Lateral transfer of organic carbon and phosphorus losses by water erosion at hillslope scale in olive orchards in Southern Spain

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Abstract

Lateral transfer of organic carbon and phosphorus by water erosion at hillslope scale can be a key component in understanding their budget in agricultural areas, particularly those located in areas where erosion rates are high. In this study dissolved organic carbon (DOC) and dissolved reactive phosphorus (DRP) in runoff, and organic carbon (OC) and total phosphorus (TP) in sediment were measured in three olive orchards. These measurements were carried out in a three year runoff plots trial under two different soil management systems (temporary cover crop in the lanes, CC, and conventional tillage, CT). DOC losses (7.8–13.6 kg ha^{-1} yr^{-1}) were equivalent, and OC losses (101–432 kg ha^{-1} yr^{-1}) were higher than those measured in other agricultural and forest systems. Thus, both sources of OC, dissolved in runoff and in sediment, should not be neglected as a relevant flux to water bodies in the region and in the soil organic carbon (SOC) balance at hillslope scale. Losses of DRP (0.03–0.21 kg ha^{-1} yr^{-1}) were in the lower to medium range of published values in agricultural areas, while losses of TP in sediment (2–39 kg ha^{-1} yr^{-1}) were in the higher range of those reported form agricultural areas in the Mediterranean region, as the combined result of enrichment in sediment and high sediment losses. There is the scope for a large reduction of TP by reducing sediment losses through appropriate CC management. Average annual concentration of DOC in runoff and OC and TP in sediment was correlated with that of the top 5 cm of the soil in the lanes of the orchards. When analyzed at event scale, in DOC, OC and DRP presented a moderated trend towards a larger concentration for runoff events of low magnitude, below 10 to 20% runoff coefficient approximately. However, these trends at event scale presented a large scattering that precludes the determination of robust correlations for prediction and model calibration purposes.

Keywords: organic carbon, phosphorus, olive, runoff, erosion, hillslope.

Introduction

The effect of soil management on soil degradation processes in olive growing areas has been the subject of considerable research in the last decades, especially in Spain (Gómez et al., 2014). This is so because soil degradation by accelerated water erosion has been noted as one of the major threats to sustainability of olive plantations in the Mediterranean region (Beaufoy, 2001; Gómez and Giráldez, 2009). The reasons for this severe soil degradation, caused by water erosion, are a combination of cultivation in sloping areas and the Mediterranean type of climate with periodic and strong rainfall events mingled with drought periods. Furthermore, this phenomenon is fostered by inadequate soil management practices based on maintaining bare soil, killing weeds via tillage or herbicide application to prevent competition for soil water (Gómez et al., 2014). This dramatic erosion has been reported in technical reports since the early 1960´s (Bennet, 1960) but some studies suggest that it has been in progress in the region, albeit at a more moderate rate, since the early XIX century (Vanwalleghem et al., 2011).

In olive, and in general in tree crops, much less information is available for phosphorous (P) and organic carbon (OC) losses associated to surface runoff and sediment losses in comparison to runoff and water erosion losses, . In a four year experiment Gómez et al. (2009b) compared available P (Olsen P) losses in an olive orchard under conventional tillage (CT) and cover crop (CC). CT treatment was the soil management with higher OC and Olsen P losses, e.g. 0.32 and 0.02 Olsen P (kg ha^{-1} yr^{-1}) in CT and CC, respectively. In an analogous experiment during a two year period in a different soil type, Francia et al. (2006) measured higher total phosphorus (TP) losses in CT compared to CC (0.11 *vs*. 0.07 kg ha^{-1} yr^{-1}). These P loadings are usual around the

Mediterranean basin, with average values at large catchment scale ranging from 0.3 to 1 kg ha^{-1} yr^{-1}, mostly associated to water erosion events in agricultural areas (Volf et al., 2013). In contrast to other P sources, e.g. human or industrial source pollution, a reduction of P contribution from agricultural areas requires appropriate management over large areas, and interaction with a considerable number of stakeholders (farmers). This is only possible if there is available information on the impact of different management on actual P losses and the main mechanisms for its transport to water bodies, which is not the case in olive orchards, or any other Mediterranean permanent crop.

Another relevant issue in Mediterranean agricultural areas is the low level of SOC content (usually in the 5–10% g kg^{-1} range) and the consequent negative impact on soil quality (Gómez et al., 2014). Although research about the potential for carbon sequestration in agricultural soils has led to an interest on the role of carbon losses by runoff and water erosion in the total carbon budget (Dawson and Smith, 2007) the information about it is minimum for Mediterranean tree crops. Gómez et al. (2009b) measured average OC losses of 234 and 6.3 kg ha^{-1} yr^{-1} for CT and CC respectively. These magnitudes of OC losses are within the upper range of those measured in other agricultural areas of Europe, e.g. UK (Quinton et al., 2006), and represent a significant fraction of the estimated assumed carbon inputs by vegetation in an olive orchard (Nieto et al., 2010). The available information on the transport of dissolved OC in runoff in Mediterranean tree crops is scant as well, although some studies (e.g., Pardini et al., 2003) indicate that it can represent a significant fraction of OC losses and therefore, have a significant impact on water quality while others indicate that DOC has the potential to diminished the eutrophication impact of phosphorus (Carpenter et al., 1998).

Previous studies suggest that soil management might have a large impact in the OC and P losses through runoff and sediment in olive orchards, but also indicate the need of an improved quantification considering the relative contribution of both (dissolved and in sediment) fractions and the effect of soil type and management. Therefore, a field experiment was designed with the following purposes:

(a) To evaluate losses of total phosphorous (TP) and organic carbon (OC) in sediment, and dissolved reactive phosphorus (DRP) and dissolved organic carbon (DOC) in runoff in olive orchards at hillslope scale under natural rainfall in relation to the soil type and management system (CT or CC).

(b) To evaluate the variability of the TP and OC losses in sediment and the concentration of DRP and DOC in runoff during the season and among years of contrasting rainfall.

(c) To investigate the possible correlation between the TP and OC in sediment and the concentration of DRP and DOC in runoff with the P and OC contents of the topsoil for the different soil types and management systems, and explore the potential for model calibration.

MATERIAL AND METHODS

Experimental sites

The experiment was carried on in three commercial olive orchards located in Andalusia, southern Spain (Figure 1). The olive farm in Córdoba, hereafter called “La Conchuela”, was 10 km west of Córdoba; the second experimental site, “Benacazón”, was established about 26 km west of Seville and the third farm, “Lanjarón”, was located 45 km south of Granada. Table 1 summaries some characteristics of the study sites and some soil properties averaged for the 0–50 cm depth.

Runoff plot experiments

Table 2 shows some of the most relevant information about the runoff plots in the three sites. At La Conchuela, an integrated sample was taken at the outlet of a tipping bucket system to measure runoff from the plots. To determine the average sediment concentration of runoff a collection system based on that of Khan and Ong (1997) was used. Additionally, a sediment trap was located upstream of the tipping buckets. Total sediment coming from the plots was calculated as the sum of trapped sediment (oven dried at 105 ºC) plus the one calculated multiplying total runoff measured by the average sediment concentration. The experiment was completed with an automated rain gage.

At Benacazón, the runoff generated on each plot was led to a system of three fiberglass collection tanks with flow splitters (ratio 1:15) allowing the measurement of up to 110 m^3 equivalent to 230 mm of runoff. Once carefully leveled, the splitters were kept free of leaves, small branches and other organic residues with a small protection net located upstream. The experiment site was completed with two automatic rain gages.

At the Lanjarón site, there was a drawer collector (6 x 0.40 m) and three sediment and runoff tanks (50 cm in diameter and 100 cm in height), with flow splitters (1:9) between two consecutive tanks. In order to complete the measurements, an automatic rain gage was installed.

Figure 2 depicts the experimental sites, showing how at the three sites, the longest dimension of the plots was parallel to the maximum slope.

Soil management

At each of the three experimental sites two soil management: conventional tillage (CT) and temporary cover crops (CC) were implemented as close as possible to those of commercial farms. The CC were planted along the lanes (between the tree rows), parallel in La Conchuela and Benacazón and perpendicular in Lanjarón to the maximum slope (see Figure 2). Tables 3 and 4 present some information about the vegetation management along the lanes at the plots of the three study sites, and other agronomic operations, respectively.

Runoff, sediment and soil sampling and analysis

On the first working day after a single rainfall event, larger than 40 mm, or after a weather front consisting of several rain pulses or events, the runoff collectors and sediment traps were sampled, and the data logger information recorded. In Benacazón and Lanjarón, runoff volume and wet sediment weight were measured in the tanks. In the case of La Conchuela sediment from the sediment traps was weighted and a subsample taken; a sample from the runoff collector was also collected.

Due to problems with the samples for sediment concentration from Lanjarón, the determination of sediment losses was only possible in a limited number of events.

After filtering the runoff samples by 0.45 µm, DOC was determined using a combustion sampler Shimadzu, model TOC-5000, while DRP was determined by the Molybdate

Blue method (Murphy and Riley, 1962). Sediment subsamples were air dried to analyze OC by dry combustion using an elemental analyzer, model CHNS Eurovector EA 3000, and TP by soil digestion with hydrofluoric and perchloric acid (Lim and Jackson, 1982), dissolving the residue in 6M HCl and determining P in solution by Molybdate Blue method.

In winter 2009 and spring of 2012 all the runoff plots were sampled at the three sites on the top 0-5 depth for determination of OC, TP, and Olsen P, according to Olsen and Sommers (1982). At each site three composite samples were taken from each treatment (evenly distributed among the available plot per site) in the lane area and other four composite samples were taken in the area below the canopies.

