



Combined role of ground cover management in altering orchard surface—subsurface erosion and associated carbon–nitrogen–phosphorus loss

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Abstract

The combined role of ground cover management in controlling soil erosion and nutrient loss from new orchards is still less understood. In this study, four ground cover management practices, orchard with grass cover (OG), orchard with interplant cover (OI), orchard with straw cover (OS), and orchard with bare ground (OB), were designed to identify their impacts on soil erosion and associated carbon–nitrogen–phosphorus loss in new orchards by rainfall simulation tests with rainfall intensities of 60, 90, and 120 mm h⁻¹ and 90 min rainfall duration. The results showed that OS had the lowest surface flow coefficient (6.6%) and highest subsurface flow coefficient (32.5%). The highest soil loss rate occurred in the OB plot (65.4 g m⁻² min⁻¹), and the lowest soil loss rate occurred in the OS plot (0.5 g m⁻² min⁻¹). OS plot showed better effectiveness in improving soil erosion. However, the increased infiltration capacity was facilitated in terms of causing non-point source pollution. The C-N-P ratios of surface flow in different cover measures (OB, OI, OG, and OS) were 1.4:1.2:0.9:1, 1.8:1.7:1.2:1, and 2.3:1.9:1.2:1, respectively. The ratios of sediment in different cover measures were 7.3:9:2.3:1, 2:1.5:1.2:1, and 1.2:1:0.8:0.7, respectively. Cover management plots play an active role in reducing nutrient loss in surface flow and sediment, but the increased infiltration in covered management plots is associated with the risk of groundwater contamination in subsurface flow. The C-N-P ratios of subsurface flow in OB and covered managed plots (OI, OG, and OS) were 1:3.3:1.6:2.7, 1:1.5:2.2:2.4 and 1:1.2:1.5:1.3, respectively. Therefore, when managing the phenomenon of soil erosion through ground cover measures, attention should also be focused on the function of cover measures in regulating non-point source pollution underground, such as subsurface flow. This research recommends a combination of cover management measures to further mitigate erosion and the risk of groundwater contamination.

Keywords Soil erosion · Surface–subsurface flow · Ground cover management · Carbon–nitrogen–phosphorus loss · New orchard

Introduction

Rapid development of orchards has been the most important source of soil erosion in the hilly area of southern China during the last two decades (Ahuja 1990; Xu et al. 2012; Li et al.

2014; Chen et al. 2019). The most important stages of orchard erosion are the early establishment stage and the young forest stage of the fruit trees (Fig. 1). New orchards are inherently more fragile and less resistant to erosion, which can easily lead to severe soil erosion (Cerdá and Doerr 2005; Duan et al. 2020). The early stages of orchard development are threatened

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by a variety of factors. The management methods currently used in new orchards are still traditional. The removal of native vegetation during the preparation process may be affected by heavy mechanical transport, as well as the application of herbicides and fertilizers, resulting in compacted soil surfaces and high tolerances, with heavy herbicide use even reducing the vegetation coverage to less than 5% (Cerdà and Jurgensen 2008; Cerdà et al. 2009; Atucha et al. 2012; Shi et al. 2014; Zheng et al. 2014). Meanwhile, the frequency of extreme rainfall, the low cover of young orchards, and the steep slope topography all contribute to further soil erosion, even causing serious rill and groove erosion in orchards (Duan et al. 2020; Ma et al. 2022). Therefore, under the influence of multiple factors, it is necessary to focus on the early stages of orchard construction and to prioritize reasonable measures for the sustainable development of orchards.

Ground cover management has been a more effective approach to erosion management in recent years and has

been widely used in erosion prevention (Peng and Wang 2012; Liu et al. 2014a, b; Duan et al. 2020). These include vegetation cover management and mulch management. Vegetation cover management and mulch management focus on different functions. In vegetation cover management measures, the vegetation cover canopy and apoplastic material can intercept raindrops and reduce their kinetic impact and can reduce the impact of runoff and erosion by improving the physical conditions of the soil through the plant root system (Zuazo et al. 2005; Zheng et al. 2008; Liu et al. 2014a, b). Meanwhile, groundcover vegetation provides mechanical protection for the soil by increasing infiltration and reducing splash erosion and concentrated flow erosion (Kinnell 2005; Raya et al. 2006; Novara et al. 2011). Mulch management can reduce splash erosion and soil loss in an environmentally friendly way by increasing the surface roughness to improve infiltration rates, absorbing the effects of raindrops and reducing the detachment of soil aggregates (Adekalu et al. 2007; Kukal



Fig. 1 Serious soil erosion in new orchards

and Sarkar 2010). Gholami et al. (2013) showed that straw mulching at the 99% confidence level had a significant effect on changing runoff and soil erosion characteristics.

However, existing cover studies have focused more on its ability to regulate water and sand on slopes, and less on its impact on runoff processes such as subsurface flow. In a rain-fall event, not only the impact of surface flow on soil loss but also the impact of subsurface flow is included (Zheng et al. 2014; Liu et al. 2016). Subsurface flow is an important component of runoff and plays an important role in watershed runoff regulation, water retention, sediment transport, and nutrient loss. With the frequent occurrence of climate extremes in recent years, promoting soil water retention through cover management is particularly important to ensure orchard yields under stresses such as extreme drought. In the southern red loam low hills, rainfall types such as long ephemeral periods have a positive impact on promoting runoff forms such as subsurface flow, promoting orchard development (Ma et al. 2022).

Nonpoint source pollution due to soil erosion and human disturbance is also a very common occurrence in orchards. Pesticides, fertilizers, and herbicides are applied in large quantities to increase orchard yields, but the low efficiency of pesticide and fertilizer use is accompanied by soil erosion and a large loss of nutrients such as C-N-P, resulting in nonpoint source pollution, which is one of the main causes of surface water quality deterioration (Sharpley et al. 2008; Vymazal and Brezinova 2015; Wang et al. 2018; Srinivas et al. 2020). Excessive fertilization has even led to China's agricultural nonpoint source pollution exceeding that of developed countries in breadth and depth, which is not conducive to the sustainable development of orchards (Xu et al. 2022). Meanwhile, as the number of subsurface flows in orchards continues to increase, so does the amount of nutrients they carry, causing potential pollution of groundwater. The environmental pollution caused by nonpoint source pollution is not conducive to the sustainable development of orchards and the reuse of soil.

When choosing measures to manage the ecological problems associated with orchard development, there has traditionally been a preference for one or the other, either erosion control or nonpoint source pollution management. Vegetation cover measures can control soil erosion by intercepting runoff and sediment or reduce the loss of nutrients carried by slowing erosion. There is often a lack of attention and quantitative research on how well some of the measures that have positive implications for erosion control have been able to regulate nonpoint source pollution.

