Cover Crop Effects on Surface Runoff and Subsurface Flow in Rainfed Hillslope Farming and Connections to Water Quality

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Abstract: Surface runoff and subsurface flow patterns were monitored in hillside runoff plots in almond and olive orchards with soils covered with spontaneous plants over two hydrological years. The experimental runoff plots were located on the south flank of the Sierra Nevada (Lanjaron, SE Spain) at 580 m a.s.l. with an area of 40 m² (10 m × 4 m). The surface and subsurface discharge were collected and measured at different soil depths (0, 5, 10, 25, and 50 cm), and the dissolved nutrient concentrations (NO₃–N, NH₄–N, PO₄–P, and K) were determined. According to the findings, the subsurface flow pathways drained most of the rainfall water compared with surface runoff, which was affected by plant cover. The influence of rainfall intensity (Iₚ) on surface runoff was more meaningful than that on subsurface flow. Throughout the monitoring period, the runoff coefficients at soil depths of 0, 5, 10, 25, and 50 cm averaged 0.04, 0.11, 0.14, 0.17, and 0.18, respectively. Subsurface flow was one of the dominant pathways for N and K loss, whereas P loss mainly occurred via surface runoff. Moreover, the concentrations in subsurface flow were higher than the recommended level for standard water quality for NO₃–N, NH₄–N, and PO₄–P. Subsurface flow was the main route of dissolved nutrient delivery, making these nutrients available to the root systems of trees, where nutrient uptake is more likely to occur. Thus, by lessening surface runoff and encouraging surface vegetation coverage to facilitate the recycling of nutrients and buffer the rainfall’s impact on the soil surface, nutrient loss control can be achieved.

Keywords: runoff; nutrient transport; hillslope farming; surface and subsurface flows; Mediterranean climate

1. Introduction

Runoff generation is the process by which rainfall losses are deducted to form net rainfall, with infiltration being the most important factor, in addition to others such as vegetative interception, stemflow, and evapotranspiration [1–4]. Surface runoff can erode the soil by means of detachment, as well as through rill erosion, and can transport high concentrations of plant nutrients [5]; as a result, surface runoff is generally the focus of research and the target of mitigation strategies [1,6]. Also, field drains are important runoff pathways in agricultural land [7,8] and, therefore, could be an important pathway for pollution risk associated with nutrient loss [4,9]. Drainflow can thus be a highly efficient hydrological pathway linking the hillslope to the stream and, consequently, it is potentially a significant contributor to water quality. Many studies have indicated that significant particulate losses may take place in subsurface pathways through field drains and that drainflow pathways may be particularly important in situations where surface runoff may not occur [10–12]. There are limited data comparing direct measurements of pollutant loads in both surface and subsurface pathways; therefore, it could be vital to monitor the latter.
pathway to determine if it is a more important transfer pathway than surface runoff from agricultural soils.

Agricultural runoff and sediment generation lead to a decrease in soil fertility and biological productivity resulting from the exportation of organic matter and plant nutrients, among other negative effects [13–15]. The interaction between rainfall and the soil surface can cause some fertilizer amendments to be desorbed into the solution and leachate, while others remain adsorbed and able to move with the detached soil particles caused by runoff [16–18]. Plant nutrient losses exert an important environmental impact, particularly N and P, which negatively affect groundwater and surface water [19–21]. In addition, these nutrients may threaten water quality in the context of climate change [22,23]. In this line, plant nutrient losses from agriculture are of great concern because of both agricultural on-site and environmental off-site impacts [24,25]. Concretely, on-site, the detachment and transport of sediments by water is responsible for large soil losses, which have practical and economic implications for land managers. Off-site, sediment inputs into streams and other receiving waters may result in colmation, sedimentation within the surface water system, and increased turbidity, thus disturbing aquatic ecosystems [26].

The Mediterranean region is characterized by a pronounced water deficit in the summer, high irregularity in torrential rainfall events in the autumn and winter, and a high frequency of drought intervals without appreciable rainfall [27,28]. This is exacerbated by global warming and climate change provoked by greenhouse gas emissions, triggering flash floods and extreme storm events with important consequences for soil degradation in agricultural lands [29]. Many agricultural areas of European Mediterranean countries are characterized by the presence of rainfed fruit crops such as almonds (Prunus dulcis Mill.), olives (Olea europea L.), and grapes (Vitis vinifera L.), which are well adapted to the particular rainfall regime features. These rainfed fruit trees are regularly grown on the hillslopes of mountainous land in conjunction with shallow soils and scarce soil cover, leading to a high risk of water erosion [30,31].

The olive is one of the most typical and economically predominant crops in the Mediterranean, covering about 10 Mha worldwide, of which more than 2.78 Mha is cultivated in Spain. Most Spanish olive plantations are under rainfed conditions (1.91 Mha, 69%) [32], concentrated in southern Spain (Andalusia) with 1.68 Mha, where many rainfed orchards are on hillslope land (61%) [33]. Similarly, almonds are the third most widely cultivated crop, after olives and grapes, and traditionally have been related to marginal rainfed zones because of their drought tolerance. The worldwide area of almond cultivation is more than 2.16 Mha, with Spain having the greatest area, at 744,470 ha (34%) [34]. Most of these plantations (79%) are under rainfed (584,474 ha) conditions [32], many of which are in Andalucia with a cultivation area of 214,375 ha (80% rainfed). Consequently, these figures demonstrate the high economic significance of rainfed crops for agroecosystems in southern Spain.

The aim of this work was to undertake a plot-based study of the surface and subsurface flow pathways and the potential plant nutrient transfer mechanisms that contribute to stream flow over a number of runoff events in hilly almond and olive orchards with plant cover (SE Spain). The results of this study contribute insights into the hydrological processes in the soil of mountainous areas and provide a basis for boosting the water conservation function in hillslope farming areas.