RESULTS

Organic carbon (OC) and total Phosphorous (TP) in sediment and topsoil

Table 5 presents the OC and TP concentrations in the top soil (0-5 cm depth) of the experimental plots. These concentrations were higher in the top 5-cm of the soil compared to the upper 50 cm of the soil profile, Table 1. Data show too how the three experimental sites do not present large differences in OC content in the top soil although it is apparent a trend towards higher OC concentration in the area below canopies (with the exception of the CC treatment at Benacazón). A slightly higher concentration in the CC treatments compared to the CT ones along the lane area, and the absence of a significant increase in the top soil concentration in OC during the three years of the experiment are visible too. A similar trend is perceived for the TP content

(Table 5), although differences in TP concentration between different sites were larger than for OC.

Annual runoff and sediment losses

Figure 3 summarizes the annual rainfall and runoff results from the experimental sites. The experiment encompassed three contrasting years, in terms of rainfall, with two of them (2009-10 and 2010-11) well above the locations' average and a third one (2011-12) extremely dry. This resulted in a large variation among years, with very high runoff and sediment losses in years 2009-10 and 2010-11, particularly in the first one. The large rainfall and runoff losses were associated to the periods of intense rainfall that occurred in the region during winter and spring of 2009-10 and from fall to spring of 2010-11, which is reflected in the results from the three sites (Figures 3 and 4). At La Conchuela, differences in runoff and sediment between both treatments (CC and CT) were not statistically significant, partly due to the large variability among replicated plots. Differences in average sediment losses between treatments had a tendency to be larger than those observed for runoff. Sediment losses tended to be slightly higher in the CT treatment, Figures 3 and 4. At Benacazón it was observed also a comparable pattern in runoff and sediment, with differences between treatments in sediment losses being larger than those observed for runoff. However, due to the large variability among replicated plots these differences were not statistically significant. Once again, sediment losses were generally larger in the CT compared to the CC treatment during the three years, especially during the two last ones. At Lanjarón, annual runoff and also (for the few measured events) sediment losses were similar for both treatments, being higher in the more rainy years, 2009-10 and 2010-11, (Figures 3 and 4).

Organic carbon (OC) and dissolved organic carbon (DOC) losses

Table 6 summarizes the average losses in OC and DOC at the different sites and treatment, their averaged concentration in sediment and runoff and their variability. In La Conchuela and Benacazón average OC losses in sediment were in the range of 101 to 432 kg ha^{-1} yr^{-1} while the losses of DOC in runoff were an order of magnitude smaller, in the range of 7.8 to 13.6 kg ha^{-1} yr^{-1}. OC losses in Lanjarón were much lower than in La Conchuela and Benacazón. In Lanjarón OC losses in sediment and dissolved in runoff were similar, 12-14 and 9-13 kg ha^{-1} yr^{-1}, respesctively. As in the case of runoff and sediment losses not statistically significant differences were observed in OC and DOC losses between CT and CC treatment. Figures 5 and 6 present the concentration of DOC in runoff and OC in sediment showing a large variability within the season at the three sites. It is patent a higher DOC concentration in events happening early in the season (after the summer drought) or during the dry year 2011-2012, and a systematic pattern of higher DOC concentration in CC compared to CT samples in La Conchuela and Benacazón during most of the evaluated period. This is more clearly observed in the summary statistics presented in Table 6. In Figure 6 a systematic tendency to higher OC concentration in CC compared to CT samples can be observed in the three sites. No clear trend for annual variations of OC concentration in sediment along the year is found.

Total phosphorus (TP) and dissolved total phosphorus (DRP) losses

Table 7 depicts the average results of the losses of TP in sediment and DRP in runoff at the three sites. TP losses were very high at La Conchuela and Benacazón ranging from 38 to 39 and from 2 to 5 kg ha^{-1} yr^{-1} respectively while in Lanjarón, losses in sediment were around 0.2-0.3 kg ha^{-1} yr^{-1}. DRP were in the range of 0.03 to 0.13, 0.048 to 0.051, and 0.17 to 0.21 kg ha^{-1} yr^{-1} for La Conchuela, Benacazón and Lanjarón respectively. These differences can be explained by the variations in concentration among sites, which were higher for DRP in Lanjarón and for TP in Lanjarón and La Conchuela. Overall there were not statistical significant differences in TP and DRP losses between the CT and CC treatments. Figure 7 shows the concentration of TP in sediment samples measured at the different events at the three sites. There is a large variability without a clear trend in annual variations of TP concentration along the year. Figure 8 presents the concentration of DRP in runoff samples measured at the different events at the three sites. It is clear also a large variability, with the highest concentrations of DRP usually happening early in the season (after the summer drought). It is not obvious a systematic pattern to higher DRP concentration in CC compared to CT, see also Table 7, although most of the largest concentrations have been measured in samples coming from CC treatments.

OC and TP concentrations in sediment in relation to event magnitude

DOC in runoff and OC in sediment for the three sites and two treatments *vs.* event runoff coefficient (runoff divided by rainfall in percentage) are plotted in Figure 9. For events of low magnitude, with a runoff coefficient below 15% approximately, DOC concentration presents high variability and some high or very high concentration, especially at very low runoff coefficient values. The higher the runoff coefficient is, the lower the DOC concentration is measured, towards a value around 8 mg L^{-1}. OC concentration in sediment follows a comparable trend although it is less clear the transition runoff coefficient, around 20 to 30%, and the value at which the concentration of OC seems to decrease for large events varied with sites, ranging from 0.6 to 2%.

Figure 10 presents the DRP in runoff and TP in sediment for the three sites and two treatments *vs*. event runoff coefficient. For DRP concentration there is an analogous trend to that of DOC with much higher variability and also to higher concentrations for runoff events below 30%, but lower for large runoff events with tend to be around 0.01-0.02 mg L^{-1}. For TP there was not a clear correlation with runoff coefficient, particularly for La Conchuela where values ranged from 200 to 800 mg kg^{-1}.

DISCUSSION

Annual runoff and sediment losses

This experiment did not find a large significant decrease in runoff with the use of CC compared to the CT treatment. This is in contrast with results from previous studies, mostly in temperate climate (Hartwig and Ammon, 2002), but in line with previous studies on tree crops on Mediterranean soils (Gómez et al., 2011; Leonard and Andrieux, 1998). These studies have noted that the shallower soils and the existence of consolidated subsurface layers (naturally present or due to heavy traffic) during harvest in olive groves, result in a limited impact of CC in reducing runoff generation, especially in very rainy years as 2009-10 and 2010-11 were. These small differences in runoff have important implications for soil water balance when shifting from CT to CC to reduce soil erosion in olives grown in semiarid conditions. They have been discussed in detail in Gómez et al. (2014) and can be summarized in the need of a careful management of the cover crop in spring to prevent competition for soil water and the use, if available, of deficit irrigation to minimize risk. Realizing the actual impact on runoff losses when shifting from CT to CC can help to improve our understanding of water balance on olive orchards.

The mitigation in soil losses when using CC compared to CT in our experiment was also smaller to that described in previous studies in olives, some of which on the same experimental plots (Gómez et al., 2011; 2009a, 2009b). This can be explained in the case of Benacazón and La Conchuela due to the coincidence at the same season of the seeding operations and extremely high precipitations, leaving bare soil surface exposed in late fall during two rainy years (2009-10 and 2010-11).. Even under these challenging conditions for the development of the CC, an overall reduction in sediment losses at Benacazón and La Conchuela occurred. The implications of these results is that CC management at farm scale should be designed to limit the extension of a bare surface when implanting the CC. Possible alternatives may well be the use of a self-seeding CC, using minimum surface disturbance or zero-tillage seeders, and/or the spread of the farm's sown over several years seeding, and disturbing, only a fraction every year.

Organic carbon (OC) and dissolved organic carbon (DOC) losses

The three year averaged DOC losses in runoff ranged between 7.8 to 13.6 kg ha^{-1} yr^{-1} without significant differences between CT and CC treatments. This can be explained by the limited reduction of runoff between both treatments and a trend towards a higher OC concentration in runoff from the CC plots (Table 6), which is correlated with a higher soil OC content in the topsoil of the CC plots too (Table 5) and in the transported sediment (Table 6) compared to the CT plots. To our knowledge these are the first estimations of losses of DOC in runoff from Mediterranean tree crops, and they are relatively high in comparison with data reported for other land uses and latitudes. They are within the range reported by Johnson et al. (2006) for different forested and non-forested catchments, 17.3 kg ha^{-1} yr^{-1}, and of those reported by Wilson and Xenopoulus (2009) for agricultural areas in Ontario (19.3 kg ha^{-1} yr^{-1}). The annual losses of DOC measured in our experiment are conditioned by the presence of two very rainy years, and a long term average value might be probably slightly lower. The three years average concentration of DOC ranged from 4.1 to 13.9 mg·L^{-1}. These values are within the higher range of those measured in other more humid or cold environments (Johnson et al., 2006; Wilson and Xenopoulus, 2009) suggesting the relevance of this component of organic carbon fluxes in Mediterranean orchards in rainy years which, in the case of Andalusia, occur periodically every 3 - 5 years. The fraction of the total OC in dissolved forms compared to the total losses due to water erosion (runoff plus sediment) were between the 3 to 7% of total OC losses, due to the relatively large sediment loss during the two first rainy years. Only in year 2011-12 in the CC plots, with very low sediment losses, the fraction of OC lost and dissolved increased to 13-18%. These fractions are in the very lower range of those reported by Johnson et al. (2006), with 50% of the total OC fluxes measured in their catchments in Southern Amazon lost as DOC.