Based on some experience of orchard management in hilly areas of southern China, four measures of orchard with grass cover (OG), orchard with interplant cover (OI), orchard with straw cover (OS), and orchard with bare ground (OB) were selected. This paper focuses on determining the effects of different cover management practices on soil erosion and associated carbon, nitrogen and phosphorus losses in new orchards. The

objectives of the study were to (i) reveal the rule of different measures in surface–subsurface flow and sediment yield; (ii) analyze the characteristics of nutrient loss in C-N-P and other measures; and (iii) comprehensively evaluate the effects of different measures on controlling soil and water loss and nutrient loss. This study provides guidance and reference for controlling soil erosion and nonpoint source pollution in orchards.

Methods and materials

Area of study

The research was carried out in Jiangxi Ecological Science and Technology Park of Soil and Water Conservation, which is located in the southwest suburb of De'an County, Jiujiang City, Jiangxi Province, China. The study area is located in the subtropical monsoon climate zone, which has adequate light and abundant rainfall. The average annual temperature in this area is 11.6–19.6 °C, and the frost-free period is 240–307 days. The distribution of the precipitation season is uneven, with more than 70% of the annual precipitation mainly concentrated in spring and summer. The red soil weathered from the quaternary sediment is strongly aluminized and viscous. In this typical hilly mountainous terrain, sloping land is commonly cultivated in orchards as the citrus, as citrus planting helps to increase economic income. However, the large area of citrus planting and unreasonable use of land have caused serious environmental issues such as soil erosion and nonpoint source pollution in the area.

Plot construction and measure arrangement

In this study, the runoff plot experiment method was used to conduct simulation experiments, and four runoff plots with a size of 6.0 m (length) × 3.0 m (width) × 1.0 m (depth) were established (Fig. 2). The four plots were separated from each other by a 1-m deep boundary wall, and the wall was set 10 cm higher than the soil surface to ensure that the collected runoff came from the respective plots and was not disturbed by other surrounding plots. The slope gradient of all four plots was set at 20° according to the field investigation. Each of the plots had two runoff (surface runoff and subsurface runoff) outlets. The surface runoff was collected by a surface trough, and then the runoff was delivered into a tank by a plastic pipe. The outlet of the subsurface runoff was set at a depth of 60 cm beneath the surface soil, the subsurface flow was collected by an L-type collecting board set into the wall (Liu et al. 2016), and the subsurface runoff was guided into the runoff tank by a plastic pipe.

Four ground cover measurements, orchard with grass cover (OG), orchard with interplant cover (OI), orchard with straw cover (OS), and orchard with bare ground (OB), which stem from local orchardist experiences, were designed in this paper

to test their impacts on soil erosion and nutrient loss. For the OG measurement, the legume grass type clover with high nitrogen fixation capacity was wildly planted for fast growth, density surface coverage, and the potential to improve soil quality. The clover was seeded over one year before rainfall simulation and maintained by mowing and weeding every half-year. Interplant was a common measure in the new orchards for the purpose of economic income. In this study, the interplant type was peanut which was the predominant crop on sloping land in the red loam hills. Straw continuously covered the soil surface at a density of 0.5 kg m^{-2} , and the straw was maintained semiannually. The bare control management was weeded every three months, with no plowing, while other management practices, such as fertilization and fruit tree pruning, were the same as those in the other three plots. The fertilization amount of all four runoff plots was 1500 kg ha^{-1} . The fertilizer was applied one week before the simulated rainfall, and the four plots were covered with rain gear one time after application to avoid the effects of natural rainfall.

Simulated rainfall

In the simulated rainfall test, the spray nozzle for the lower spray type, the nozzle water pressure condition was set to 0.08 MPa, the position of the nozzle is perpendicular to the plot, and the vertical distance is 4.75 m; thus, most of the raindrops can be prompted to reach their final velocity. In this study, we focused on the impacts of extreme rainfall conditions on orchard soil erosion; according to the local long-term meteorological observation results, the rainfall intensity was set at 60, 90, and 120 mm h^{-1} to represent heavy rain, storm rain, and extreme rainstorms, respectively. Rain intensity was achieved by an adjustable size pump, and the rainfall duration was set at 90 min.

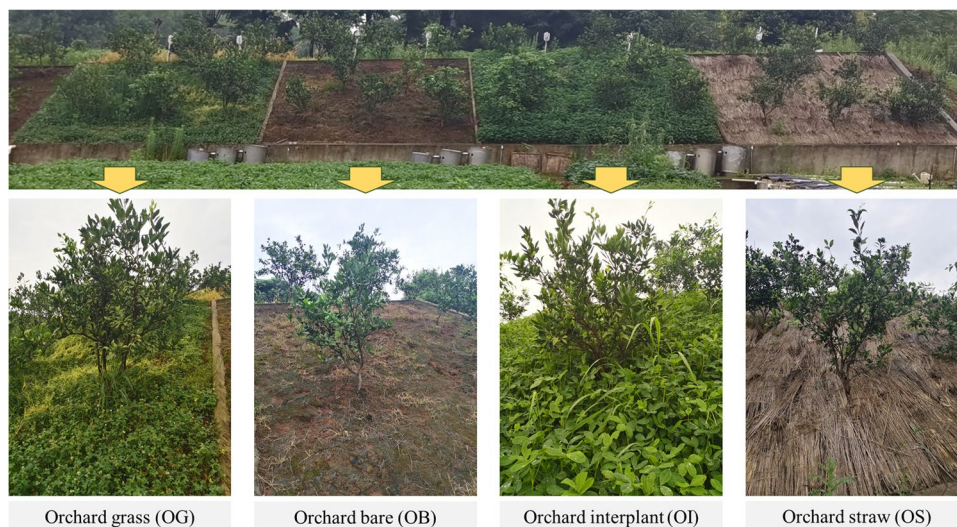
During the rainfall simulations, surface and subsurface runoff volumes were collected every 3 min once generated,

and soil loss from surface flow was simultaneously collected with the surface flow by a 300 mL bottle of water and sand mixture sample. All the surface flow, subsurface flow, and sediment of each rainfall test were collected separately. The concentrations of total nitrogen (TN) and total phosphorus (TP) lost in surface flow, subsurface flow, and surface eroded sediment, and the dissolved organic carbon (DOC) in surface–subsurface flow and total organic carbon (TOC) in surface eroded sediment were analyzed by three mixed samples from the total collected surface–subsurface flow and sediment samples of each rainfall simulation. The total lost C-N-P was then calculated. All the samples were transferred to a laboratory for immediate testing. All the rainfall simulation tests were repeated three times, and the interval time between two rainfall simulations was over one week. After each rainfall simulation, the runoff plots were covered by plastic ponchos to avoid natural rainfall impacts. The rainfall simulated tests were finished from May to August in 2019, and during this period, the ground coverages of OG, OI, and OS management were similar at 70%.

