farmers

324    seems to hinder the widespread adoption of these measures.

325

**6. CONCLUSIONS**

327    The use of straw mulch was very efficient to reduce soil and water losses under simulated

328    rainfall on intensively managed clementine plantations with intense use of agrichemicals.

329    The mulching reduced overland flow amounts, sediment concentration and soil losses with a

330    factor of 1.3, 4.63 and 6, respectively. These reductions and changes could be attributed to

331    the impacts of straw mulch on splash erosion and overland flow velocity. Our research

332    furthermore demonstrated that straw mulching produced a clear delay in runoff initiation

333    and runoff amount due to the straw. Therefore, we conclude that mulching would seem a

334 feasible solution to use local agricultural residues to mitigate non-sustainable soil and water

335 losses found in conventional clementine orchards in the Mediterranean belt.

336

345

346 **References**

347 Angulo-Martínez, M., Beguería, S., Navas, A., Machin, J. 2012. Splash erosion under natural

348 rainfall on three soil types in NE Spain. Geomorphology, 175, 38-44.

349 Ben-Salem, N., Álvarez, S., López-Vicente, M., Ben-Salem, N., Álvarez, S., López-Vicente, M.,

350 2018. Soil and Water Conservation in Rainfed Vineyards with Common Sainfoin and

351 Spontaneous Vegetation under Different Ground Conditions. Water 10, 1058.

352 Bhatt, R., Khera, K.L. 2006. Effect of tillage and mode of straw mulch application on soil

353 erosion in the submontaneous tract of Punjab, India. Soil and Tillage Research, 88(1),

354 107-115.

355 Bisal, F. 1960. The effect of raindrop size and impact velocity on sand-splash. Canadian

356 Journal of Soil Science, 40(2), 242-245.

357    Bono, E. 2010. Naranja y desarrollo. La base agrícola exportadora de la economía del País

358        Valenciano y el modelo de crecimiento hacia afuera. PUV, Valencia, 203 pp.

359    Butzer, K.W., Mateu, J.F., Butzer, E.K., Kraus, P. 1985. Irrigation agrosystems in eastern

360        Spain: Roman or Islamic origins? Annals of the Association of American Geographers,

361        75(4), 479-509.

362    Calleja-Cervantes, M.E., Fernández-González, A.J., Irigoyen, I., Fernández-López, M.,

363        Aparicio-Tejo, P.M., Menéndez, S., 2015. Thirteen years of continued application of

364        composted organic wastes in a vineyard modify soil quality characteristics. Soil

365        Biology and Biochemistry 90, 241–254.

366    Carollo, F.G., Ferro, V., Termini, D. 2002. Flow velocity measurements in vegetated channels.

367        Journal of Hydraulic Engineering, 128(7), 664-673.

368    Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A., Keesstra, S.D., 2018a. Hydrological and

369        erosional impact and farmer's perception on catch crops and weeds in citrus organic

370        farming in Canyoles river watershed, Eastern Spain. Agriculture, Ecosystems &

371        Environment 258, 49–58.

372    Cerdà, A., Rodrigo-Comino, J., Giménez-Morera, A., Novara, A., Pulido, M., Kapovic-Solomun,

373        M., Keesstra, S.D. 2018b. Policies can help to apply successful strategies to control

374        soil and water losses. The case of chipped pruned branches (CPB) in Mediterranean

375        citrus plantation. Land Use and Policy, 75, 734-745. DOI:10.1016/j.landusepol2017.12

376    Döring, T.F., Brandt, M., Heß, J., Finckh, M.R., Saucke, H. 2005. Effects of straw mulch on soil

377        nitrate dynamics, weeds, yield and soil erosion in organically grown potatoes. Field

378        Crops Research, 94(2), 238-249.

379    Elías Castillo, F. & Ruiz Beltrán, L. 1979. Precipitaciones máximas en España. Estimaciones

380        basadas en métodos estadísticos. ICONA, Ministerio de Agricultura, Madrid.