We observed relatively high losses of OC in sediment in Benacazón and La Conchuela with 3 year averages ranging from 101 to 432 kg ha^{-1} yr^{-1}, and no significant differences between CT and CC treatments. This can be understood because of the moderate reduction in sediment losses provided by the CC compared to the CT treatment due to the specific circumstances of the experimental years discussed above. This reduction was compensated by the higher concentration of OC in the sediment from the CC plots

(Tables 6). This higher concentration was also correlated with higher soil OC content in the topsoil of the CC plots (Table 5). The OC losses measured in this experiment are much higher than those noted for other field crop areas in Europe. For instance, Quinton et al. (2006), reported losses from 3.8 to 24.1 kg ha^{-1} yr^{-1}. It is apparent that as in the case of dissolved OC, our results are conditioned by the large rainfall during the first two years. However, previous studies together with our results for the year with moderate rainfall and well implanted cover crop (year 2011-12 at Benacazón and La Conchuela for CC) suggest that even in conditions where erosion losses can be reduced to acceptable levels, the relatively high concentration in OC will result in non-negligible OC fluxes compared to other agricultural systems in Europe. In fact, these results agree with those found by Gómez et al., 2009b for four years (2003-04 to 2007-08) at the Benacazón site, where the average OC losses in the sediment from olive orchards were 6.3 kg ha^{-1} yr^{-1} for the CT but only 0.4 t ha^{-1} yr^{-1} for the CC treatment.

Total phosphorus (TP) and dissolved reactive phosphorus (DRP) losses

The three year averaged DRP losses in runoff ranged between 0.03 to 0.21 kg ha^{-1} yr^{-1} without significant differences between CT and CC treatments. This lack of differences can be explained by the same reasons than for DOC which have been discussed above: limited reduction of runoff between both treatments and a trend towards a higher TP concentration in runoff coming from the CC plots (Table 7). However in this case we did not observe differences in TP content in the topsoil of the CC compared to the CT plots (Table 5). These losses are in the same range of those measured by Díaz et al. (2013) in two agricultural catchments under field crops in the region, from 0.2 to 0.03 kg ha^{-1} yr^{-1}, with average annual concentrations, from 0.01 to 0.17 mg L^{-1}. The measured concentration of DRP is also similar to the concentrations of values assumed in modelling transport studies of TP by runoff in Mediterranean agricultural areas Gassmann et al. (2014) but are in lower range of those proposed for crop or orchard zones in other regions such as semi-arid areas of China (Du et al., 2014). The average measured concentrations also tend to be in the lower range of the values measured in a laboratory experiment using rainfall simulation on similar soils of southern Spain by Saavedra and Delgado (2006). Our study shows that annual losses of DRP seem to be moderate compared to other agricultural situations due to their relatively low concentration in runoff. The fraction of the P losses dissolved in runoff compared to the total TP losses due to water erosion (runoff plus sediment) was relatively small ranging from 0.1 to 2.4% of total TP losses at the two sites with complete sediment and runoff records. This is due to a combination of the already mentioned low losses as dissolved forms with the relatively large sediment losses, especially during the two first rainy years. Díaz et al. (2013) obtained similar results with the majority of losses due to transport in the sediment and not in dissolved forms in similar soils in the region, in a study performed on field crops. Saavedra and Delgado (2006) in similar soils, but with rainfall simulation experiments at, ~1 m^2 scale, found also that the main mechanism for TP transport was associated to sediment, approximately 86% of the total. These results suggest that the relative importance of dissolved P as a mechanism of TP fluxes under Mediterranean agricultural conditions might be related to the scale, and that small scale experiments might over-estimate the relevance of this mechanism.

Average annual losses of TP associated to sediment losses were in the range of 5 to 39 kg ha^{-1} yr^{-1} as obtained at La Conchuela presenting no clear differences between CT and CC treatments, and a significant trend to reduced losses in the CC treatment at Benacazón (Table 6). These annual TP losses were higher than those reported by Díaz et al. (2013) for field crops in the region, in the range of 1 kg ha^{-1} yr $^{-1}$, and are within the upper range of the TP losses estimated for other Mediterranean agricultural areas such as the northern Adriatic (Volf et al., 2013). There are studies indicating a negative P balance in many traditional olive orchards in the region (García-Ruiz et al., 2012) as well as field surveys showing P content below the optimum requirement for olive production (Gómez et al., 2009a). Our results suggests that in addition to provide a high TP load and high eutrophication risk associated to large erosion rates, water erosion is contributing to a degradation of the soil quality reducing the P content.

Evolution of OC, DOC, TP and DRP and correlation with soil concentration and event magnitude

The annual evolution of OC and TP losses in our experiment tend to be highly correlated to the total runoff and sediment fluxes as expected, although their concentration in runoff and sediment presented some differences. Average concentration of these magnitudes during the experiment tended to be correlated with the topsoil concentration, Figure 11. However the variation of concentration of OC, DOC, TP and DRP varied during the year and among sites.

Higher concentration of DOC, sometimes extremely high (Figure 5), seems to happen early in fall or in year 2011-12 which was a dry year with events of moderate intensity falling on a relatively dry soil. In this situation, the amount of fresh particulate organic matter on the soil surface is larger, the runoff velocity is lower and there is a higher contact time for dissolving OC, while at the same time lower runoff volume is smaller and therefore dilution capacity ir reduced. The rainfall water in the region has a dissolved OC content of ~5 mg L^{-1} (Lombardo et al., 2012), and our results indicates that there is a significant enrichment in runoff water, especially during these periods of lower runoff coefficient (Figure 9) and especially at Lanjarón. This higher enrichment at Lanjarón is correlated with the higher OC content and likely to the higher surface roughness of the plots due to reduced traffic compared to the other two sites. Similar results were found for OC concentration in sediment. In this case the events with lower runoff coefficient tend to transport finer sediment from the uppermost layer of the soil which normally have an increased concentration in OC. In the large runoff events, with large runoff coefficient, OC tended to be lower due to less selectivity in sediment transport and the development of micro-rills which resulted in the transport of a more homogeneous sediment material. Although these trends are visible in Figure 10, there is a large scattering that precludes the development of a reliable regression which predicts this evolution in relationship to runoff coefficient for modeling purposes. It is difficult to isolate the contribution to that scattering of the interaction of different mechanisms controlling dissolved and sediment OC transport, from spatial variability, known to be significantly large in runoff plot experiments (Gómez et al., 2001), and from variability induced by sampling error, also known to be significantly large in this kind of experiments (Harmel and King, 2005). It is observable that the average annual concentration of DOC and OC in runoff and sediment from different sites and treatments might be estimated for modeling purposes from the OC content of the top 5 cm of the soil along the lanes' area. However, we did not found a similar correlation at event scale given the large variability presented. Possibly, in an experiment under controlled conditions and a larger number of replications a clearer correlation can be found, but it might be possible too that these controlled conditions might not be representative of the complexity of the olive farms situations. The results in Figure 11 show the best correlation between OC and TP in runoff and sediment with any of the possible combinations (lane, tree, average of tree and lane area) of the OC and TP concentration in the topsoil. The correlation found with the values corresponding with the lane area, are in agreement with previous studies in olive orchards indicating that most of the runoff and sediment generation happens in the lanes since the below canopy area is an area of relatively large infiltration capacity (Guzmán et al., 2013).

The annual variability of DRP concentration in runoff presented a similar trend to that discussed for OC (Figure 8), albeit with a larger scattering in its correlation with event runoff coefficient (Figure 10). We understand that similar trend as an indicator of being controlled by the same mechanisms that regulate the annual evolution of DOC content, previously mentioned. However, the larger scattering and the negative correlation with soil TP content (Figure 11) suggests that it is a much more complex mechanism. It is possible that the applied fertilizer (in the case of CC) as well as the possible transfer of some of the P as fertilizer to the orchard in the canopy area, in solid form in Lanjarón and liquid in La Conchuela and Benacazón through the drip irrigation system, has a dominant effect over the overall, and event by event variation, of the dissolved TP. This is particular noticeable in the case of the transport of TP through the sediment by runoff. We found a similar situation to that observed for OC with a clear correlation in average annual concentration of TP in sediment with that of the top soil in the lane area but no correlation with event TP concentration with runoff magnitude through the runoff coefficient (Figure 10). These results open the same possibility of estimating average annual concentration values of sediment for modeling analysis, but do not provide empirical base for predicting event by event concentration values.

CONCLUSIONS

A three year experiment in three different orchards in Andalusia has allowed the development of an experimental dataset to evaluate organic carbon and total phosphorus in sediment and runoff in relation to soil type and management. Temporary cover crop, CC, managed in orchard lanes did not provide a significant reduction in surface runoff compared to CT. This agrees with previous studies and highlights the relevance of the design of cover crop management strategies in orchards in order not to worsening the water balance (and so potential productivity) in comparison to CT.. It has also implications when evaluating offsite contribution of DOC and DRP in runoff from olive orchards, particularly in rainy years. CC resulted in a significant decrease of soil losses compared to CT, but presented relatively high erosion years due to a combination of intense rainfall during the cover crop seeding period, in fall and early winter. This stresses the need for careful planning of cover crop management that minimize the period with bare soil. This might be achieved with a combination of self-seeding cover crop and/or fractioning the seeding, when needed, over several years to minimize the probability of these periods with high erosion risk in CC management.

DOC losses in runoff were equivalent to those measured in other agricultural and forest systems in the world, presenting a relatively high concentration. They represent a small fraction of the total OC fluxes in olive orchards associated to water erosion due to the larger losses in the sediment under the high erosion rates measured. Both sources of organic carbon should not be neglected as relevant fluxes to water bodies in the region and in OC balance in soils. Although losses through water erosion can be severely reduced with appropriate use of CC, the relatively high concentration of OC in runoff and sediment suggests that these fluxes will remain relevant, especially in rainy years.