Data analysis and collation

To determine the effect of different cover management practices on surface–subsurface flow generation and sand production, samples were collected, and the water content of the soil, the flow coefficient (ROC), and soil loss rate (SLR) were determined based on data received from simulated rainfall experiments. The surface flow coefficient is the ratio of the depth of runoff or (total amount of runoff) to the depth of precipitation (or total amount of precipitation) in the same time period. The equations for the flow coefficient and soil loss are as follows:

Fig. 2 Citrus orchards with different ground cover management, including orchard grass (OG), orchard bare (OB), orchard interplant (OI), orchard straw (OS)



$$ROC = \frac{RD}{PD} \times 100\% \tag{1}$$

where *ROC* is the runoff coefficient (%), *RD* is the runoff depth (mm), and *PD* is the precipitation depth (mm).

$$SLR = \frac{SLA}{PA} \tag{2}$$

where *SLR* is the soil loss rate ($\text{g m}^{-2} \text{min}^{-1}$), *SLA* is the soil loss amount (t), and *PA* is the runoff plot area (km^{-2}).

The total nitrogen and total phosphorus contents were measured using a UV–Vis spectrophotometer (AB/EQ-063) and a visible spectrophotometer (AB/EQ-256), respectively. Dissolved organic carbon (DOC) was measured by Multi N/C 2100 S Analyzer (Analytik Jena, Germany). Total organic carbon TOC data were determined using an elemental analyzer (vario MACRO CUBE, Elementar, Germany).

Pearson correlation coefficients were used to analyze the relationship between surface flow, subsurface flow, sediment, and C-N-P and to determine their correlation. All data were statistically analyzed using SPSS 26.0, and all graphs were created using Excel software and Origin 2021 software.

Results

Surface flow

Figure 3 presents the surface flow coefficients under different rainfall intensities and cover managements. The surface flow coefficients first increased with the duration of rainfall and

then reached a relatively stable value; thus, the surface flow coefficients displayed an increasing–stabilizing trend. The largest and smallest mean surface flow coefficients occurred in the OB and OS plots, with values of 83.1% and 17.8%, respectively. With an increase in rainfall intensity, the differences in the surface flow coefficient between the bare plot and cover management plots increased. At 60 mm h^{-1} rainfall intensity, the surface flow coefficient of OB was 14.2–20.0% higher than that of other covered plots, while 47.7–65.8% and 26.5–65.3% higher at 90 and 120 mm h^{-1} , respectively. Cover management practices exhibited a significantly positive impact on reducing surface flow but gradually weakened with an increase in rainfall intensity.

Different cover management practices showed significant differences in reducing surface flow generation. The best performer was OS management, with a surface flow coefficient of only 2.6–21.7%, followed by OG and OI management. However, the gaps in the capacity of different cover managements to reduce surface flow were narrowed with increased rainfall intensity. Under 60 mm h^{-1} rainfall intensity, the surface flow coefficient mean values of OI were 4.2% and 5.8% greater than those of OG and OS, respectively. When the intensity increased to 90 and 120 mm h^{-1} , the differences decreased to 6.2% and 18.6% for OG management, and 16.1% and 38.8% for OS management, respectively.

Subsurface flow

The subsurface flow generation in the plots with vegetation cover management showed an increasing–stabilizing–increasing

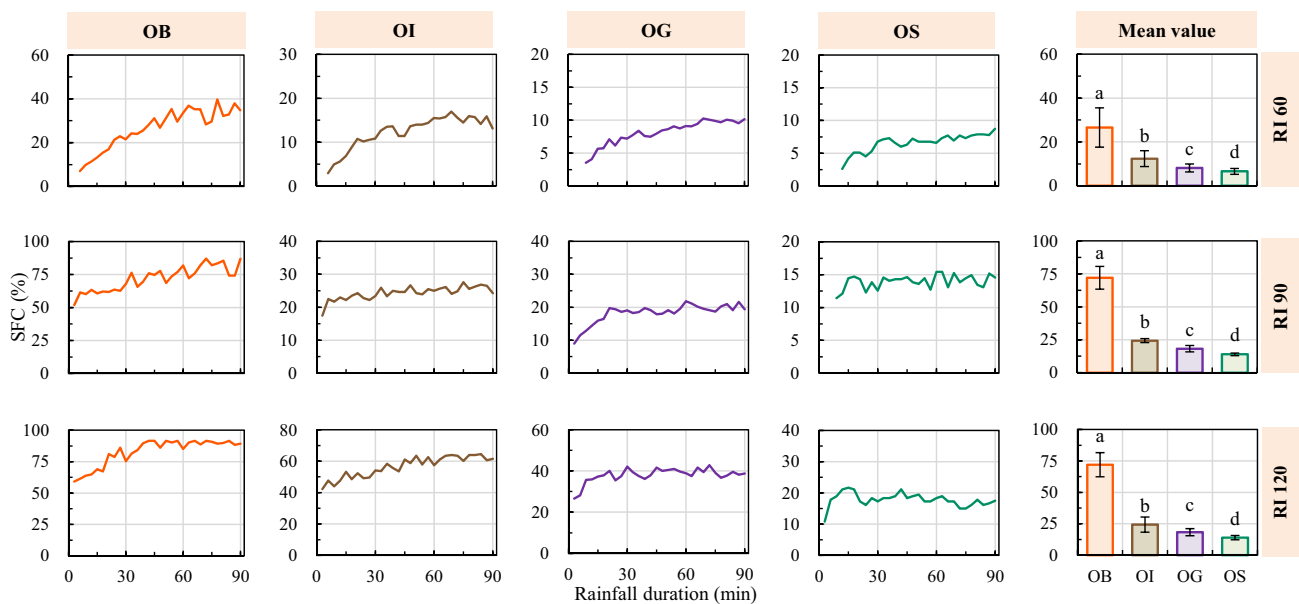


Fig. 3 The processes of surface flow coefficients of four cover managements under three rainfall intensities (SFC means surface flow coefficient, RI means rainfall intensity, OB means orchard bare, OI means orchard interplant, OG means orchard grass, OS means orchard straw)

trend. All subsurface flow coefficients increased sharply to a stable value, followed by a slow increase, while the SSFC of OB showed an increasing–stabilizing–decreasing trend (Fig. 4). For managed plots, the initial subsurface flow generation time was slightly faster than that of the bare plot, with differences within 10 min at 60 and 90 mm h⁻¹ rainfall events. Stronger rainfall intensities accelerated the subsurface flow response, and the initial times among plots were almost the same at 120 mm h⁻¹. The higher the intensity of rainfall is, the earlier the response of subsurface flow generation.