2. Materials and Methods
2.1. Study Area and Soil Management

Geologically, the study zone belongs to the Alpujarride complex of the internal zones of the Betic Cordilleras, where a series of tectonic units are present as a consequence of normal and reverse low-angle faults. The dominant soil parent material is colluvium and residuum derived from mica schist, and the slopes dominantly comprise phyllites and mica–schist, with weathered regolith covers of only a few centimeters in depth. The study area covers one of the tributaries of the River Izbor, which is connected to the Guadalfeo River. Concretely, the experiment was carried out under field conditions in the Sierra
Nevada Mountains (Lanjaron, SE Spain) at 580 m a.s.l. The experimental plots were part of a rainfed almond (*Prunus dulcis* cv. Desmayo Largueta) (36°55′50″ N and 3°30′01″ W) plantation consisting of more than 60-year-old trees and an olive (*Olea europea* L. cv. Picual) (36°51′44″ N and 3°29′50″ W) plantation consisting of 52-year-old trees with 44% and 39% vegetation cover on average, respectively. Both experimental plots were located in terrains with a slope exceeding 25%, showing features that are often found in mountainous zones of the Mediterranean (Figure 1).

The study area has a climate that corresponds to the Köppen classification of Csa, relating to the Mediterranean with dry and warm summers, with a mean annual rainfall of about 490 mm and high variability in rainfall intensity and frequency, most of which is concentrated in a rainy period (autumn and winter), with intense short-duration storms. However, in recent years, the rainfall frequency and amount have progressively reduced because of the effects of the changing climate [29]. Near the experimental orchards (<20 m from the plots), rain gauges (Thies Clima) were installed to collect rainfall data and estimate the maximum intensity at 30 min ($I_{30}$) and the erosivity index ($EI_{30}$, R factor) [35].

\[
E = 0.119 + 0.0873 \log_{10} I, \quad I \leq 76 \text{ mm h}^{-1} \quad (1)
\]
The soils in the study zone, Eutric regosols [36], have a loamy texture. The main physico-chemical soil properties, as shown in Table 1, were determined in soil samples replicated three times and at different soil depths. Regarding the soil moisture characteristics, the volumetric water content at field capacity, the permanent wilting point, and the available water content in the almond plots were 0.17, 0.07, and 42 mm, and for the olive plots, these values were 0.21, 0.13, and 41 mm, respectively. The soil stoniness for the almond and olive plots was 23 and 24%, respectively. The experimental orchards were managed with fertilizer application in the form of 15:15:15 NPK at a rate of 453 kg ha\(^{-1}\) year\(^{-1}\), corresponding to traditional and local cultivation practices.

2.2. Runoff Plots, Sampling, and Chemical Analysis

The surface (0 cm) and subsurface flow at different soil depths (5, 10, 25, and 50 cm) were monitored in 4 closed plots (replicated twice for each crop) (Figure 2). To measure drainage waters, four galvanized metal boxes at each depth were inserted into the soil as gravitation lysimeters (4 m \(\times\) 0.5 m \(\times\) 0.05 m (5, 10, 25, and 50 cm)) as part of a bigger closed erosion plot (10 m \(\times\) 4 m) with surface runoff measurements in an area of 2 m \(\times\) 4 m containing one tree. The runoff water draining from the plots at each soil depth was collected in a drainage system that terminated at the measuring storage tanks. After the field installation, the soils of the runoff plots were left for two years in order for them to return to their initial conditions, or at least to return to similar conditions to the surrounding soils, and to allow the colonization of spontaneous plants.

The collected runoff water samples were analyzed for the ionic composition of nitrogen (NO\(_3\)-N and NH\(_4\)-N\(_4\)), phosphorus (PO\(_4\)-P), and potassium (K) in accordance with the standard methods for the examination of waters [37].

The soil texture, bulk density (\(\rho_b\)), pH\(_{H_2O}\) (1:2.5), cation exchange capacity (CEC), total nitrogen (N\(_T\)), soil organic carbon (SOC), and plant-available phosphorus (P) and potassium (K) were determined using the standard methodologies for soil examination [38]. All these determinations were performed in samples from two soil depths (0–25 and 25–50 cm).
Table 1. Soil characteristics for each woody fruit orchard at different soil depths.

| Plots | Slope (%) | Depth (cm) | Clay (g kg\(^{-1}\)) | Silt | Sand (g kg\(^{-1}\)) | \(N_T\) (\(\text{mg kg}^{-1}\)) | SOC (\(\text{mg kg}^{-1}\)) | K (\(\text{mg kg}^{-1}\)) | P (\(\text{mg kg}^{-1}\)) | \(\rho_b\) (\(\text{Mg m}^{-3}\)) | CEC (cmolC kg\(^{-1}\)) | pH |
|-------|-----------|------------|-----------------------|------|----------------------|-----------------------------|-----------------|-------------|-----------------|------------------|------------------|-----------------|---|
| Almond | 33 | 0–25 | 93 ± 12 | 215 ± 32 | 692 ± 65 | 0.45 ± 0.03 | 9.4 ± 2.4 | 68.7 ± 26.2 | 6.4 ± 2.2 | 1.17 ± 0.04 | 15.8 ± 4.4 | 7.4 ± 0.1 |
|       |           | 25–50 | 106 ± 15 | 244 ± 19 | 650 ± 41 | 0.40 ± 0.05 | 8.2 ± 3.1 | 77.7 ± 16.5 | 7.0 ± 3.9 | 1.20 ± 0.02 | 15.7 ± 5.6 | 7.7 ± 0.2 |
| Olive | 26 | 0–25 | 133 ± 19 | 200 ± 17 | 667 ± 31 | 0.58 ± 0.02 | 8.5 ± 3.3 | 90.4 ± 12.7 | 4.6 ± 1.4 | 1.19 ± 0.04 | 10.2 ± 4.9 | 7.5 ± 0.4 |
|       |           | 25–50 | 118 ± 11 | 271 ± 22 | 611 ± 17 | 0.62 ± 0.08 | 8.9 ± 2.5 | 94.7 ± 32.7 | 5.2 ± 4.6 | 1.24 ± 0.07 | 9.7 ± 7.8 | 7.7 ± 0.5 |