Concentrations of DRP in runoff were in the lower range of published values and represented a minor fraction of the total TP losses by water erosion in the olive orchards. Loads of TP by sediment were in the higher range of those reported from agricultural areas in the Mediterranean due to a combination of enrichment in sediment and high sediment losses. There is the scope for a large reduction in of TP by reducing sediment losses through appropriate CC management.

There was a correlation between average annual concentration of DOC in runoff and OC in sediment and of TP in sediment with that of the top 5 cm of the soil in the lanes of the orchards. This suggests that most of the sediment and runoff are coming from these areas, and also that it is possible for modeling analysis to approximate this parameter from top soil analysis. It was not possible to find a similar correlation with average annual concentration in runoff for TP, suggesting a much more complex interaction of this parameter with fertilization. We observed a large variability at event concentration for DOC, OC, DRP and TP. We found for DOC, OC, and DRP, a trend towards a larger concentration for runoff events of small magnitude, below 10 to 20% runoff coefficient approximately. However they presented a large scattering that precludes the determination of robust correlations for prediction and model calibration purposes.

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Location	Latitude	Longitude	Average annual precipitation (mm)	Average annual temperature (° C)	Altitude (m.a.s.l.)	Year of orchard planting	Cropping system	Soil classification Soil Survey Staff, 1999/ - FAO, 2006
La Conchuela	37°48`54``N	4°53`53`` W	655	17.5	147	1993	6x7m ; drip-irrigated	Typic Haploxerert – Haplic Vertisol
Benacazón	37°20`35``N	6°14`46`` W	534	18.6	98	1985	8x6m ; drip-irrigated	Petrocalcic Palexeralf – Luvic Cambisol
Lanjarón	36°54`15``N	3°28`38`` W	471	14.5	565	1976	8x8m ; rainfed	Typic Xerochrept – Haplic Cambisol
	Sand ($g\ kg^{-1}$)	**Silt ($g\ kg^{-1}$)**	**Clay ($g\ kg^{-1}$)**	**pH H_2O**	**Corg (%)**	**Norg (%)**	**P total ($mg\ kg^{-1}$)**	**P Olsen ($mg\ kg^{-1}$)**
La Conchuela	80	410	510	8.7	0.88	0.07	550	5.3
Benacazón	400	450	150	8.8	0.26	0.04	265	14.3
Lanjarón	550	230	220	7.2	0.97	0.06	127	4.6

Table 1: Main characteristics of the experimental sites. Soil properties are average of the top 50 cm of the soil at the three experimental sites.

Location	Number of plots and construction year	Dimensions: wide x long (m)	Slope inclination (%)	Trees in the plot	Plot boundaries	Runoff collecting system
La Conchuela	Six, built in 2008	14 x 24	13.4	Three rows of four trees	Steel beams on a concrete foundation	Tipping-bucket gauges with a 5-min resolution
Benacazón	Six, two built in 2003 and four in 2005	8 x 60	11	Two rows of ten trees	Soil ridges and steel beams on a concrete foundation	Fiberglass tanks with flow splitters
Lanjarón	Two built in 1998	8 x 24	30	One row of three trees	Galvanized enclosure	Steel collector, tanks with flow splitters

Table 2: Characteristics of the runoff plots.

Management	La Conchuela		Benacazón		Lanjarón	
	CT	**CC**	**CT**	**CC**	**CT**	**CC**
	2 plots, since 2008-09	4 plot since 2008-09	2 plots since 2003-04	4 plots since 2005-06	1 plot since 2008-09	1 plot since 2008-09
Lanes	Bare soil	During 2009-10 and 2010-11 sown manually in November with (*Lolium multiflorum*) at 80 kg of seed per ha. In year 2011-12 the CC grew up spontaneously from the seed produced by the CC the previous year	Bare soil	From 2009 to 2011 two plots sown in late October with *Lolium multiflorum* at 80 kg of seed per ha, the other two were seeded with a mix of different selected species at 15 kg of seed per ha. Seeding of 2009-10 repeated in the four plots during January 2010. In 2011-12, CC grew up naturally from the seed produced the previous year	Bare soil	Spontaneous vegetation, mostly grasses
	Chisel plowing (2-3 times per year)	Chemically mowed in April using Touchdown Premium (3 L ha^{-1} using 300 L of solution per ha)	Chisel plowing (2-3 times per year)	*Lolium* grass cover chemically mowed in May using Touchdown Premium (3 L ha^{-1} using 300 L of solution per ha) while the mixed CC was mowed	Chisel plowing (2-3 times per year)	Mowed in late spring
Tree lanes	Periodical use of herbicide (Fluroxipir and Flazasulfuron)		Periodical use of herbicide (Fluroxipir and Flazasulfuron)		Periodic mowing	

Table 3: Summary of soil management operations at the different sites and treatments.

Location	La Conchuela	Benacazón	Lanjarón
Fertilization	14N 14P 16K fertilizer at 200 kg ha at the time of seeding. Olive trees were fertigated during the irrigation season	14N 14P 16K fertilizer at 200 kg ha at the time of seeding. Olive trees were fertigated during the irrigation season	Fertilizer was applied to the treatment plots in the form of 15-15-15 NPK at a nominal rate of 453 kg ha-1 and urea 301.5 kg ha^{-1} $year^{-1}$
Irrigation	The trees were deficit irrigated, by dripping, and the water applied during the irrigation season, April to September, was, on average, the equivalent of 200 mm	The trees were deficit irrigated, by dripping, and the water applied was on average the equivalent of 230 mm	Not irrigated
Harvesting	Harvesting is semi-mechanized using tree-shakers. Done, varying with year from late November to early-February	Harvesting is made manually during October	Harvesting is made manually during December

Table 4: Summary of agronomic operations at the different sites.

Year Site	Treatment	Location	2009 OC (%)	2009 TP (mg·kg^{-1})	2012 OC (%)	2012 TP (mg·kg^{-1})
La Conchuela	CC	T	1.39 (0.22)	753 (23)	1.26 (0.12)	561 (15)
	CC	L	0.65 (0.05)	601 (45)	0.44 (0.01)	455 (17)
	CT	T	1.27 (0.3)	780(105)	1.98 (0.04)	722 (47)
	CT	L	0.54 (0.05)	548 (51)	0.39 (0.03)	509 (10)
Benacazón	CC	T	1.09 (0.03)	369 (52)	1.06 (0.40)	402 (27)
	CC	L	1.18 (0.09)	194 (24)	1.36 (0.01)	249 (18)
	CT	T	0.84 (0.11)	322 (45)	0.91 (0.20)	471 (58)
	CT	L	0.94 (0.09)	273 (62)	0.96 (0.05)	206 (9)
Lanjarón	CC	T	1.36 (0.04)	255 (24)	1.31 (0.03)	264 (19)
	CC	L	0.92 (0.07)	243 (27)	0.89 (0.07)	130 (9)
	CT	T	1.42 (0.19)	244 (34)	1.59 (0.07)	230 (10)
	CT	L	0.67 (0.06)	207 (46)	0.75 (0.03)	128 (16)

Table 5: Summary of average values, and standard deviation between brackets, of organic carbon (OC) and total phosphorus (TP) in the top 5 cm of the soil profile. N=3. T means tree area, and L lane area.

Site	Treatment	Average DOC annual	Average DOC	STD DOC	Average OC annual	Average OC conc.	STD OC conc.	Average OC enrichment	STD OC enrichment

		losses (kg ha^{-1} yr^{-1})	conc. (mg L^{-1})	conc. (mg L^{-1})	losses (kg ha^{-1} yr^{-1})	(%)	(%)	(%)	(%)
La Conchuela	**CC**	13.6	9.1	5.2	432.1	1.7	1.9	305.2	345.6
	CT	10.2	8.7	7.1	302.4	1.4	1.6	299.7	343.0
Benacazón	**CC**	7.8	12.6	11.4	101.5	1.8	0.8	149.2	49.8
	CT	9.9	8.9	4.9	161.0	1.0	0.6	113.2	53.7
Lanjarón	**CC**	12.8	20.9	23.6	13.5	2.1	0.6	232.2	62.9
	CT	9.2	21.4	47.4	11.7	1.5	0.6	210.6	83.7

Table 6: Summary of annual results at the three sites related to organic carbon (OC) losses in sediment or as dissolved organic carbon (DOC) in runoff. STD means standard deviation. Enrichment ration calculated from sediment and top soil organic carbon concentration.

Site	Treatment	Average DRP annual losses (g ha^{-1} yr^{-1})	Average DRP conc. (mg L^{-1})	STD DRP conc. (mg L^{-1})	Average TP annual losses (g ha^{-1} yr^{-1})	Average TP conc. (mg kg^{-1})	STD TP conc. (mg kg^{-1})	Average TP enrichment (%)	STD TP enrichment (%)
La Conchuela	**CC**	28.5	0.02	0.02	38046.4	606.7	194.4	114.9	36.8
	CT	127.0	0.02	0.02	39264.5	663.8	149.6	125.6	28.3
Benacazón	**CC**	48.5	0.10	0.13	2033.2	429-0	178.2	193.7	80.5
	CT	51.1	0.05	0.08	5538.8	358.2	112.9	149.6	47.1
Lanjarón	**CC**	206.2	0.45	1.09	282.5	436.4	145.1	262.9	124.3
	CT	168.1	0.20	0.35	233.6	307.6	54.9	206.9	122.3

Table 7: Summary of annual results at the three sites related to total phosphorus (TP) losses in sediment or as dissolved reactive phosphorus (DRP) in runoff. STD means standard deviation. Enrichment ratio calculated from sediment and top soil total phosphorus concentration.