The plots with cover management had a higher subsurface flow generation capacity than the bare plot. The mean subsurface flow coefficient of plots with cover management was 4.2–15.2% greater than that of OB at a rainfall of 60 mm h⁻¹. When the rainfall intensity increased to 90 and 120 mm h⁻¹, the differences increased to 5.7–16.9% and 7.7–23.5%, respectively. The surface conditions with cover management were more favorable to produce subsurface flow, and the higher the rainfall intensity was, the greater the subsurface flow generation.

The cover management plots were beneficial for subsurface flow generation but had differences in subsurface flow generation. OS has the best performance, followed by OG and OI. The mean subsurface flow coefficient of the plot with OS was 6.2–11.0% greater than that of OG and OI at a rainfall of 60 mm h⁻¹, while it was 5.8–11.2% and 5.9–15.8% higher at 90 and 120 mm h⁻¹, respectively. Hence, higher rainfall intensities led to higher subsurface flow coefficients.

Sediment yield

As shown in Fig. 5, the hydrological response time was the earliest for OB and the lowest for OS. However, as the rainfall intensity increased, the difference in response time between them was not significant, and the response time of each plot was advanced. Bare surfaces had a higher sand production capacity and soil erosion rate than cover-managed surfaces (Fig. 5). The mean SLR values of OB were 1.9–4.3 g m⁻² min⁻¹ higher under 60 mm h⁻¹ than those of cover-managed plots, while they were 32.6–38.3 g m⁻² min⁻¹ and 47.3–63.7 g m⁻² min⁻¹ higher than those of cover-managed plots under 90 and 120 mm h⁻¹ rainfall intensities, respectively. Cover management significantly improved surface sediment production, and the improvement function increased with the intensity of rainfall.

The contribution of different coverage management practices to sediment reduction was different (Fig. 5). OS had the lowest soil loss rates, followed by OG and OI. Even under 120 mm h⁻¹ rainfall intensity, the SLR values of OS did not exceed 5 g m⁻² min⁻¹. The SLR mean values of OS were 0.6–2.4 g m⁻² min⁻¹ less than those of OG and OI at 60 mm h⁻¹, while OS was 1.0–5.7 and 8.8–16.4 g m⁻² min⁻¹ less than those of OG and OI at 90 and 120 mm h⁻¹ rainfall events, respectively. Soil erosion rates gave a clear indication of the effect of cover management on sediment production and that OS had a strong effect in reducing soil erosion.

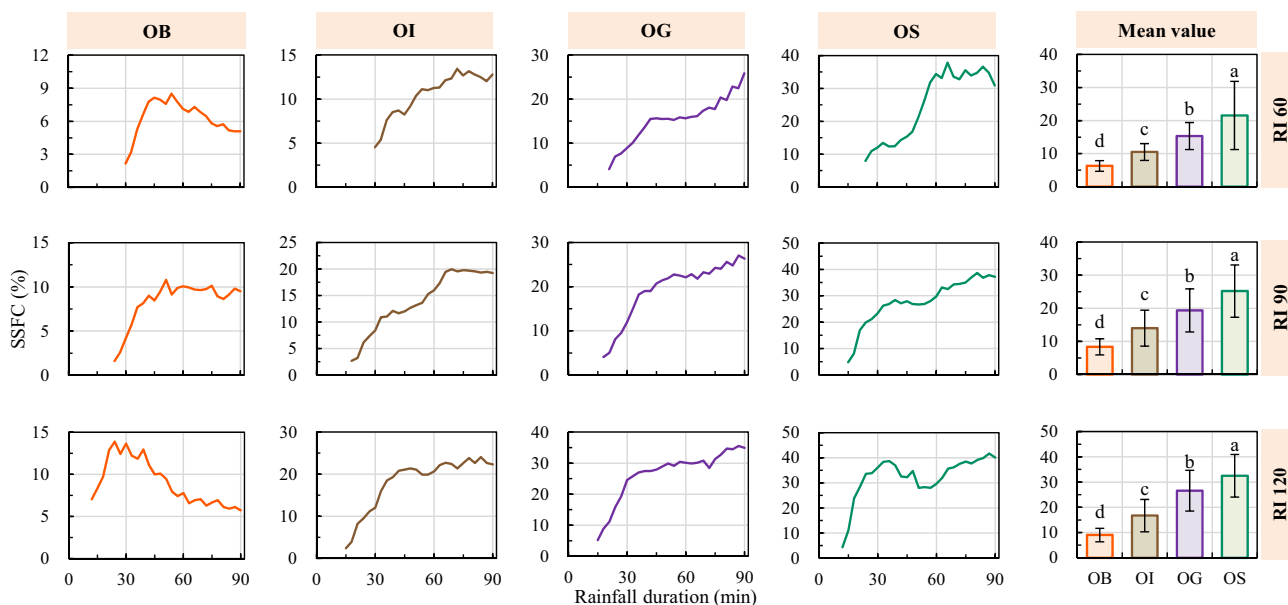


Fig. 4 The processes of subsurface flow coefficients of four cover managements under three rainfall intensities (SSFC means subsurface flow coefficient, RI means rainfall intensity, OB means orchard bare, OI means orchard interplant, OG means orchard grass, OS means orchard straw)