381    Finch, H.J.S., Samuel, A.M., Lane, G.P.F., 2014. 8 - Cropping techniques, in: Lockhart &

382          Wiseman's Crop Husbandry Including Grassland (Ninth Edition). Woodhead

383          Publishing, pp. 193–217.

384    García-Ruiz, J.M., Beguería, S., Nadal-Romero, E., González-Hidalgo, J.C., Lana-Renault, N.,

385          Sanjuán, Y., 2015. A meta-analysis of soil erosion rates across the world.

386          Geomorphology 239, 160–173.

387    García-Ruiz, J.M., Nadal-Romero, E., Lana-Renault, N., Beguería, S., 2013. Erosion in

388          Mediterranean landscapes: Changes and future challenges. Geomorphology 198, 20–

389          36.

390    Gholami, L., Sadeghi, S.H., Homaee, M. 2013. Straw mulching effect on splash erosion,

391          runoff, and sediment yield from eroded plots. Soil Science Society of America Journal,

392          77(1), 268-278.

393    Gómez, J. A., Romero, P., Giráldez, J. V., Fereres, E. 2004. Experimental assessment of runoff

394          and soil erosion in an olive grove on a Vertic soil in southern Spain as affected by soil

395          management. Soil Use and Management, 20(4), 426-431.

396    Gómez, J.A., Infante-Amate, J., de Molina, M.G., Vanwalleghem, T., Taguas, E.V., Lorite, I.,

397          2014. Olive cultivation, its impact on soil erosion and its progression into yield

398          impacts in Southern Spain in the past as a key to a future of increasing climate

399          uncertainty. Agriculture 4, 170–198.

400    Helvey, J., Patric, J.H. 1965. Canopy and litter interception of rainfall by hardwoods of

401          eastern United States. Water Resources Research, 1(2), 193-206.

402    Iserloh, T., Fister, W., Seeger, M., Willger, H., Ries, J.B., 2012. A small portable rainfall

403          simulator for reproducible experiments on soil erosion. Soil and Tillage Research 124,

404          131–137.

405     IUSS Working Group WRB, 2014. World Reference Base for Soil Resources 2014, World Soil

406          Resources Report. FAO, Rome.

407     James, C.S., Birkhead, A.L., Jordanova, A.A., O'sullivan, J.J. 2004. Flow resistance of emergent

408          vegetation. Journal of Hydraulic Research, 42(4), 390-398.

409     Jat, M.L., Bijay-Singh, Stirling, C.M., Jat, H.S., Tetarwal, J.P., Jat, R.K., Singh, R., Lopez-Ridaura,

410          S., Shirsath, P.B., 2018. Chapter Four - Soil Processes and Wheat Cropping Under

411          Emerging Climate Change Scenarios in South Asia, in: Sparks, D.L. (Ed.), Advances in

412          Agronomy. Academic Press, pp. 111–171.

413     Kadlec, R. H. 1990. Overland flow in wetlands: vegetation resistance. Journal of Hydraulic

414          Engineering, 116(5), 691-706,

415     Kairis, O., Karavitis, C., Kounalaki, A., Salvati, L., Kosmas, C., 2013. The effect of land

416          management practices on soil erosion and land desertification in an olive grove. Soil

417          Use Management 29, 597–606.

418     Keesstra, S.D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L.,

419          Quinton, J.N., Pachepsky, Y., Van Der Putten, W.H., Bardgett, R.D., Moolenaar, S.,

420          Mol, G., Jansen, B., Fresco, L.O., 2016. The significance of soils and soil science

421          towards realization of the United Nations sustainable development goals. SOIL 2.

422     Keesstra, S., Nunes, J., Novara, A., Finger, D., Avelar, D., Kalantari, Z., Cerdà, A. 2018. The

423          superior effect of nature- based solutions in land management for enhancing

424          ecosystem services. Science of the Total Environment, 610, 997-1009.