Figure captions.

Figure 1: Location map of the experimental sites.

Figure 2: View of the runoff plots at the three experimental sites.

Figure 3: Cumulative annual rainfall and runoff results for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph).

Figure 4: Cumulative annual sediment losses results for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Note that Lanjarón had incomplete data record presenting only some events.

Figure 5: Annual evolution of dissolved organic carbon (DOC) concentration for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph).

Figure 6: Annual evolution of organic carbon (OC) concentration in the lost sediment for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Note that Lanjarón had incomplete data record presenting only some events.

Figure 7: Annual evolution of dissolved total phosphorus (DRP) concentration in runoff for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph).

Figure 8: Annual evolution of total phosphorus (TP) concentration in the lost sediment for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón

(lower graph). Note that Lanjarón had incomplete data record presenting only some events.

Figure 9: Event concentration of OC dissolved in runoff and in sediment vs. event runoff coefficient.

Figure 10: Event concentration of dissolved reactive P (DRP) in runoff and total P (TP) in sediment vs. event runoff coefficient

Figure 11: Correlation between average annual values of OC and TP concentration in sediment and dissolved in runoff with top soil concentration in OC and TP.

Figure 1: Location map of the experimental sites.

La Conchuela

Benacazón

Lanjarón

Figure 2: View of the runoff plots at the three experimental sites.

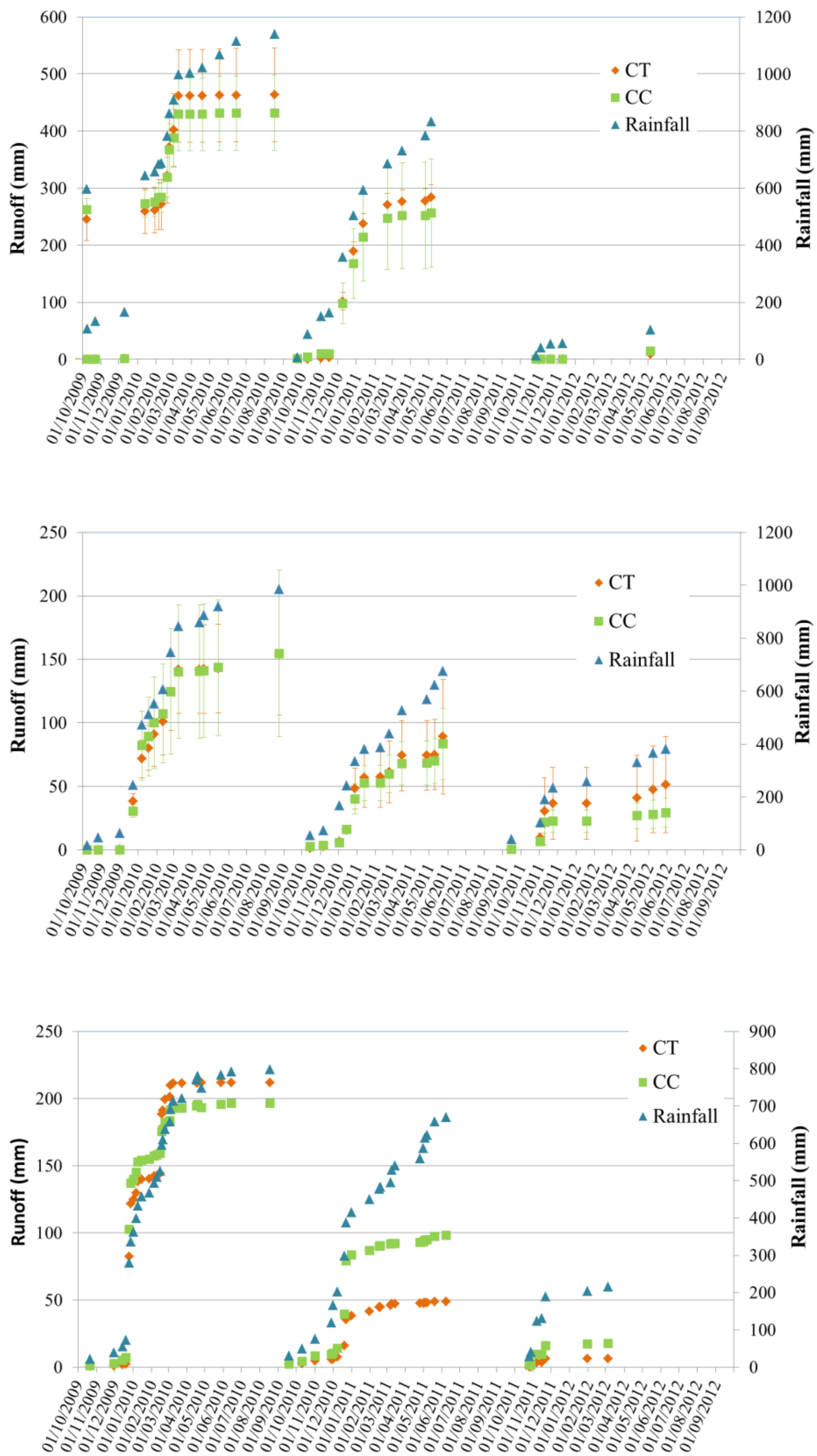


Figure 3: Cumulative annual rainfall and runoff results for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Error bars indicates standard deviation.

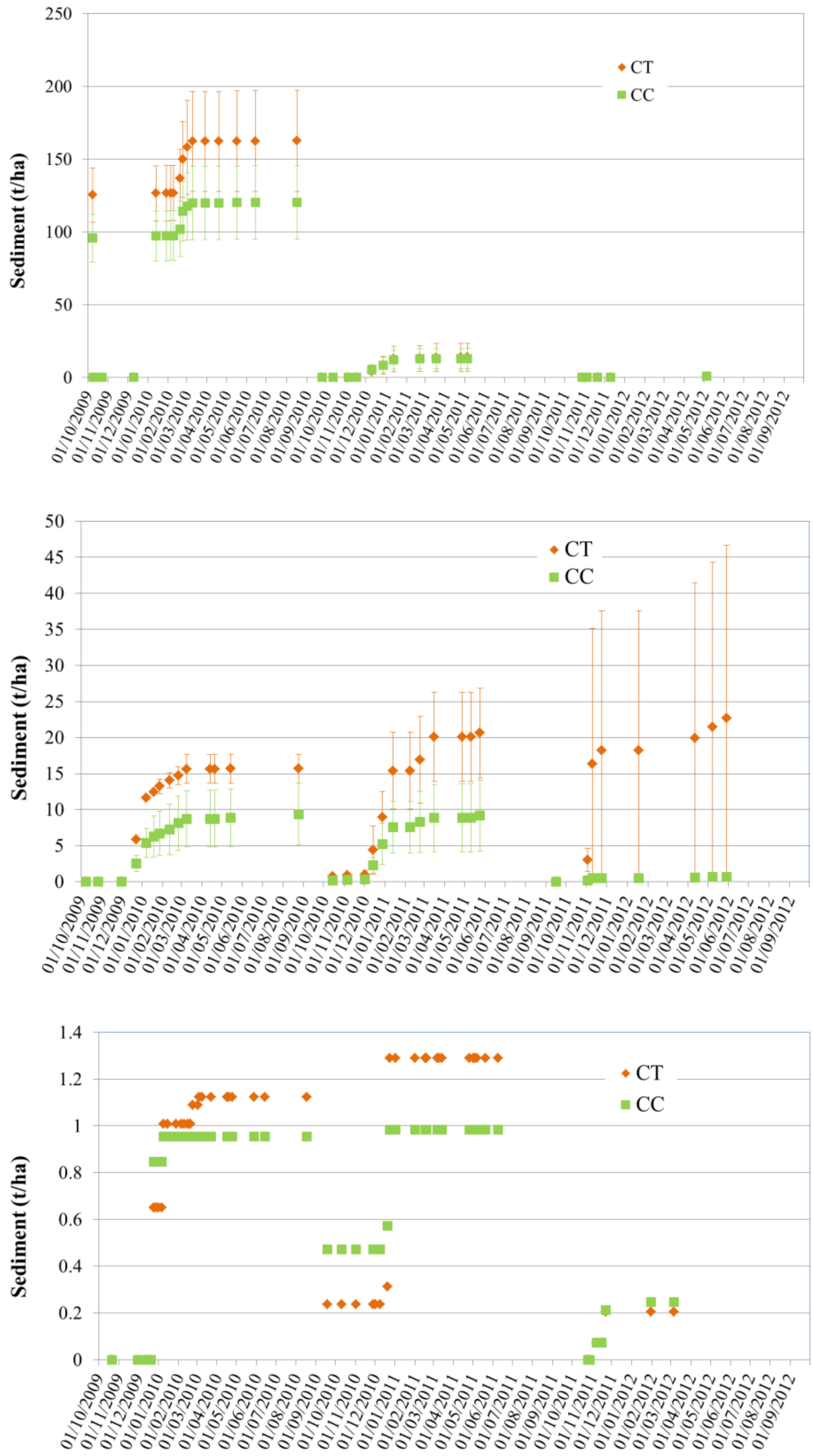


Figure 4: Cumulative annual sediment losses results for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Error bars indicates standard deviation. Note that Lanjarón had incomplete data record presenting only some events.