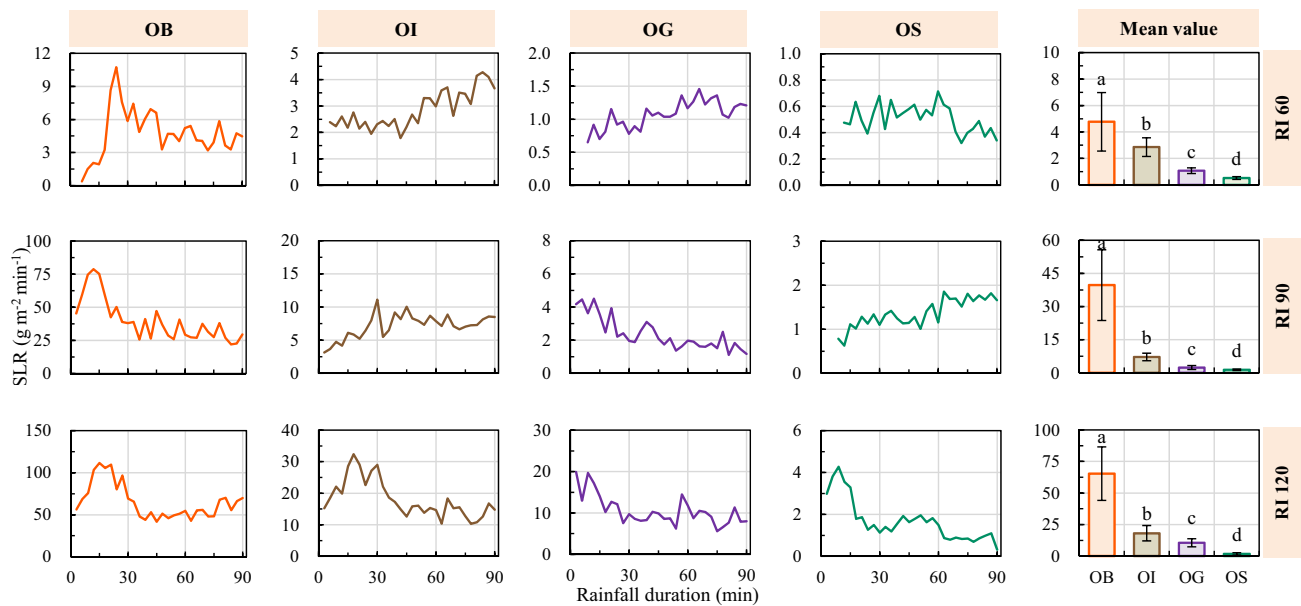


Fig. 5 The processes of soil loss rates of four cover managements under three rainfall intensities (SLR means soil loss amount, RI means rainfall intensity, OB means orchard bare, OI means orchard interplant, OG means orchard grass, OS means orchard straw)

Nutrient loss

As shown in Fig. 6, with increased rainfall intensity, nutrient (TN, TP, DOC, and TOC) loss increased. The TN content varies under different cover management practices. The content ratio of TN in surface flow between OB and covered managed plots (OI, OG, and OS) was 1.8:1.7:1.2:1. The ratio of TN content in the sediment between OB and covered managed plots (OI, OG, and OS) was 2:1.5:1.2:1. However, plots with cover management were more conducive to subsurface flow production, and the average TN content in subsurface flow was significantly higher than that in the OB plot. There are covered management plots to curb nonpoint source pollution, but there is a risk of groundwater pollution.

Plots with different cover management showed different performances. The ratios of TP in surface flow and sediment between OB and with cover management plots (OI, OG, and OS) were 2.3:1.9:1.2:1 and 1.2:1:0.8:0.7, respectively. TP contents showed the opposite behavior in the subsurface flow. The ratio of TP content in OB to that in the covered management plots was 1:1.2:1.5:1.3. The TP content in the sediment was significantly higher than that in the runoff. The TP content in sediment was approximately 19.7 g higher than that in runoff.

The ratios of DOC in surface flow and subsurface flow in OB and covered managed plots were 1.4:1.2:0.9:1 and 1:3.3:1.6:2.7, respectively, while the ratios of TOC in sediment in OB and covered managed plots were 7.3:9:2.3:1. The content of DOC in subsurface flow in cover management plots is higher than that of OB. The OI plot has the best performance.

Correlation analysis

There was a significant correlation between nutrients and soil erosion. As shown in Fig. 7, the correlations of nutrients (DOC, TOC, TN, and TP) with surface flow, subsurface flow, and sediment were significant overall ($p < 0.001$). This result shows that the process of soil erosion is closely related to nutrient loss, and the process of soil and water loss is accompanied by the risk of nonpoint source pollution.

Discussion

Effects of cover management on runoff generation

Due to unreasonable management, orchards often have serious risks of soil–water–nutrient loss. Ground cover management has been proven beneficial in altering runoff generation processes in orchards (Gómez et al. 2009; Atucha et al. 2012; Liu et al. 2012; Chen et al. 2019; Duan et al. 2020). The orchards with cover management produced significantly less surface flow and more subsurface flow than bare orchards. Figure 8 illustrates the proportion of rainfall redistributed under different rainfall intensities and cover management. Different patterns of flow proportions were compared between orchards with ground cover management and OB, with the highest proportion of OS subsurface and the lowest proportion of surface flow (38% and 12%), followed by OG (20% and 22%), OI (13% and 31%), and OB (7% and 60%). These results suggest that orchards managed with ground cover vegetation are more