Means in the column followed by ± standard deviation; \(N_T\), total nitrogen; SOC, soil organic carbon; K, available potassium; P, extractable phosphorus (Olsen); \(\rho_b\), bulk density; CEC, cation exchange capacity.
The plant cover was based on spontaneous vegetation and was composed of species such as *Armeria* sp., *Avena sativa* L., *Anagallis arvensis* L., *Brachypodium* sp., *Bromus madritensis* L. Cent., *Campanula* sp., *Calendula arvensis* L., *Convolvulus althaeoides* L., *Crepis* sp., *Diplotaxis virgata* (Cav) DC, *Medicago* sp., *Malva parviflora* L., *Phagnalon rupestre* L. DC, *Velezia rigida* L., *Papaver rhoeas* L., *Rapistrum rugosum* L., *Sisymbrium* sp., *Scabiosa* sp., *Sonchus arvensis* L., and *Trigonella monspeliaca* L., among others. The development of this vegetation was undisturbed in the two seasons before the beginning of this experiment, allowing us to re-establish the growth of native plants. In the following seasons, after engaging in plant cover control via mechanical mowing, the residues were left for mulching. Plant cover percentages were estimated visually by counting the number of grid intersections, which intercepted vegetation in a 1 m × 1 m grid divided into squares of 10 by 10 cm (a total of 100 squares).

2.3. Statistical Analysis

One-way analysis of variance (ANOVA) was performed to ascertain whether the various soil depths differed in terms of runoff. Differences between individual means were tested using the least-significant difference (LSD) test at $p < 0.05$ using the Statgraphics v. 5.1 package program. Finally, the data were analyzed via correlation analysis to evaluate the relationships among runoff, rainfall parameters, and physico-chemical soil properties ($p < 0.01$).

3. Results and Discussion

3.1. Rainfall, Surface Runoff, and Subsurface Flow

During the monitoring period of two hydrological years (657.8 and 454.5 mm), 29 rainfall events were registered, concentrated in the autumn and winter. The rainfall depth values during the study period ranged from 1.6 mm to 206.2 mm, with strong contrasts in quantity and intensity within and between years, registering storms discharging great amounts of water in short periods of time. That is, the maximum unexpected rainfall event (206.2 mm) occurred in December followed by another in January (103.9 mm). Similarly, the $I_{30}$ for storms varied considerably between 17.3 and 0.81 mm h$^{-1}$, which led to different $EI_{30}$ from 655.8 to 0.25 MJ mm ha$^{-1}$ h$^{-1}$, and both maximum values coincided with the highest rainfall event occurring throughout the two hydrological years. Rainfall events of high intensity that provoke significant rates of water erosion are not rare in the Mediterranean zone [39], with daily events with more than 200 mm of rainfall sometimes being registered [40,41], as was determined in the present study. Most of the rainfall events recorded in the autumn and winter had a high runoff potential (intensity), as pointed out by other authors in the Mediterranean area [42–45]. Therefore, $EI_{30}$ was highly variable, in line with the rainfall amount and its distribution in different intensities. In this sense, Figure 3 shows the frequency of rainfall depth and $I_{30}$ throughout the monitoring period, being 35% between 10 and 30 mm, and 38% between 5 and 10 mm h$^{-1}$, respectively. Thus, rainfall intensity and its duration play an important role in surface runoff processes. In this context, Siebers et al. [46] reported that the impact of rainfall intensity on nutrient discharge must be considered more intently by controlling the drainage process to avoid plant nutrient losses from soils.

Figure 4 shows the results of the one-way analysis of variance concerning the effect of the soil depth on the average surface and subsurface flows. For both crop plots, the average values for surface runoff differed significantly ($p < 0.05$) from those recorded for the subsurface. Throughout the entire experimental period, the lowest runoff values were determined for surface runoff, at 0.89 and 1.12 mm, with these values for subsurface flow being between 4.97 and 5.32 mm and between 2.90 and 4.16 mm for almond and olive plots, respectively. In addition, during the monitoring period, the runoff coefficients of the almond and olive plots at soil depths of 0, 5, 10, 25, and 50 cm averaged 0.03, 0.15, 0.16, 0.20, and 0.19 and 0.04, 0.07, 0.11, 0.13, and 0.16, respectively. Thus, the runoff coefficients at different soil depths for the hillslope were 0.04, 0.11, 0.14, 0.17, and 0.18, respectively.
Figure 3. Frequency of the rainfall depth (A) and maximum intensity at 30 min (I_{30}) (B) for the monitoring period. Values inside the columns are percentages with respect to the total events.

Figure 4. Surface runoff (0 cm) and subsurface flow (5, 10, 25, and 50 cm) in almond and olive plots during the monitoring period. Different lowercase letters (a or b) are statistically different at 0.05 level by the least significance difference (LSD) test.

These surface runoff rates notably differ from those recorded in the study area under conventional tillage without plant cover for almond and olive orchards, at 15.0 and 4.0 mm, respectively [47,48]. This proved that the cover crop based on spontaneous plants markedly reduced the development of water erosion processes by reducing surface runoff; therefore, the plant biomass reduced raindrop splashes by intercepting raindrops and absorbing their energy. The effectiveness of controlling surface runoff was proportional to the percentage of cover when rain occurs (44% vs. 39% for almond and olive) [49]. In addition, the various species of spontaneous vegetation with different plant architectures, such as low species, provided close ground cover, and the trailing plants also formed a mat on the soil surface, which provided a litter layer beneath. Moreover, the contact between the litter and soil surface may have fostered the humification process, with a potential soil organic carbon increase under this plant cover.