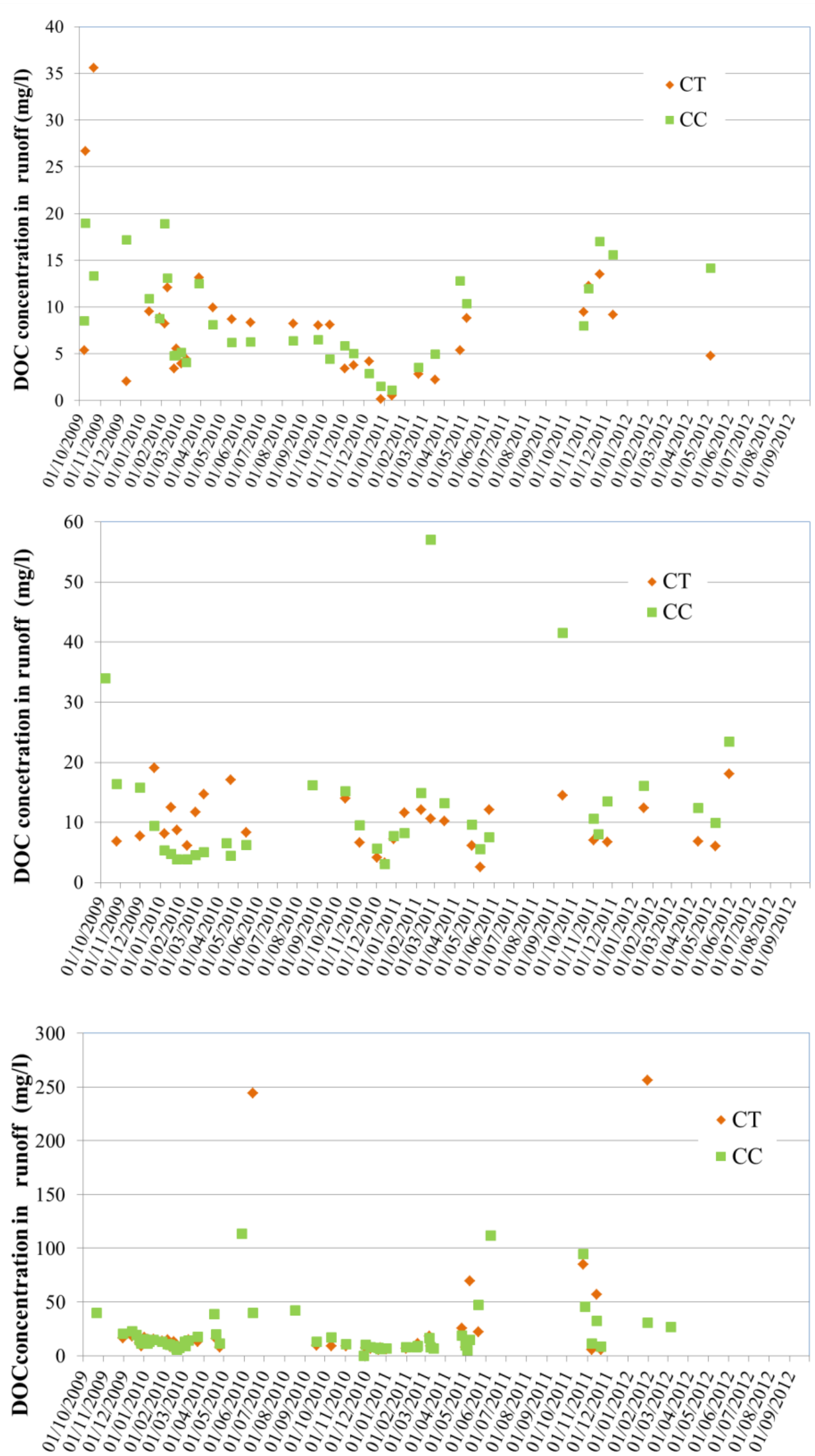


Figure 5: Annual evolution of dissolved organic carbon (DOC) concentration for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph).

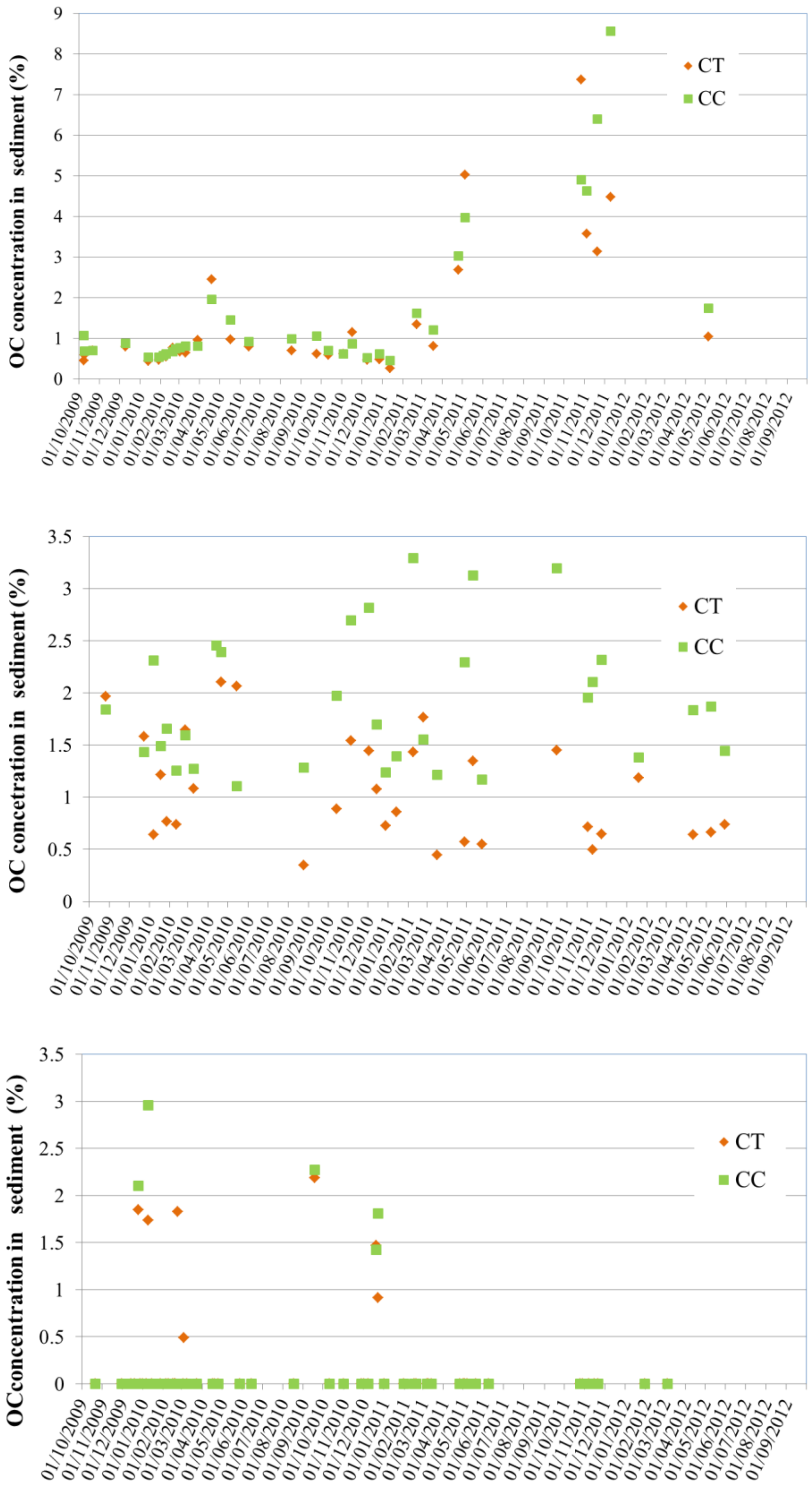


Figure 6: Annual evolution of organic carbon (OC) concentration in the lost sediment for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Note that Lanjarón had incomplete data record presenting only some events.