425     Kort, J., Collins, M., Ditsch, D. 1998. A review of soil erosion potential associated with

426          biomass crops. Biomass and Bioenergy, 14(4), 351-359.

427     Li, X.H., Yang, J., Zhao, C.Y., Wang, B. 2014. Runoff and sediment from orchard terraces in

428          southeastern China. Land Degradation & Development, 25(2), 184-192.

429 Likar, M., Vogel-Mikuš, K., Potisek, M., Hančević, K., Radić, T., Nečemer, M., Regvar, M.,

430       2015. Importance of soil and vineyard management in the determination of

431       grapevine mineral composition. Science of The Total Environment 505, 724–731.

432 Liu, Y., Tao, Y., Wan, K.Y., Zhang, G.S., Liu, D.B., Xiong, G.Y., Chen, F. 2012. Runoff and

433       nutrient losses in citrus orchards on sloping land subjected to different surface

434       mulching practices in the Danjiangkou Reservoir area of China. Agricultural Water

435       Management, 110, 34-40.

436 Mannering, J.V., Meyer, L.D. 1963. The effects of various rates of surface mulch on

437       infiltration and erosion. Soil Science Society of America Journal, 27(1), 84-86.

438 Marqués, M.J., Bienes, R., Cuadrado, J., Ruiz-Colmenero, M., Barbero-Sierra, C., Velasco, A.,

439       2015. Analysing perceptions attitudes and responses of winegrowers about

440       sustainable land management in Central Spain. Land Degradation & Development 26,

441       458–467.

442 Martínez-Valderrama, J., Ibáñez, J., Del Barrio, G., Sanjuán, M.E., Alcalá, F.J., Martínez-

443       Vicente, S., Ruiz, A., Puigdefábregas, J., 2016. Present and future of desertification in

444       Spain: Implementation of a surveillance system to prevent land degradation. Sci.

445       Total Environ. 563–564, 169–178.

446 Moll, E.P., Igual, J.J. 2006. Production costs of the organic Clementine crop in the region of

447       Valencia (Spain). Spanish Journal of Agricultural Research, 4(1), 17-25

448 Mulumba, L.N., Lal, R. 2008. Mulching effects on selected soil physical properties. Soil and

449       Tillage Research, 98(1), 106-111.

450 Picazo-Tadeo, A.J., Reig-Martínez, E. 2006. Outsourcing and efficiency: the case of Spanish

451       citrus farming. Agricultural Economics, 35(2), 213-222.

452    Pitman, J.I. 1989. Rainfall interception by bracken litter—relationship between biomass,

453        storage and drainage rate. Journal of Hydrology, 111(1-4), 281-291.

454    Prats, S.A., dos Santos Martins, M.A., Malvar, M.C., Ben-Hur, M., Keizer, J.J. 2014.

455        Polyacrylamide application versus forest residue mulching for reducing post-fire

456        runoff and soil erosion. Science of the Total Environment, 468, 464-474.

457    Prats, S.A., MacDonald, L.H., Monteiro, M., Ferreira, A.J., Coelho, C.O., Keizer, J.J. 2012.

458        Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a

459        pine and a eucalypt plantation in north-central Portugal. Geoderma, 191, 115-124.

460    Prosdocimi, M., Jordán, A., Tarolli, P., Keesstra, S., Novara, A., Cerdà, A. 2016. The immediate

461        effectiveness of barley straw mulch in reducing soil erodibility and surface runoff

462        generation in Mediterranean vineyards. Science of The Total Environment, 547, 323-

463        330.

464    Ramakrishna, A., Tam, H.M., Wani, S.P., Long, T.D. 2006. Effect of mulch on soil temperature,

465        moisture, weed infestation and yield of groundnut in northern Vietnam. Field Crops

466        Research, 95(2), 115-125.

467    Sadeghi, S.H., Kiani Harchegani, M., Asadi, H., 2017. Variability of particle size distributions of

468        upward/downward splashed materials in different rainfall intensities and slopes.