On the other hand, shallow root species that deployed their roots in the topsoil helped to reduce water erosion by bolstering soil shear strength, while the increased root density with different species also reduced the soil’s susceptibility to erosion. That is, the plant roots penetrating the soil matrix encouraged porosity and thus infiltration, allowing the root zone to act as a partial sink for runoff in hillslopes, as demonstrated by considering the surface runoff with respect to the average subsurface flow in the almond (0.89 vs. 5.18 mm) and olive (1.12 vs. 3.80 mm) plots.

In this context, the implementation of plant cover as a conservation agriculture strategy in hilly agricultural soils has significant potential for water-soil management, particularly
in drought-prone soils in arid and semiarid areas [50,51]. Furthermore, mulching based on plant residue at the soil surface on sloping land serves as a vapor barrier (dry mass barrier) against water loss through evaporation, reduces raindrop impact energy, slows surface runoff, and therefore increases infiltration [52].

Table 2 shows the coefficients of correlation between runoff at each soil depth and rainfall parameters, denoting significant values for surface runoff for rainfall, \( I_{30} \), and \( E_{30} \), especially for the almond plots. A general decreasing trend was found for correlation coefficients occurring with soil depth. With the increase in rainfall intensity, both the surface and subsurface flows increased, but the surface runoff generation was more significantly correlated than that of the subsurface runoff. It is well known that runoff and its outflow rate are influenced by several factors such as precipitation depth, intensity, vegetation cover, soil texture, and soil moisture. However, it is mainly rainfall intensity that initiates surface runoff, and if it is greater than soil infiltration, a layer of water is formed on the soil surface that begins to run down the slope because of gravity. Thus, the regression models that consider \( I_{30} \) fluctuation accurately predict surface runoff with acceptable efficiency (0.532 and 0.743 for the almond and olive plots, \( p < 0.01 \)), agreeing with the results of Liu et al. [53]. However, Mazur [9] found that rainfall depth was significantly correlated with surface and subsurface water runoff and that \( E_{30} \) was significantly related with surface runoff. The relationship between subsurface flow and rainfall was generally not significant; however, the correlation coefficients were weaker for the almond plots (0.326–0.374) than for the olive plots (0.556–0.401) because the amount of subsurface outflow cannot be inferred from the amount of rainfall.

### Table 2. Correlation coefficients between the runoff from each soil depth (cm) and rainfall parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Almond Plots</th>
<th>Olive Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Surface</td>
<td>Subsurface</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>( R )</td>
<td>0.606 **</td>
<td>0.374</td>
</tr>
<tr>
<td>( I_{30} )</td>
<td>0.532 **</td>
<td>0.465</td>
</tr>
<tr>
<td>( E_{30} )</td>
<td>0.592 **</td>
<td>0.211</td>
</tr>
</tbody>
</table>

R, rainfall depth; \( I_{30} \), maximum rainfall intensity at 30 min; \( E_{30} \), erosivity index. **, significant at \( p < 0.01 \).

These findings indicate that for our semi-arid study area, where rainfall is unevenly distributed over the seasons, more soil water is needed to maintain water demand by crops during the non-rainy season; therefore, cover crops are a key factor for rainfall harvest.

### 3.2. Nutrient Leachates by Runoff Waters

The average \( \text{NO}_3^-\text{N} \) concentration in the runoff ranged from 7.92 to 23.6 mg L\(^{-1}\) and from 8.08 to 26.7 mg L\(^{-1}\) for the almond and olive plots and showed the following order for soil depths: 50 > 25 > 10 > 5 > 0 and 50 > 25 > 5 > 10 > 0, respectively (Table 3). The levels of \( \text{NO}_3^-\text{N} \) are usually associated with source availability and local environmental factors, with well-drained soils having a strong propensity for the transition of groundwater that represents a potential risk for its pollution by nitrates. That is, in hillslope plantations, nitrogen transportation could occur because of the presence of well-drained soils, mineral fertilizers, rainfall intensity, and the high solubility of \( \text{NO}_3^-\text{N} \), as was shown by the significant differences in concentrations at upper soil depths (0, 5, 10, and 25 cm) with respect to deeper depths (50 cm). In this sense, Manninen et al. [54] reported that at least 51%, and up to 93%, of dissolved N was exported by subsurface drainage, with smaller amounts occurring via surface runoff. The dominant contribution of subsurface flow with a higher \( \text{NO}_3^-\text{N} \) concentration in drainage waters could be attributed to the implementation of plant cover, which was able to enhance soil water infiltration. Hence, effective measures have been taken to minimize the \( \text{NO}_3^-\text{N} \) concentration in surface runoff, and thus, runoff volume reduction should be the primary concern for controlling the
potential runoff pollution in lowlands for surface waters. Also, this provides the proper conditions for NO$_3$–N uptake by the root system of almond and olive trees at deeper soil layers. In addition, cover crops are a key factor for N uptake and the denitrification process, which could be considered responsible for the natural remediation of NO$_3$–N in shallow groundwater [55,56].

Table 3. Average nutrient concentration in the surface and subsurface flows for the almond and olive plots.