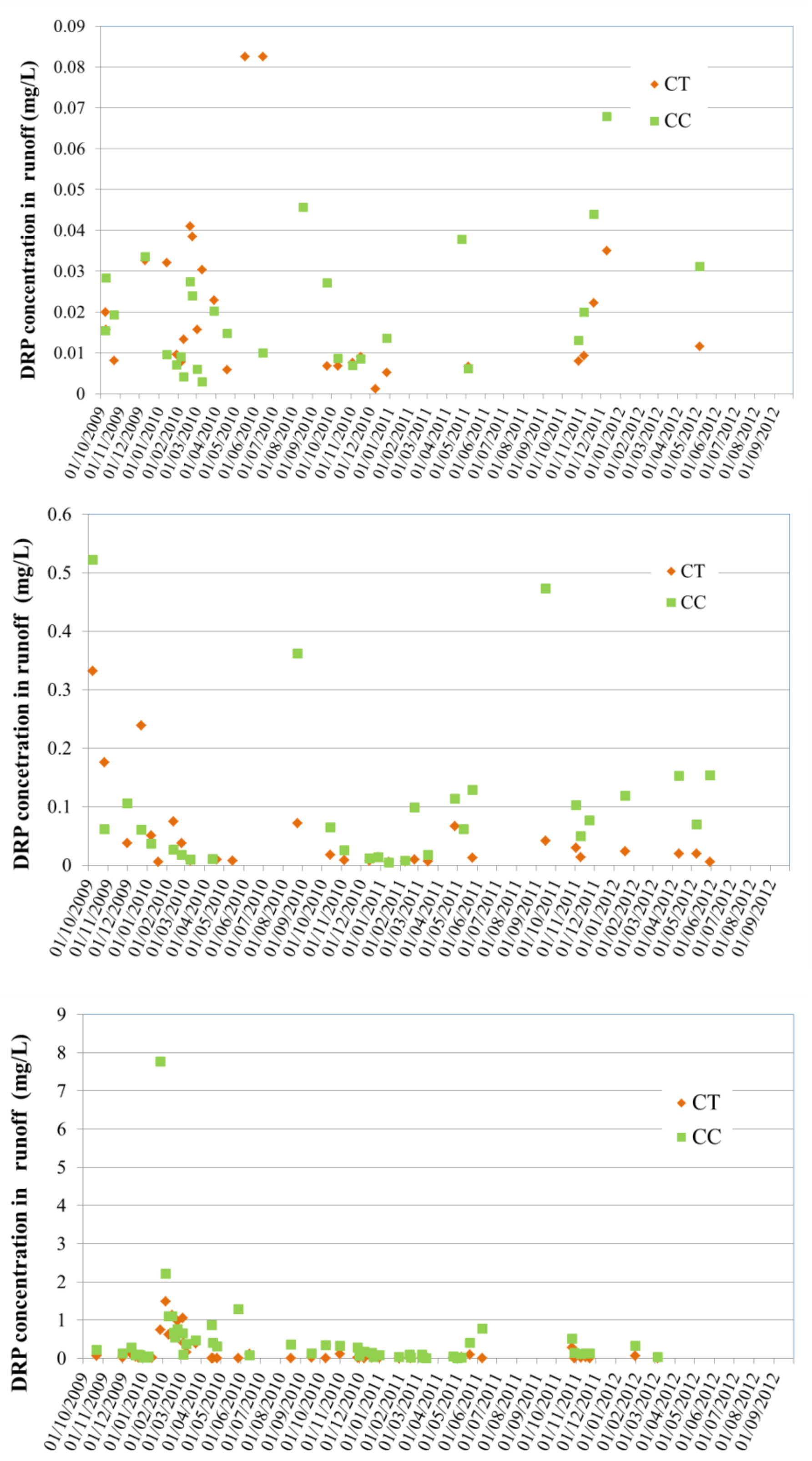


Figure 7: Annual evolution of dissolved reactive phosphorus (DRP) concentration in runoff for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph).

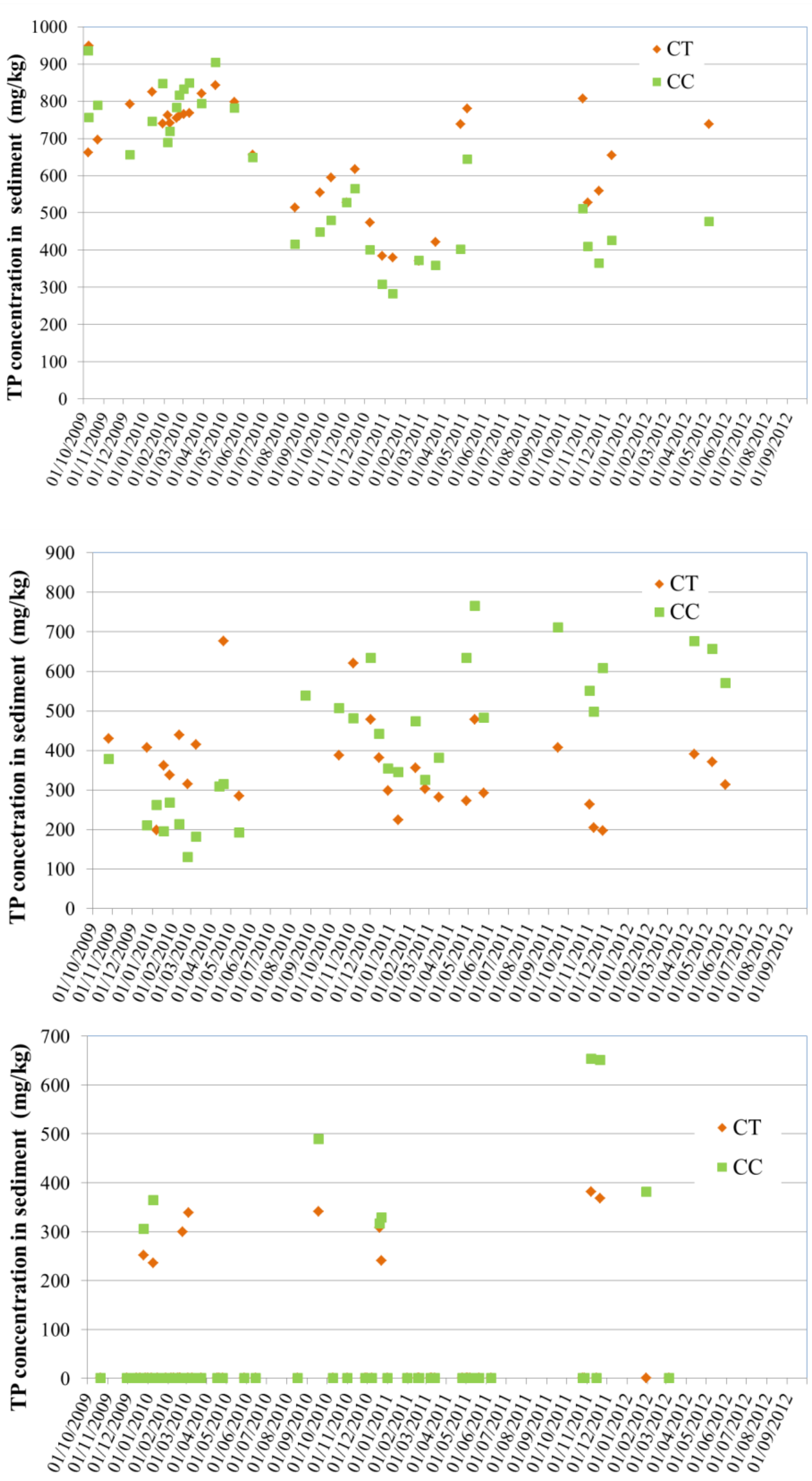
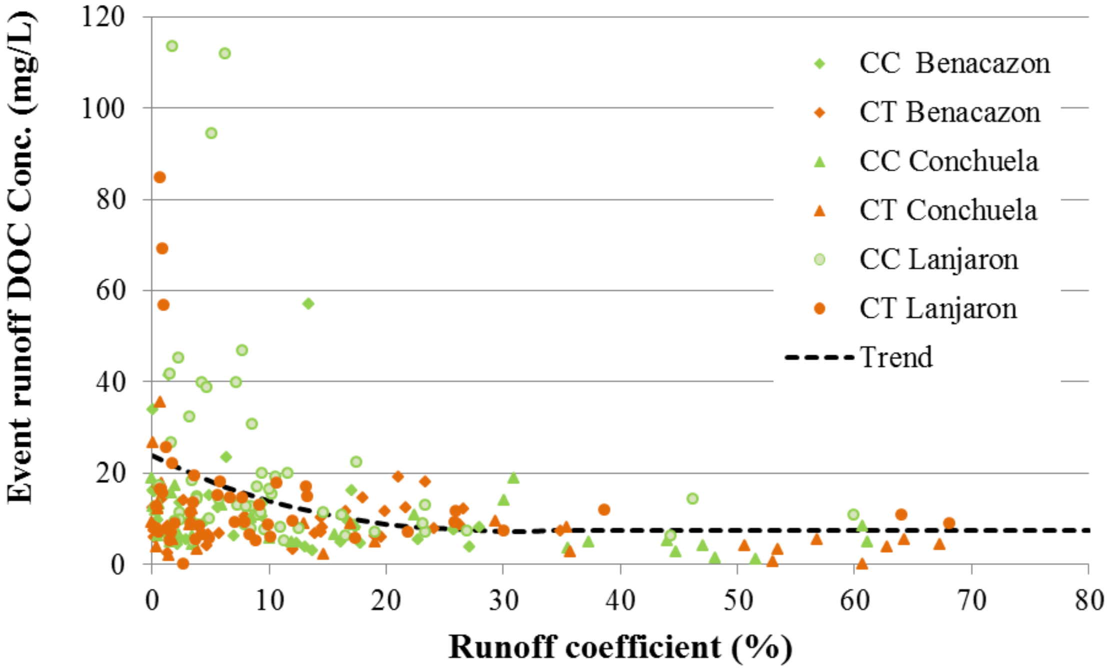


Figure 8: Annual evolution of total phosphorus (TP) concentration in the lost sediment for the three sites: La Conchuela (top graph), Benacazón (middle graph), Lanjarón (lower graph). Note that Lanjarón had incomplete data record presenting only some events.