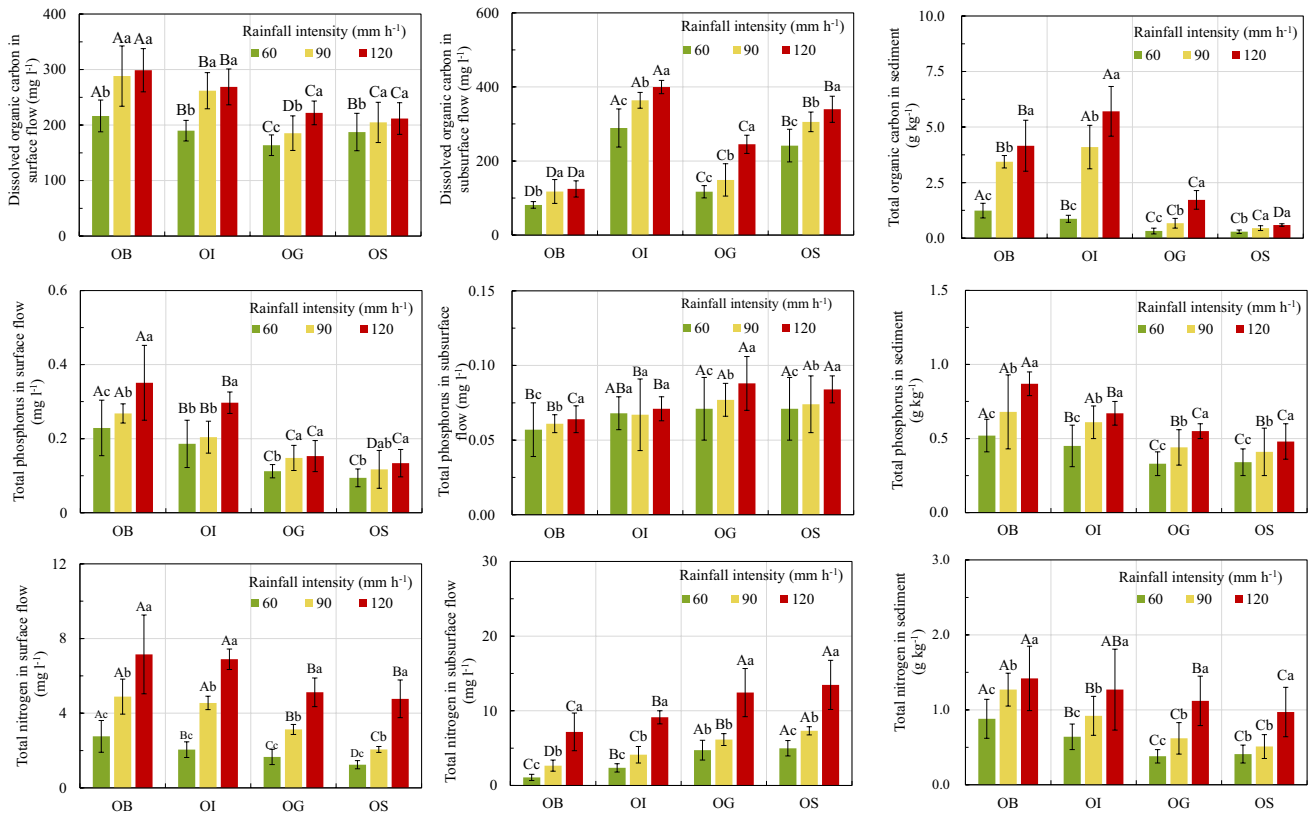


Fig. 6 The processes of nutrient loss rates of four cover managements under three rainfall intensities (OB means orchard bare, OI means orchard interplant, OG means orchard grass, OS means orchard straw);

TN means total nitrogen, TP means total phosphorus, DOC means dissolved organic carbon, TOC means total organic carbon)

effective in reducing water erosion than those managed without cover at the young age of fruit trees. Ground cover can disperse and absorb runoff energy, improving rainfall interception and infiltration (Francia Martinez et al. 2006; Zhu et al. 2020). Meanwhile, the ground cover provided a rough surface condition that plays a significant role in runoff generation (Issa et al. 2001; Rodríguez-Caballero et al. 2012). The increased surface roughness slows the flow rate of runoff and increases infiltration rates, thus reducing surface flow. However, different cover management focuses on different functions.

Orchards managed with crop intercropping and grass covering have a three-dimensional structure from which the interception effect of the plant canopy, while increasing the surface roughness, significantly reduces surface flow and increases subsurface flow. Dense live grass roots increase the hydraulic conductivity of the soil, leading to the diffusion of concentrated surface flow (Liu et al. 2016). Straw mulch has a higher proportion of subsurface flow compared to OG and OI orchards. Dense straw mulch protects the soil from the direct effects of raindrops and helps to increase surface roughness and can also act as a buffer, weakening the kinetic energy of raindrops and protecting the topsoil, which has a strong water-holding capacity and can retain large amounts

of rainfall, thus increasing rainfall infiltration and subsurface flow (Jordán et al. 2010; Nunes et al. 2011; Liu et al. 2016).

As shown in Fig. 8, the average surface flow proportion of the OB plot was significantly higher than that of the OI, OG, and OS plots (29.3%, 39.1%, and 47.8% higher respectively). The average subsurface flow proportion for the OB plot is significantly lower than that for the OI, OG, and OS plots (5.8%, 12.5%, and 18.5% respectively). This was mainly due to the low infiltration capacity of the OB plot, while the OI, OG, and OS plots had significantly higher infiltration rates than OB due to the effects of plant roots expanding the soil pore space, increasing runoff flow paths or mulch increasing roughness and improving infiltration.

The benefits of plots under cover management also differed at different rainfall intensities, and this difference was more pronounced at higher rainfall intensities (120 mm h⁻¹). At a rainfall intensity of 60 mm h⁻¹, the OS surface flow was lower than that of the OI and OG plots (6.0% and 1.7% lower, respectively), while the subsurface flow was 12.5% and 7.1% higher than that of the OI and OG, respectively; at a rainfall intensity of 120 mm h⁻¹, the OS surface flow was 38.8% and 20.2% lower than that of the OI and OG plots, respectively, but OS had a higher subsurface flow coefficient than the OI and OG