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Almond Plot</th>
<th>Olive Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO$_3$–N</td>
<td>NH$_4$–N</td>
<td>PO$_4$–P</td>
</tr>
<tr>
<td>0 (Surface)</td>
<td>7.92 a</td>
<td>0.30 a</td>
</tr>
<tr>
<td></td>
<td>(±6.12)</td>
<td>(±0.20)</td>
</tr>
<tr>
<td>5</td>
<td>16.8 ab</td>
<td>0.27 a</td>
</tr>
<tr>
<td></td>
<td>(±8.07)</td>
<td>(±0.14)</td>
</tr>
<tr>
<td>10</td>
<td>17.08 ab</td>
<td>0.26 a</td>
</tr>
<tr>
<td></td>
<td>(±7.76)</td>
<td>(±0.12)</td>
</tr>
<tr>
<td>25</td>
<td>19.8 b</td>
<td>0.31 a</td>
</tr>
<tr>
<td></td>
<td>(±5.96)</td>
<td>(±0.18)</td>
</tr>
<tr>
<td>50</td>
<td>23.6 c</td>
<td>0.35 a</td>
</tr>
<tr>
<td></td>
<td>(±5.18)</td>
<td>(±0.16)</td>
</tr>
</tbody>
</table>

Values with different letters within a column are statistically different at the 0.01 level (LDS); values in brackets are ± standard deviation.

Table 3 shows that the average NH$_4$–N concentrations in runoff samples ranged from 0.26 to 0.35 mg L$^{-1}$ for the almond plots and from 0.23 to 0.59 mg L$^{-1}$ for the olive plots, displaying the following order in terms of soil depth: 50 > 25 > 0 > 5 > 10 and 50 > 5 > 10 > 25 > 0, respectively. In general, a similar trend to that of NO$_3$–N was denoted for NH$_4$–N, although not with increasing gradual concentrations in relation to soil depth, particularly at the depths of 5, 10, and 25 cm. NH$_4$–N can be adsorbed onto soil particles and become involved in cation exchange reactions; therefore, vertical leaching is not frequent. In this context, Nieder et al. [57] stated that besides the fact that the sorption of NH$_4$–N can happen in clay mineral lattices, the silt fraction is also able to adsorb NH$_4$–N in the non-exchangeable form.

Commonly, NO$_3$–N is the dominant N fraction in subsurface drainage water from agricultural fields because NH$_4$–N is easily bound to soil particles or nitrified by microorganisms [58], as was found in the present experiment. Overall, the moderate NH$_4$–N concentrations determined could be associated with the absence of organic amendments (manure) applied in these plots, but its source is attributable to the mineral fertilizers (NH$_4$NO$_3$ and (NH$_4$)$_2$HPO$_4$) used. Also, NH$_4$–N could be transformed into NO$_3$–N via the nitrification process, which would provide preferential transport of easily mobile NO$_3$–N during rainfall events.

In relation to PO$_4$–P, the average concentrations in the surface and subsurface flows ranged from 0.010 to 0.026 mg L$^{-1}$, with the highest average value being reached in the olive plots (Table 3). The PO$_4$–P values determined during the monitoring period differed significantly in relation to the upper soil depths (0, 5, and 10 cm) with respect to the deeper depths (25 and 50 cm), with a similar trend observed for both plots.

Dissolved P in surface runoff occurs via the desorption, dissolution, and extraction of P from soil and plant material, with these processes being affected by the interaction between rainfall and the thin layer of the soil surface. Therefore, dissolved P is the most dominant form in surface drains, while particulate P represents a smaller fraction of the total P leaving the drains. In this context, the NO$_3$–N concentrations were greater in subsurface drainage than in surface runoff, whereas PO$_4$–P displayed the opposite trend, with greater
concentrations in surface runoff, which is in line with the results of Melland et al. [59] and Norberg et al. [60]. According to Turtola and Yli-Halla [61], elevated P concentration in surface runoff water could be attributed to the build-up of P in the upper few centimeters of the soil following the application of fertilizers. Kleinman et al. [62] stated that even legacy sources of P that occur in low concentrations relative to agronomic requirements can contribute significant loads of P to surface runoff under ordinary hydrological conditions. Also, these authors reported the need for strategies that take advantage of the capacity of soils to buffer dissolved P losses, such as periodic tillage to reduce vertical P stratification in untilled soils for short-term solutions to mitigate P losses [62]. In this experiment with the implementation of plant cover, the P and N loads in runoff and drainage represent losses from the hillslope and root zone and reflect the potential transport of these nutrients that could reach a stream or groundwater aquifer, particularly during heavy rainfall events. Along this line, Xia et al. [63] pointed out that in addition to the benefits of cover crops in controlling runoff, straw mulching reduced annual runoff, sediment yield, and N and P loss by 13–55% from sloping land.

For both the almond and olive plots, the highest K concentrations were registered in subsurface flow from a soil depth of 50 cm (3.64 and 4.26 mg L\(^{-1}\)), followed by surface runoff (2.37 and 3.89 mg L\(^{-1}\)) (Table 3). The soluble K concentrations in the runoff from the remaining soil depths displayed intermediate values between 1.24 and 2.21 mg L\(^{-1}\). The K concentrations in runoff were quite high. Although this element is relatively mobile and does not directly result in eutrophication, its impact and risk as a potential pollutant should be taken into account when excessive potassium fertilizers are applied. In contrast, in a study by Yao et al. [64], a higher nutrient concentration of K and N in surface runoff than in subsurface flow waters was determined. The dissolved K in the soil solution can be leached to greater depths or to surface waters; however, in soils, it is commonly bound to clays and organic materials (in our soils, <133 and <9.4 g kg\(^{-1}\), respectively). Therefore, adsorbed K is mostly associated with fine particles, but it can also be eroded with particulate material by runoff water. Consequently, subsurface drainage may be an important pathway for soluble K movement, which is obviously affected by fertilizer application rate and timing, soil characteristics, and cover crops. In this context, Korucu et al. [65] evaluated the effect of cover crops (rye plants) with respect to bare soil on K transportation caused by surface runoff, with concentrations of 10.6 and 43.0 mg L\(^{-1}\), respectively.