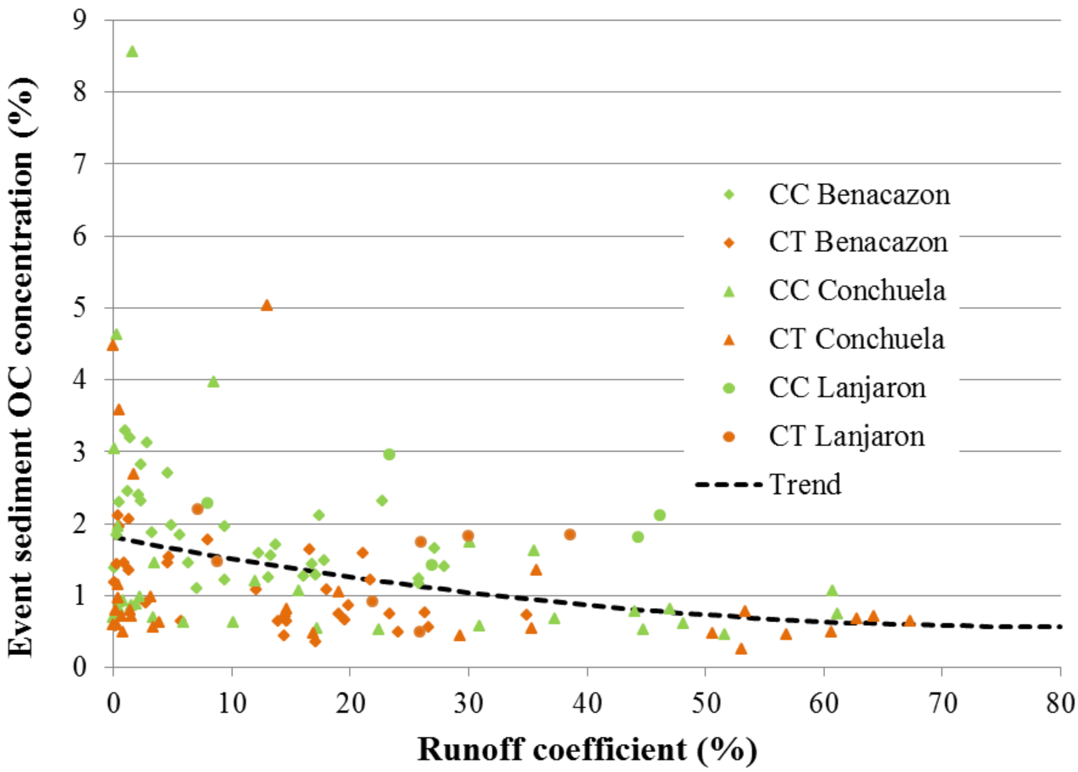


Figure 9. Event concentration of OC dissolved in runoff and in sediment vs. event runoff coefficient.

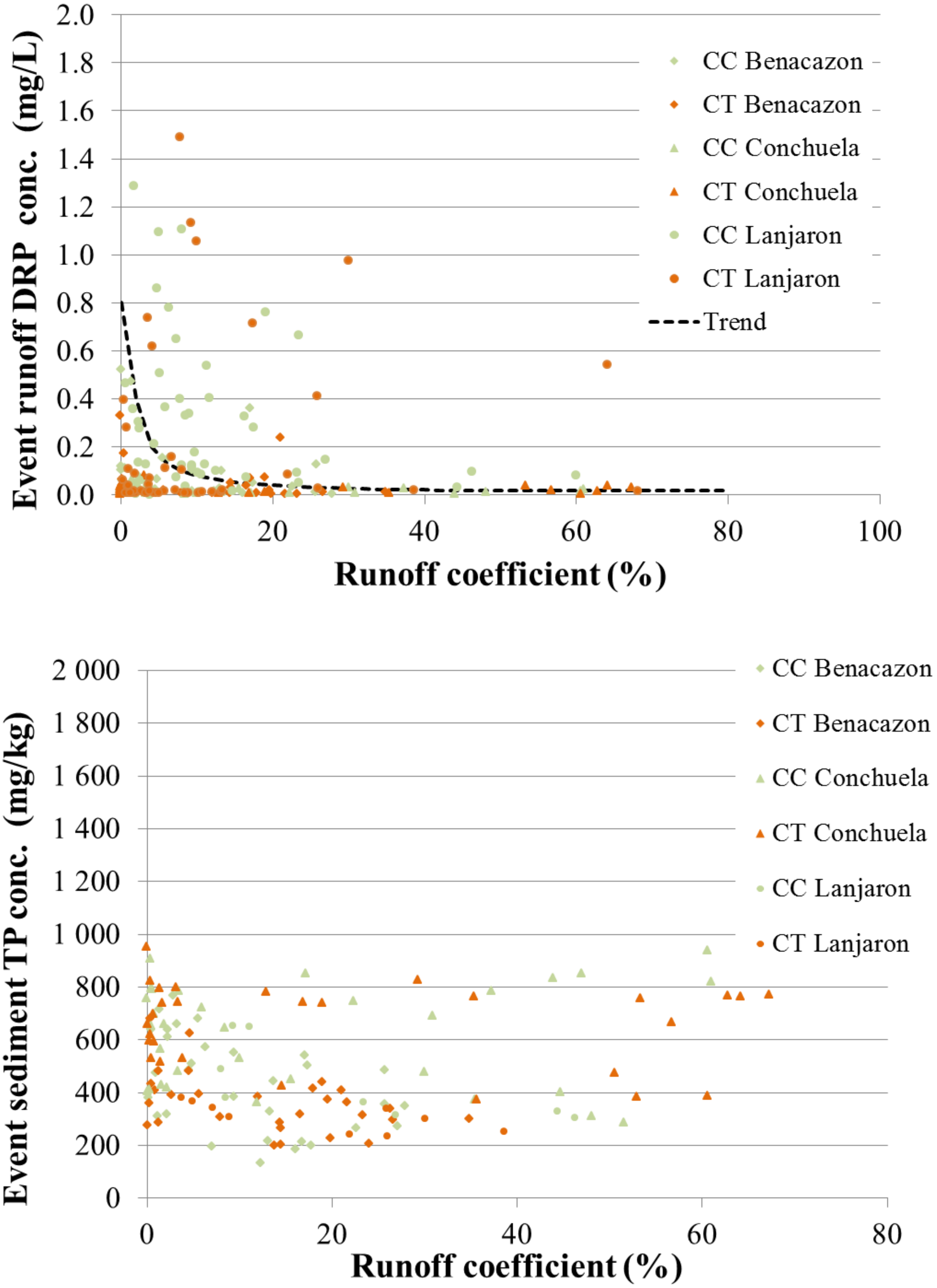


Figure 10: Event concentration of dissolved reactive P (DRP) in runoff and total P (TP) in sediment vs. event runoff coefficient.

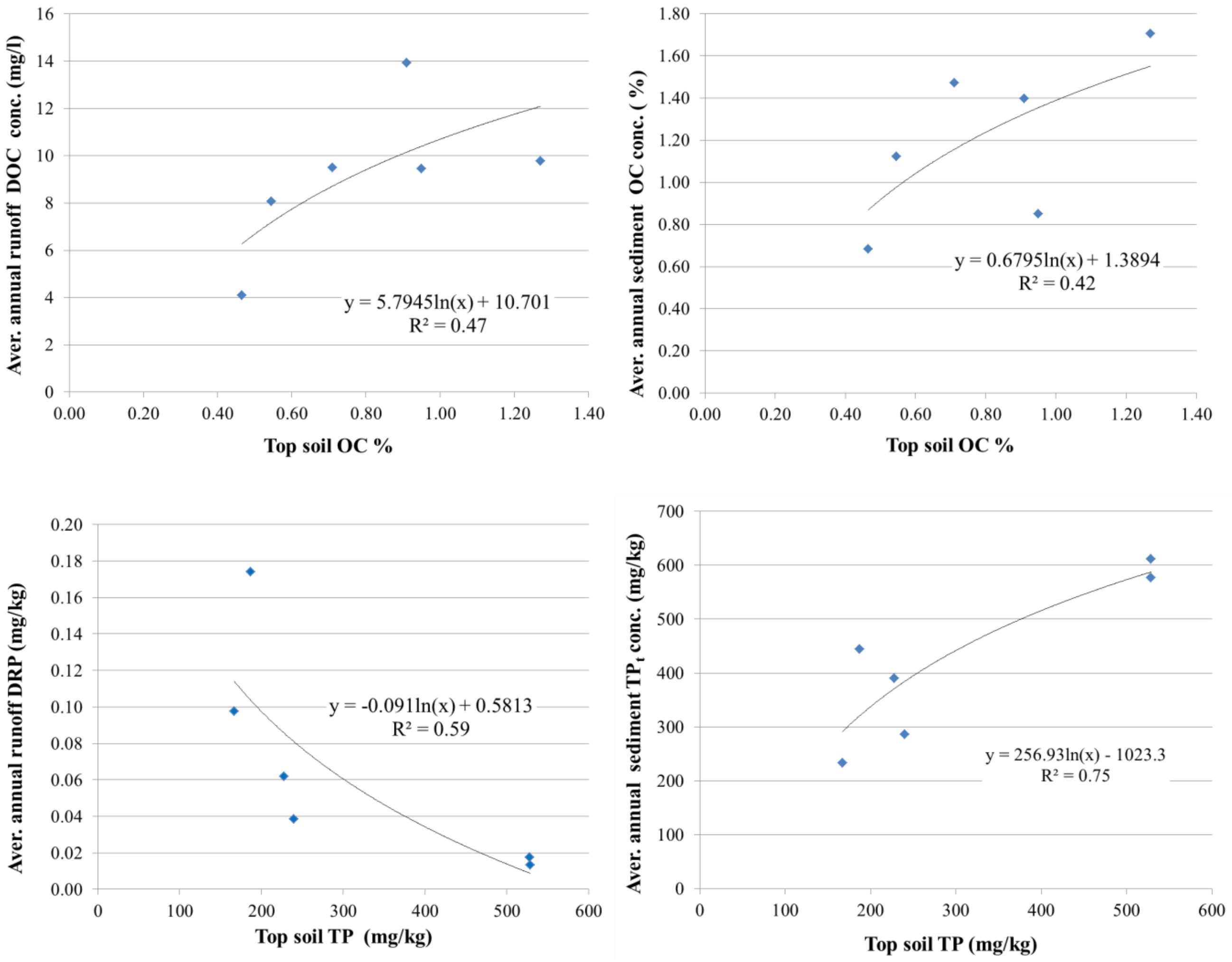


Figure 11: Correlation between average annual values of OC and P concentration in sediment and dissolved in runoff with top soil concentration in OC and TP.