469        Geoderma 290, 100–106.

470    Saleh, A., 1993. Soil roughness measurement: Chain method. Journal of Soil and Water

471        Conservation 48, 527–529.

472    Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M.J., García-Díaz, A., 2016. Soil loss in an

473        olive grove in Central Spain under cover crops and tillage treatments, and farmer

474        perceptions. J Soils Sediments 1–16.

475    Tu, C., Ristaino, J.B., Hu, S. 2006. Soil microbial biomass and activity in organic tomato

476        farming systems: Effects of organic inputs and straw mulching. Soil Biology and

477        Biochemistry, 38(2), 247-255.

478    Vanmaercke, M., Poesen, J., Maetens, W., de Vente, J., Verstraeten, G., 2011. Sediment yield

479        as a desertification risk indicator. Science of the Total Environment 409, 1715–1725.

480    Vega, J.A., Fernández, C., Fonturbel, T., González-Prieto, S., Jiménez, E. 2014. Testing the

481        effects of straw mulching and herb seeding on soil erosion after fire in a gorse

482        shrubland. Geoderma, 223, 79-87.

483    Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J., Smith, C.J., 2009. Tolerable versus actual soil

484        erosion rates in Europe. Earth-Science Reviews 94, 23–38

485    Verma, T.S., Bhagat, R.M. 1992. Impact of rice straw management practices on yield,

486        nitrogen uptake and soil properties in a wheat-rice rotation in northern India.

487        Fertilizer Research, 33(2), 97-106.

488    Xu, Q. X., Wang, T. W., Cai, C. F., Li, Z. X., & Shi, Z. H. 2012. Effects of soil conservation on soil

489        properties of citrus orchards in the Three-Gorges Area, China. Land Degradation and

490        Development, 23(1), 34-42.

491    Zhao, C., Gao, J. E., Huang, Y., Wang, G., Zhang, M. 2016. Effects of vegetation stems on

492        hydraulics of overland flow under varying water discharges. Land Degradation and