In general, the average nutrient concentrations for surface runoff determined in this experiment particularly contrast with those reported by Francia et al. [47] in the study area under conventional tillage without plant cover for hillslope orchards with NO\(_3\)-N, NH\(_4\)-N, PO\(_4\)-P, and K concentrations of 25.5, 7.3, 2.7, and 5.2 mg L\(^{-1}\), respectively.

By comparing the linear relationships among rainfall parameters and plant nutrients, I\(_{30}\) was most positively correlated with nutrients in the olive plots and to a lesser extent in the almond plots. Concretely, the coefficients for the olive and almond plots (I\(_{30}\) vs. PO\(_4\)-P) were 0.605 and 0.641, respectively, while the EI\(_{30}\) factor was negatively correlated with K at \(-0.395\) and \(-0.369\) (\(p < 0.01\)), respectively, and for rainfall, no significant correlations were found for any nutrients. In this context, Coelho et al. [66] pointed out that plant cover demonstrated a low risk for subsurface and nutrient movement. Therefore, this cropping strategy is well suited to areas with a high risk of both surface and subsurface movement.

Implications for Groundwater Quality

Agricultural intensification in hilly areas is a potential pollution risk for waterways and a decline in the value of the ecosystem services of surrounding environments. Overall, with the exception of two values found for surface runoff (7.92 and 8.08 mg L\(^{-1}\)), the NO\(_3\)-N concentrations in the samples exceeded the 10 mg L\(^{-1}\) upper limit recommended by the U.S. EPA [67] and the usual range in irrigation waters reported by Ayers and Westcot [68]. Also, these authors stated that the NO\(_3\)-N concentration in most surface water and groundwater is usually less than 5 mg L\(^{-1}\), but some unusual groundwater may contain quantities in excess of 50 mg L\(^{-1}\). However, a lower concentra-
tion was proposed by Camargo et al. [69], stating that NO₃–N levels should not exceed
2 mg L⁻¹ in streams in order to protect the most sensitive freshwater species. On the
other hand, the European Nitrogen Assessment established three levels of eutrophication
risk for standing waters based on the mean concentration of total nitrogen (TN) as fol-
lows: low (mean TN < 0.5 mg L⁻¹), medium (TN between 0.5 and 1.5 mg L⁻¹), and high
(TN > 1.5 mg L⁻¹) [70].

In most of the rainfall events recorded, the NO₃-N transport by surface runoff was re-
duced; therefore, the potential contamination risk of surface waters located in the lowlands
was avoided. However, a possible contaminant risk for groundwater could be reached
(50 cm soil depth) if the depth of the groundwater level is shallow, which is not usually
the case in hilly areas. Moreover, as the rainfall events in the study area are not abundant,
but heavy rainfall storms are more frequent, the control of surface runoff is more urgent,
particularly in the context of the changing climate [44].

The NH₄–N concentrations in the runoff were higher than those considered for natural
levels for surface water and groundwater, at 0.2 mg L⁻¹ [71], but not for irrigation at
5 mg L⁻¹ [68]. However, according to Directive 98/83/EC (2020) [72], the concentration of
0.5 mg L⁻¹ of NH₄–N established by the European Union as a maximum allowable level in
drinking water was exceeded only by subsurface flow water (5 and 50 cm soil depth) in the
olive plots. The relatively high NH₄–N concentrations in subsurface flow, as was pointed
out previously, may reflect a low capacity of soils to retain it, which mainly relates to their
low cation exchange capacity (CEC), as well as the unfavorable conditions for nitrification
in groundwater.

Similarly, in most runoff samples for both crops, the concentration exceeded the estab-
lished limits usually associated with the eutrophication of surface waters of
0.010 mg P L⁻¹ [73,74], with the exception of the runoff samples from soil depths of
25 and 50 cm in the almond plots. Chambers et al. [75] highlighted thresholds for P
related to water quality, proposing a range between 0.010 and 0.10 mg P L⁻¹ to evade
eutrophication processes. The U.S.EPA [67] water quality criteria state that phosphates
should not exceed 0.05 mg L⁻¹ if streams discharge into lakes or reservoirs, and a more
restrictive limit of 0.01 mg L⁻¹ for the eutrophication of surface waters was reported by
Vollenweider and Kerekes [74]. However, the P concentration in runoff was well below
the recommended level of 2 mg L⁻¹ for agricultural use [68]. According to these findings,
there are far-reaching implications indicating that the control of pollution risk from surface
and subsurface flow waters is vital in lessening the possible eutrophication of both surface
waters and groundwater located in lowlands.

In general, the K concentration found for the study period did not exceed the upper
limit prescribed for drinking water, at 12 mg L⁻¹ [76], and the usual concentration in
irrigation water, at 2 mg L⁻¹ [68]. However, intensive hillslope farming incorporates
important amounts of plant nutrients with high risks of transport by nutrient-enriched
runoff during the rainfall period to lowlands.

At the plot scale, nutrient transport was triggered by storm events that activated
several hydrological pathways for nutrient transport and potentially may also mobi-
lize nutrients stored in soil particles by surface runoff. In this sense, remedial strate-
gies should be implemented with the aim of increasing plant nutrient use efficiency and
avoiding pollution risk to water bodies by focusing on balancing NPK inputs with out-
puts while simultaneously enhancing the management of soils and mineral fertilizers.
Thus, controlling NPK loss in agricultural runoff may be brought about by source and
transport control measures, such as plant cover in agricultural zones vulnerable to water
contamination development.

3.3. Soil Properties and Their Relationship with Surface Runoff

Various processes in hillslope areas are relevant to potential nutrient losses, such as
surface runoff, vertical flow (leaching), subsurface preferential flow affected by soil
structure and layering, and water erosion. The soil physico-chemical parameters at two
soil depths (0–25 and 25–50 cm) for each experimental plot are shown in Table 1. The soils for both crops have relatively lower SOC contents between 8.2 and 9.4 g kg\(^{-1}\), presumably due to the loss caused by water erosion under this type of environment with shallow soils that are considered marginal [77,78]. Also, depending on the soil management practices implemented (e.g., tillage and bare soil), the decomposition rate of organic matter may be augmented [79] and may impact runoff and nutrient losses considerably [15].