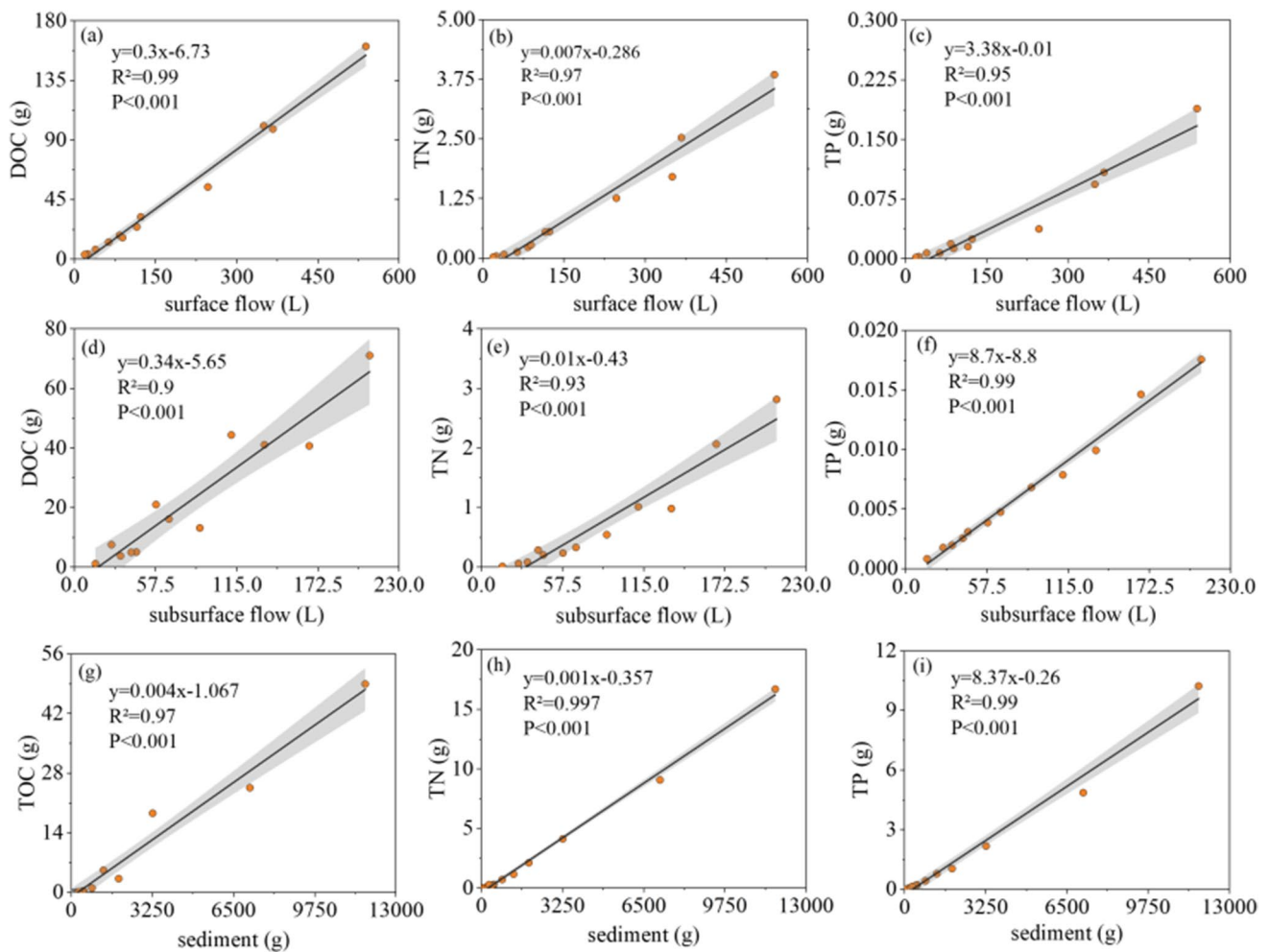


Fig. 7 Correlation between soil erosion and nutrient loss (**a** means the correlation between surface flow and DOC; **b** means the correlation between surface flow and TN; **c** means the correlation between surface flow and TP; **d** means the correlation between subsurface flow and DOC; **e** means the correlation between subsurface flow and TN;

f means the correlation between subsurface flow and TP; **g** means the correlation between sediment and TOC; **h** means the correlation between sediment and TN correlation; **i** means correlation between sediment and TP)

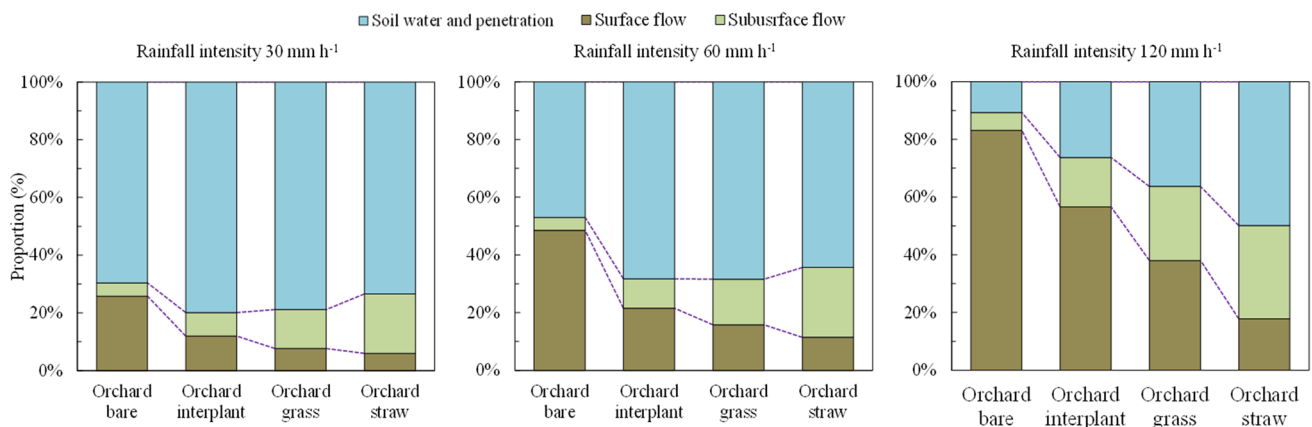


Fig. 8 Rainfall redistribution of the four cover managements under three rainfall intensities and proportions of different patterns flow generated during rainfall simulation under four cover managements

plots (15.2% and 6.6% respectively). This reflects the weakened ability of OG and OI to reduce surface flow and increase subsurface flow under extreme rainfall conditions, while OS maintained a relatively high ability to reduce flow and increase infiltration, and the benefits were more stable. This is mainly because straw mulch is more beneficial for rainfall interception and infiltration than OG and OI (Prosdocimi et al. 2016).

Effects of cover management on sediment production

The process of runoff generation is inevitably accompanied by the generation of sediment, and ground cover plays an essential role in controlling soil loss. Duan et al. (2021) found that orchards with grass cover and cover crops had significantly lower average multiyear flow coefficients and soil erosion rates than those without cover. The cover crops were effective in reducing erosion to tolerable levels and had the lowest runoff and erosion, while uncovered plots had the highest runoff and erosion (Gómez et al. 2009; Keesstra et al. 2016). In this study, SLR for OB was approximately 4 to 10 times higher than with covering measures, indicating that plots managed without mulching were extremely inefficient at intercepting sediment. The efficiency of soil retention also varied between plots managed with coverings. SLR was highest in OI ($9.4 \text{ g m}^{-2} \text{ min}^{-1}$), intermediate in OG ($4.7 \text{ g m}^{-2} \text{ min}^{-1}$), and lowest in OS ($3.6 \text{ g m}^{-2} \text{ min}^{-1}$). The plots managed with straw mulching had the best soil retention efficiency.

The different functions of the ground cover result in different benefits for sediment retention. The plant roots of the OI and OG bind the soil particles and reduce the stripping of the soil by runoff. By increasing surface roughness and soil permeability, roots increase the infiltration capacity of the soil (Baets et al. 2006). Currently, some studies have focused on the influence of the surface part of vegetation cover management on soil erosion. In fact, this reduction is caused by the combined effects of root and canopy cover (Gyssels et al. 2016; Cerdà et al. 2021). The sediment reduction benefits of plants are a combination of above- and belowground benefits. Plant roots can bind soil particles and reduce runoff scours stripping the soil. Plant branches and leaves slow the speed of raindrops, reducing splashing and sediment production. Increased infiltration reduced surface flow production and the ability of runoff to carry sediment. Straw mulch is very effective in reducing soil erosion rates to a large extent by increasing infiltration rates through increased surface roughness and plays an effective role in reducing splash water erosion in the up and down directions (Gholami et al. 2013; Cerdà et al. 2016). Straw mulch management can also reduce sediment content and soil erosion rates by reducing splash erosion and slowing surface flow rates (Keesstra et al. 2019).

The fruit trees planted in this study were citrus seedlings, which are younger, more fragile, and less able to

retain water and soil than mature fruit trees. Therefore, orchards at the seedling stage are in greater need of appropriate ground cover management strategies to reduce soil erosion rates. Young orchards are inherently lacking in effective vegetation cover and therefore have limited mitigation of soil erosion and the highest need for ground cover. Soil erosion also occurs mainly in the early stages of orchard construction, and more attention needs to be paid to soil erosion in young orchards.