493        Development, 27(3), 748-757.

**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

**Tables**

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 | 10.4 | 10.2 | 12.5 | 14.6 | 1.33 | 1.34 | 1.3 | 1.3 | 1.05 | 1.04 | 5.5 | 5.0 | 4.2 | 4.1 | 0 | 50.1 |
| SD | ±2.2 | ±2.2 | ±3.1 | ±3.1 | ±0.15 | ±0.16 | ±0.2 | ±0.2 | ±0.02 | ±0.02 | ±0.7 | ±0.7 | ±1.7 | ±1.9 | | ±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
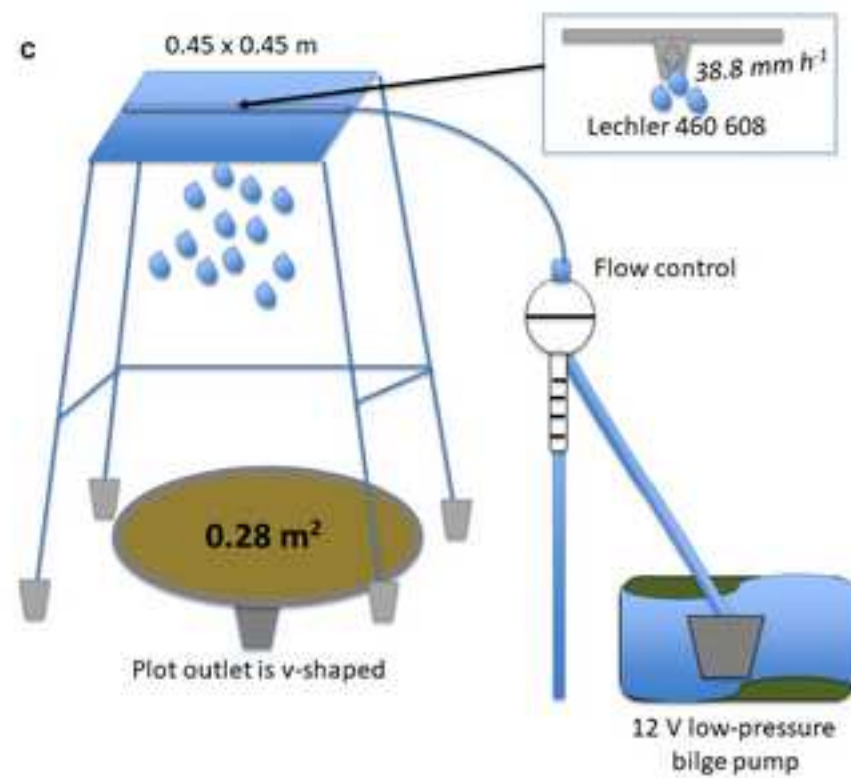