The P and K contents increased with soil depth, in contrast with the CEC, which was reduced. Concretely, spontaneous vegetation has the potential to fix and supply the plant nutrients required for their own growth, as well as transfer these nutrients after decomposition to the main crop (almond and olive trees). In this sense, Ferreira et al. [29] stated that available N, P, and SOC contents were improved in soils covered with spontaneous vegetation in rainfed woody fruit orchards. Madejón et al. [80], with a large range of crops, soil types, and environmental conditions, pointed out that no-tillage systems beneficially increased SOC storage and provided more advantageous conditions for the upper soil layers than other soil management. Thus, plant cover regulated the flow of runoff and probably helped to transform nutrients into biomass.

In general terms, the soils for both crops are loams, composed mostly of sand, silt, and a smaller amount of clay (Table 1), which can also encourage rainwater infiltration to a certain extent. This type of soil texture is associated with porosity that modulates the water holding capacity, gaseous diffusion (CO\(_2\)), and water movement inside the soil matrix. The low CEC in the soil makes it difficult for plants to adsorb plant nutrients, which potentially may lead to their loss through runoff waters, as was denoted by the NH\(_4\)–N and K contents in the surface and subsurface flows. Also, the CEC is highly dependent on the quantity and composition of clay minerals and organic matter [81,82], with low contents of these soil parameters being observed in the present study.

The pH values at different soil depths for the almond and olive plots were within normal plant growth conditions, ranging from 7.4 to 7.7. However, according to Verheye and de la Rosa [83], pH variations between the summer and winter may be highly variable in the same horizon, particularly in soil sections with high organic matter content, which was not the case in the present study. According to Mao et al. [84], soil pH is a key factor in explaining plant nutrient losses through surface runoff because soil pH vs. rainfall is highly correlated with runoff rather than with sediments.

Bulk density (\(\rho_b\)) in relation to soil depth did not vary significantly for either plot, with this parameter being highly sensitive to soil management (Table 1). In this line, a lower \(\rho_b\) is attributed to minimal damage to the soil, as plant cover can increase the organic matter content, porosity, and microbial content, all providing a healthier structure. By contrast, tillage operations can contribute to the disintegration of soil aggregates and determine the development of surface crusts, which is closely associated with water erosion. Furthermore, \(\rho_b\) generally augments with soil depth since subsurface layers have a lower organic matter content, aggregation, and root penetration compared with surface layers and, consequently, relatively less pore space could be expected. In addition, subsurface layers are also subject to the weight of the compacted soil above them.

The pooled correlation matrix among the surface runoff, rainfall, and soil parameters is shown in Table 4. Significant differences in the correlation values (\(p < 0.01\)) were determined for surface runoff compared with \(\rho_b\), SOC, rainfall, and I\(_{30}\). In line with the study by Kang et al. [85], who highlighted significant relationships for water erosion vs. \(\rho_b\) and SOC, \(\rho_b\) was negatively correlated with SOC and CEC but positively with EI\(_{30}\). In this sense, Sposito [86] and Bi et al. [87] determined a close relationship between SOC and CEC. In addition, CEC was correlated with all plant nutrients (NPK), P vs. N and K vs. P contents. Sharma et al. [88] and Bi et al. [87] reported that if SOC increases, total N increases since the N dynamics in soils are closely linked to C because most N endures in organic compounds and microbial biomass, as was found in the present experiment (SOC vs. N\(_T\)).
Table 4. Relationships among surface runoff and rainfall and soil parameters.

<table>
<thead>
<tr>
<th></th>
<th>( \text{RF}_S )</th>
<th>( \rho_b )</th>
<th>SOC</th>
<th>( T_N )</th>
<th>P</th>
<th>K</th>
<th>CEC</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>pH</th>
<th>R</th>
<th>( I_{30} )</th>
<th>( EI_{30} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{RF}_S )</td>
<td>1</td>
<td>0.652 **</td>
<td>-0.554 **</td>
<td>0.452</td>
<td>0.235</td>
<td>0.442</td>
<td>-0.305</td>
<td>-0.116</td>
<td>0.187</td>
<td>0.205</td>
<td>0.235</td>
<td>0.589 **</td>
<td>0.578 **</td>
<td>0.398</td>
</tr>
<tr>
<td>( \rho_b )</td>
<td>1</td>
<td>-0.758 **</td>
<td>0.395</td>
<td>0.478</td>
<td>0.107</td>
<td>-0.638 **</td>
<td>-0.340</td>
<td>0.378</td>
<td>0.107</td>
<td>0.354</td>
<td>0.064</td>
<td>0.425</td>
<td>0.5672 **</td>
<td></td>
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<tr>
<td>SOC</td>
<td>1</td>
<td>0.612 **</td>
<td>0.478</td>
<td>0.236</td>
<td>0.850 **</td>
<td>0.142</td>
<td>-0.415</td>
<td>0.447</td>
<td>0.554 **</td>
<td>-0.223</td>
<td>-0.078</td>
<td>-0.684 **</td>
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<tr>
<td>( T_N )</td>
<td>1</td>
<td>0.502 **</td>
<td>0.387</td>
<td>0.546 **</td>
<td>-0.216</td>
<td>0.345</td>
<td>0.015</td>
<td>0.467</td>
<td>0.341</td>
<td>0.193</td>
<td>0.389</td>
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<td>P</td>
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<td>0.532 **</td>
<td>-0.360</td>
<td>0.147</td>
<td>0.245</td>
<td>0.658 **</td>
<td>0.478</td>
<td>0.411</td>
<td>0.756 **</td>
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<tr>
<td>K</td>
<td>1</td>
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<td>0.541 **</td>
<td>-0.227</td>
<td>0.278</td>
<td>0.345</td>
<td>-0.365</td>
<td>-0.265</td>
<td>0.154</td>
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<td>CEC</td>
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<td>0.498</td>
<td>0.423</td>
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<td>Sand</td>
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<td>-0.102</td>
<td>-0.504 **</td>
<td>0.231</td>
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<td>Silt</td>
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<td>Clay</td>
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<td>-0.122</td>
<td>-0.047</td>
<td>0.587 **</td>
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<tr>
<td>pH</td>
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<td>0.478</td>
<td>0.417</td>
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<tr>
<td>R</td>
<td>1</td>
<td>-0.176</td>
<td>-0.035</td>
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<tr>
<td>( I_{30} )</td>
<td>1</td>
<td>0.834 **</td>
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<tr>
<td>( EI_{30} )</td>
<td>1</td>
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</table>