Most of the erosion in orchards is caused by small amounts of extreme rainfall (Fang et al. 2017). As shown in Fig. 5, soil erosion increased across the plots as rainfall intensity increased, but significant differences in sediment production regulation emerged between cover measures. Sediment production regulation was the worst for OI and the best for OS. The highest SLR value for OI increased from 4.3 to $32.4 \text{ g m}^{-2} \text{ min}^{-1}$ with increasing rainfall intensity; however, the highest SLR value for OS increased from 0.7 to $4.3 \text{ g m}^{-2} \text{ min}^{-1}$. It was clear that extreme rainfall weakened the regulatory function of cover measures on steep slopes. However, the plot under OS still has a good effect on soil erosion mitigation. Therefore, when planting crops to alleviate soil erosion in orchards, management measures such as straw mulching can be adopted at the same time for comprehensive management. The application of straw to cover the ground alongside vegetation management measures not only reduces the separation of soil aggregates and improves the erosion resistance of orchards (Gholami et al. 2013) but also provides organic matter for citrus seedlings and vegetation, increasing soil fertility and improving the activity of microorganisms in the soil.

It is clear that the ground cover under young orchards is unstable during extreme rainfall. Furthermore, there is a threat of human disturbance as farmers are constantly tilling their orchards to better manage them. Soil and water conservation should therefore place greater emphasis on improving ground cover and reasonable levels of vegetation. The shortcomings of a single ground cover management strategy can be compensated for by integrated management measures, and different vegetation cover measures should be properly combined (Zhao 2006; Peng and Wang 2012).

Effects of cover management on nutrient loss

Nutrient loss occurred in different forms and amounts combined with surface–subsurface flow and sediment. Factors that affect soil erosion can therefore also influence nutrient loss, such as rainfall, slope, and vegetation cover. Cover management practices play an important role in mitigating nutrient loss. There were differences in nutrient losses (TN, TP, and OC) between the plots under different management practices

(Fig. 6). The average loss of TN and OC in surface flow from plots with cover management was smaller (36.6% and 12.1%) than that in subsurface flow (62.6% and 54.7%). This is due to the increased infiltration rate of plots with cover management. The higher the infiltration capacity is, the higher the nutrient content in the subsurface flow. Compared with the OB plot, more runoff is infiltrated, and nutrients carried by runoff are also infiltrated. The average loss of TN, TP, and TOC carried by soil loss in the covered plots (1.2%, 33.2%, and 89.4%) was lower than that in the OB plot (5.1%, 74.8%, and 95.6%), mainly because the soil loss in the covered plots was less than that in OB. Both vegetation crops and straw mulching can intercept sediment, resulting in less sediment loss and fewer nutrients carried by sediment in mulched plots.

Runoff and soil erosion carry a large amount of nutrient loss (Wu and Li 1996; Chambers et al. 2000). Typically, nitrogen and OC are lost mainly in a water-soluble state, while phosphorus is lost mainly in a sorbed state. The average loss of TP in sediments (90.9%) was higher than that in runoff (9.1%) under different plots, while the average loss of TN and OC in runoff (56.4 and 97.8%) was higher than that in sediment (43.6% and 2.2%) under different plots. This is closely related to the solubility and adsorption capacity of different nutrients. TN, TP, and OC are transport carriers of nonpoint source pollutants, and research on their solubility and adsorption is helpful to further understand the mechanism of nonpoint source pollution.

Ground cover management practices are an effective means of reducing soil erosion and have some impacts on reducing nutrient loss (Duan et al. 2020). However, this impact may include some negative effects. The implementation of mulch management measures reduces nutrient loss in surface flow but increases nutrient loss in subsurface flow and increases the risk of groundwater contamination. Subsurface flow plays an important role in soil erosion and nutrient loss. Compared with surface flow, the higher the flow rate of subsurface flow, the lower the degree of soil erosion on the surface; however, with the increase of infiltration, the nutrients carried by subsurface flow increase, and the risk of nutrient loss caused by subsurface flow will also increase (Fig. 6). Therefore, when carrying out understory cover management measures, the potential risk of deep contamination from cover measures in regulating water and soil processes needs to be considered. This risk does not only exist in young fruit trees; in fact, as orchard operation continues, the more nutrients are also required by the mature orchard and held in the soil and in the deeper layers, the higher the risk of deep contamination, which is exacerbated by excessive underwater infiltration of the soil. Meanwhile, ground cover can even compete with crops for water and nutrients, reducing fruit yield (Pedersen 1997; Sirrine et al. 2008).

Different cover management practices play different roles in regulating soil erosion and its accompanying nonpoint source pollution in young orchards. However, most of the current studies mainly consider the positive effects of cover management measures and ignore some of the negative effects (Xiloyannis et al. 2008; Calatrava and Franco 2011; Duan et al. 2020; Novara et al. 2021). In fact, this paper found through experiments that plots with cover management practices play an active role in nutrient loss from subsurface flow and are prone to groundwater contamination. Therefore, when specific cover measures are taken to regulate soil erosion and nonpoint source pollution, groundwater pollution cannot be ignored.

Conclusions

This paper investigates the effects of different cover management practices on soil erosion and nutrient loss under three different rainfall intensities through simulated rainfall experiments. The results showed that cover management significantly inhibited soil erosion in young orchards. Barely managed orchards produced higher soil erosion (69.0%) than those managed with vegetation cover (30.8%). Meanwhile, vegetation cover management also plays a role in reducing nutrient loss associated with water and soil loss. The nutrient losses from surface flow and sediment (17.6% and 41.3%, respectively) in the cover management plots were significantly lower than those in the OB plot (38.9% and 58.5%, respectively). This further highlights the critical role of vegetation cover management in reducing soil erosion and nutrient loss.

However, nutrient loss in subsurface flow (41.1%) in vegetated plots was higher than that in the OB plot (21.0%). Vegetation cover management plays a positive role in reducing nutrient loss, but the risk of increasing nutrient loss in subsurface flow cannot be ignored. The results of these studies provide preliminary insights into the interaction between surface and subsurface flow and the impact of soil erosion on nutrient loss. They have implications for the prevention and control of nonpoint source pollution caused by soil erosion and nutrient loss from orchards during the juvenile period of fruit trees. This paper suggests combining vegetation management with ground cover management to compensate for the lack of vegetation management and to fully integrate the effects of vegetation and cover management. However, the impact of nonpoint source pollution on subsurface flows still needs to be further explored, and more in-depth research is needed. The specific advantages of integrated ground cover management tools need to be further investigated. And a more systematic measurement is also needed to solve the complex problem of runoff-sediment and C-N-P loss.

Author contribution LT: writing: original draft, visualization, conceptualization, methodology, formal analysis. YL: runoff plot preparation and pretreatment, writing—review and editing, supervision. YM: writing—review and editing, investigation. JD: conceptualization, methodology, investigation. YD and FC: data collection, investigation. HZ and ZL: methodology, investigation.

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Data availability Data available upon request.

Declarations

Ethical approval The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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