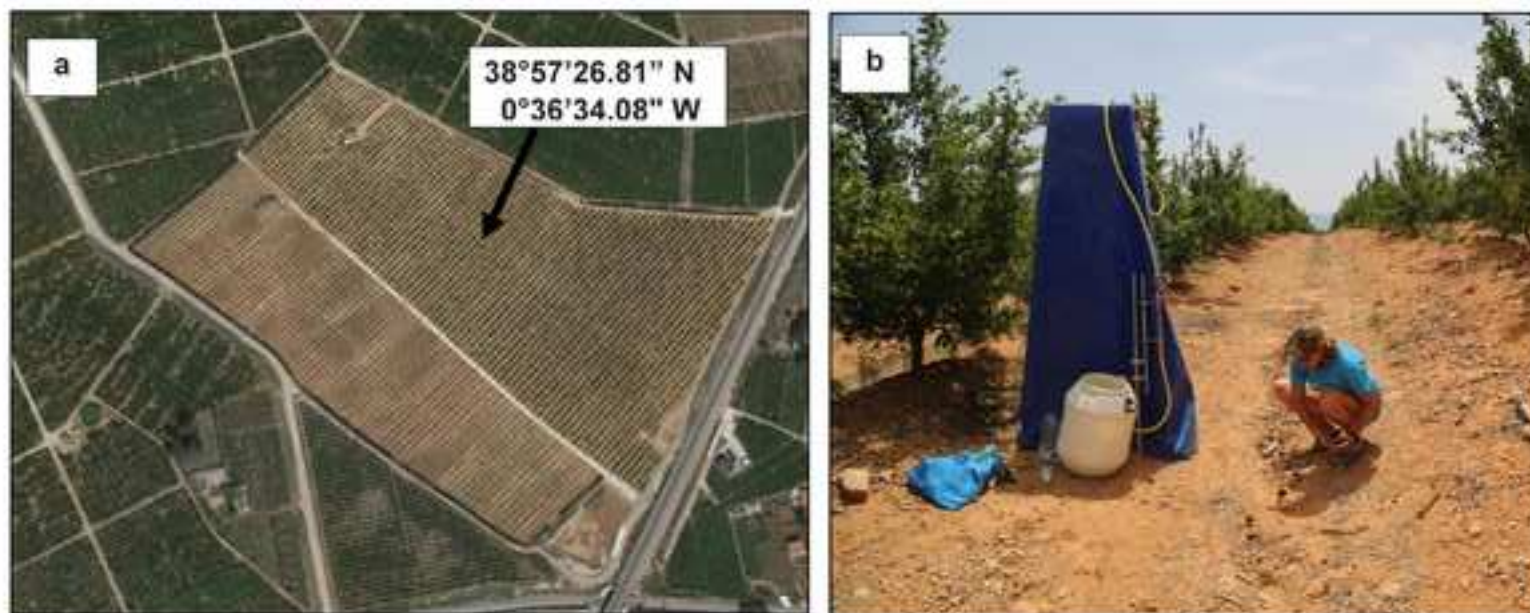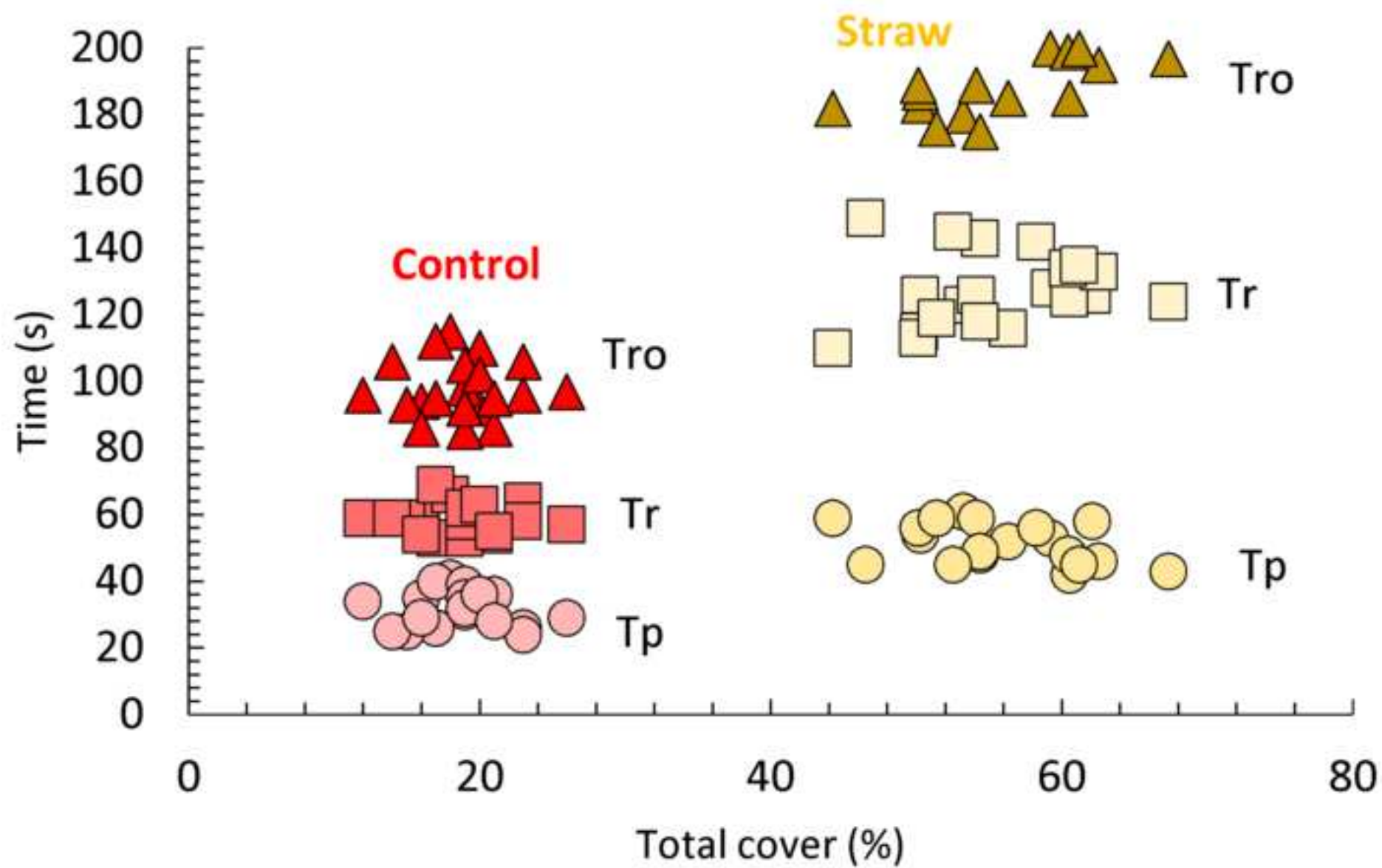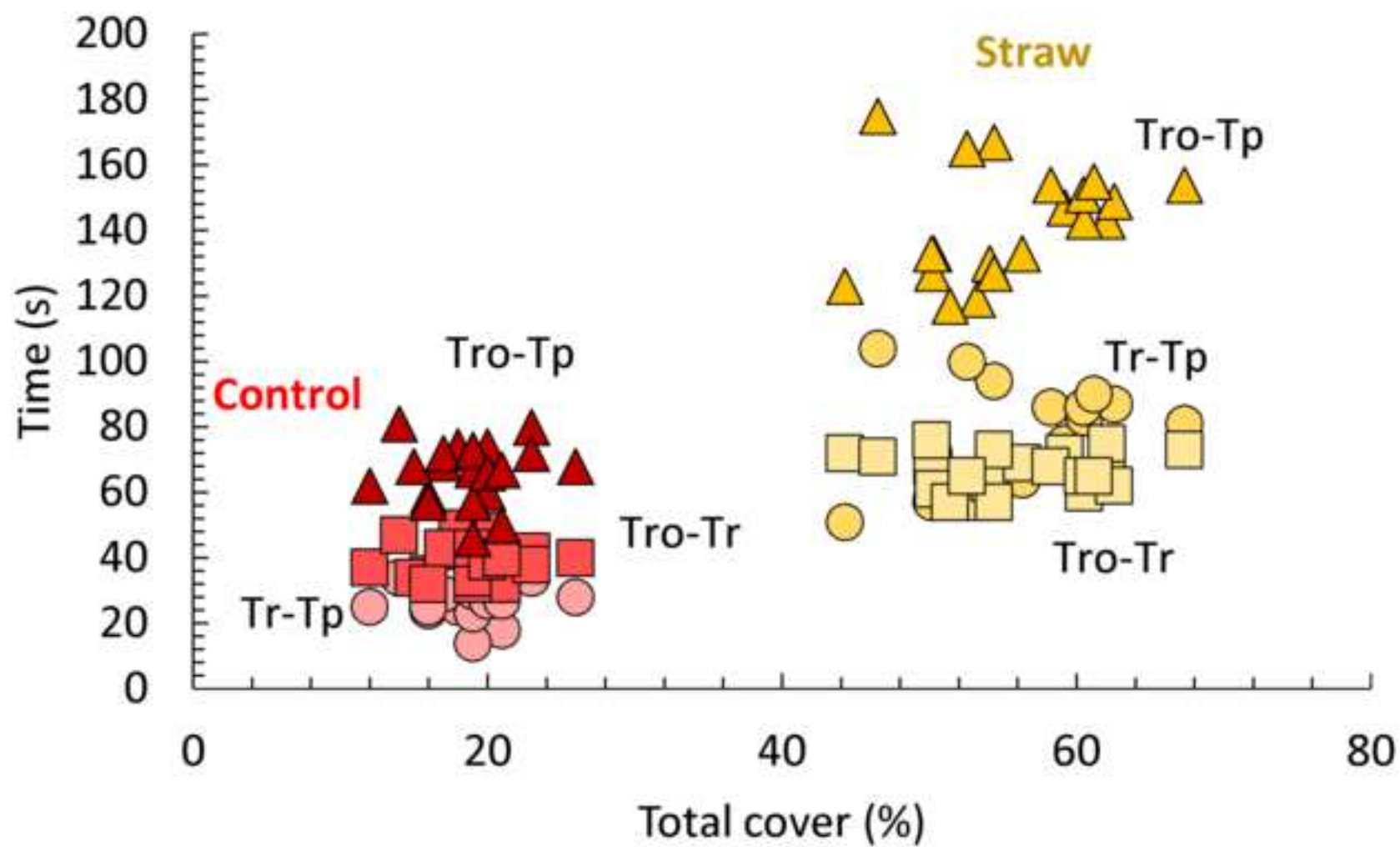
**Figure 1**

**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**

**Figure 4**

**Figure 5**

**Figure 6**