\( \text{RF}_S \), surface runoff; \( R \), rainfall depth; \( I_{30} \), maximum intensity at 30 min; \( EI_{30} \), erosivity index (R factor); SOC, soil organic carbon; \( T_N \), total nitrogen; \( P \), extractable phosphorus (Olsen); \( K \), available potassium; \( \rho_b \), bulk density; CEC, cation exchange capacity; **: significant at \( p < 0.01 \).
On the other hand, soil pH could be buffered by SOC ($r = 0.554$), and the relationship between pH and the concentration of available P depends on the pH value ($r = 0.658$). In general, a weak or absent relationship between soil texture components and the remaining soil parameters was found [89]. However, this fact contrasts with the findings of Bi et al. [87], who highlighted the close relationship between soil particle size and $N_T$, SOC, and CEC. In this context, the well-known and close relationship in predicting soil clay content based on CEC or its components [90] was confirmed with a correlation coefficient of $r = 0.498$ in the present experiment. Similarly, the recognized relationship between clay content and SOC [91,92], which is used to explain the influence of clay protection on organic C storage potential, was not determined, although the correlation coefficient between these parameters was $r = 0.447$. Finally, strong relationships among the rainfall parameters were determined including $I_{30}$ vs. CEC and sand, $EI_{30}$ vs. P and clay, and $EI_{30}$ vs. $I_{30}$.

These findings could be the first step in establishing that rainfed hillslope farming has a high risk of soil property degradation, which could trigger a greater susceptibility to water erosion and, consequently, adverse environmental impacts. To address this, it will be crucial to identify and monitor plant cover effects, representing the first step in countering land degradation as well as in planning resilient agricultural use.

4. Conclusions

Excessive runoff development was prevented by plant cover on the hillslope, which reduced surface runoff downslope because this cover led to a gradual improvement in the bulk density and a better interconnection of the soil pores, avoiding soil sealing and encouraging rainfall water infiltration. Under climate change scenarios, heavy rainfall events are expected to occur more frequently, and the ensuing surface runoff and its solute concentrations measured under these circumstances are indubitably of interest for the prediction/modeling of nutrient losses from agricultural lands and their impact on the environment.

Plant nutrient runoff from agricultural activities represents an important risk to waterway health and may have long-lasting and serious implications for the environment, ecosystem services, and humans. Accordingly, the implementation of different strategies for controlling nutrient runoff in farmlands is a key factor in preventing and remediating environmental damage from excessive mineral fertilization. Our results suggest that the flow pathways in soil from the surface to the subsurface were less restricted, presumably because of the increase in the root biomass of plant cover, thus improving soil porosity, especially influenced by fine roots, as denoted by visual appraisal in the field. According to the findings of the present experiment, a contrasting trend was determined in relation to N and P concentrations, with more P losses occurring via surface runoff and more N losses via subsurface drainage. These contrasting trends indicate that strategies are needed to mitigate these nutrient losses to surrounding water bodies, particularly those attributed to surface runoff. To avoid P transport, the focus should be on decreasing surface runoff, and the most effective way of controlling N losses is to keep the soil covered by plants. Consequently, the results demonstrate that plant cover effectively buffers the mechanical impact of raindrops on the soil surface, reducing surface runoff and fostering subsurface flow. That is, the spontaneous plant cover constituted a determining factor in the potential depletion of soil organic carbon losses and soil erosion, which subsequently could increase the content of organic matter due to the humification process.

The factors affecting the distribution of soluble N via subsurface flow are complex; however, our results suggest that targeting subsurface drainage pathways for $NO_3$–N and $NH_4$–N (e.g., optimizing the N application rate, winter–autumn plant cover) and for P in the subsurface (e.g., winter–autumn plant cover) would be effective strategies for reducing loading in runoff waters from hillslope farmlands. A large surplus of inputs is often associated with increased leachate nutrient losses from soils, and in rainfed semi-arid regions, farmers sometimes do not use adequate and balanced amounts of mineral fertilizers because of the uncertainty in rainfall. Thus, assessing agricultural N and P losses
and elucidating their main pathways are crucial for estimating the environmental risks posed by agricultural non-point-source pollution and formulating appropriate sustainable runoff control strategies in hillslope fields.

**Author Contributions:** V.H.D.Z. and B.C.R.: conceptualization, methodology, and data curation; V.H.D.Z., B.C.R., I.F.G.-T., B.G.R. and S.C.T.: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

**Funding:** This publication was partially sponsored by the following research project: “Strategies to improve the adaptation of almond cultivation to different scenarios of water scarcity and management systems NUTRESILIENCE” (AVA23.INV202301.004) co-financed by the European Regional Development Fund (ERDF) within the Operational Programme 2021/2027.

**Data Availability Statement:** All data used to prepare this manuscript are included; additional explanations will be made available upon request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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