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# Modeling the Effectiveness of Sustainable Agricultural Practices in Reducing Sediments and Nutrient Export from a River Basin

**José Pedro Ramião [1,2,3,*], Cláudia Carvalho-Santos [1,2,3], Rute Pinto [4] and Cláudia Pascoal [1,2,3]**

1 CBMA—Centre of Molecular and Environmental Biology, Department of Biology, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal
2 IB-S, Institute of Science and Innovation for Bio-Sustainability, University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal
3 Aquatic Research Network (ARNET) Associate Laboratory
4 Ecohydrology Research Group, Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON N2L 3G1, Canada
* Correspondence: zepedroramiao@gmail.com

**Abstract:** Water pollution from unsustainable agricultural practices is a global problem that undermines human health and economic development. Sustainable agricultural practices have been considered to maintain global food production without compromising water quality and ecosystem health. However, the effectiveness of sustainable agricultural practices in reducing sediments and nutrient export and the combination of practices that will best achieve water quality objectives is still under-explored. In this study, we assess the effectiveness of sustainable agricultural practices in reducing sediments and nutrients export to rivers and determine the combination of practices that would allow the highest reductions of sediments and nutrients, using the Soil and Water Assessment Tool (SWAT) in a Portuguese river basin highly affected by agricultural pollution. SWAT was calibrated and validated for river discharge, sediments, phosphorous, and nitrate loads at the outlet of the basin, with a good agreement between simulated and observed values. The effects of filter strips, fertilizer incorporation, and conservation tillage were analyzed considering both individual and combined effects. Our study shows that sustainable agricultural practices can substantially reduce sediments and nutrients export from a river basin, with the highest average combined depletion of sediments, phosphorus, and nitrate export (25%) achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously. Additional studies exploring the effect of sustainable agricultural practices across a range of climate and watershed characteristics, as well as their capacity to deal with challenges related to climate change, will further improve our understanding of the effectiveness of sustainable agricultural practices.

**Keywords:** best management practices; filter strips; diffuse pollution; SWAT



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## 1. Introduction

Water pollution is a global issue that undermines the ecosystem's health and human well-being [1]. Agriculture is a major source of water pollution and has already surpassed contamination from urban and industrial sources in many regions [2]. In the United States, agriculture is the main driver of river pollution [3]; in China, groundwater nitrogen is fully controlled by agriculture [4], while in the European Union, more than 50% of surface water bodies were not achieving a good ecological status in 2016, mainly because of pressures from agriculture [5].

Agricultural production has grown significantly during the last decades to meet increasing food demand from population growth and changes in dietary patterns [2]. Increased agricultural production has been accomplished through the expansion of agricultural land, the introduction of new crop varieties, the use of new technologies and machinery, and the intensive use of pesticides and fertilizers [5,6]. The excessive use of nitrogen and phosphorous for crop growth can contaminate water bodies by leaching and surface runoff [2]. The increased load of nutrients can cause eutrophication of inland and coastal waters, which is characterized by excessive plant and algal growth that limits light penetration, depletes dissolved inorganic carbon, raises pH, and ultimately contributes to the degradation of biodiversity and water quality of aquatic ecosystems [7]. Eutrophication can have severe economic consequences for tourism, fisheries, and drinking water treatment costs. In the United States, the annual cost of freshwater eutrophication was estimated at USD 2.4 billion, while for the European coastal waters, it was estimated at USD 1 billion [8].

The world population is expected to reach 9.8 billion in 2050 and 11.2 billion in 2100 [9], meaning that food waste will have to be reduced and/or food production will have to increase, which will likely drive agricultural expansion and intensification and, therefore, additional water quality degradation [2,6]. A wide variety of policy frameworks have been implemented to reduce agricultural pressures on the water environment [5]. In Europe, the Nitrates Directive [10] was introduced in 1991 to reduce water pollution from agricultural sources. Later on, the Water Framework Directive [11] was implemented to reduce water policy fragmentation and improve the ecological protection of all water bodies. However, despite improvements, agricultural pressures remain extremely high in many regions [12], and therefore, more ambitious measures are needed to reach water quality objectives.

Sustainable agricultural practices, including cover crops, contour farming, reduced tillage, constructed wetlands, and vegetated filter strips, have been extensively studied to reduce water pollution [13]. Filter strips are among the most effective measures, reducing sediment and nutrient loads up to 90%, depending on their width, location, weather, and catchment characteristics [13,14]. Combining individual measures can provide enhanced mitigation effects [15–17]; however, the effect of combined measures, and especially the interaction between measures, has been less explored. Therefore, despite widespread studies of individual measures to support the selection and implementation of sustainable agricultural practices, questions remain about the combination of measures that will best achieve water quality objectives.

The efficiency of measures and their combined effects can be difficult to assess due to the cost of collecting empirical data and the lag time between measures implementation and effects on water quality [13,18]. Models can help to overcome this by allowing the prediction of the effectiveness of management strategies over the long term and at a much lower cost [13,19]. Models can also allow the identification of critical source areas that, once prioritized, might have the potential to increase the efficiency of pollutant reduction and minimize the magnitude of areas that are impacted by restrictive management practices [19]. Models have already proved useful during the implementation of the Water Framework Directive by allowing: (1) the prediction of pressures and impacts on water bodies, (2) the design of monitoring networks, and (3) the demonstration of how the water status improvement will be achieved through the Programme of Measures [19].

The goal of this study is to examine the effectiveness of sustainable agricultural practices in reducing sediments and nutrient export to rivers and to determine the combination of practices that would allow the highest reductions of sediments and nutrient export, using the Cávado River basin as a case study. This is, to the best of our knowledge, one of the few studies examining the combined effect and the interaction between multiple sustainable agricultural practices and the first study examining the effectiveness of sustainable agricultural practices in the Cávado River basin, one of the most important basins in mainland Portugal to dairy production, where diffuse pollution needs to be reduced in order to achieve a good ecological status under the Water Framework Directive. We hypothesize that implementing multiple sustainable agricultural practices will allow the highest combined depletions of sediment, phosphorus, and nitrate export by improving the reduction of multiple pollutants simultaneously.

## 2. Materials and Methods

### *2.1. Study Area*

The study was performed in the Cávado River basin (1581 km$^2$) between the Atlantic and Mediterranean regions in northwest Portugal. The average annual precipitation in the basin is 1300 mm, while the minimum and maximum temperatures are 3 °C and 29 °C, respectively (data from 1999 to 2018 from two meteorological stations provided by the Portuguese Institute for Sea and Atmosphere). Granite dominates the basin geology, while Umbric Leptosols and Dydtric Antrosols are the major soil types [20]. The upstream lands (300–1100 m) are dominated by scrubland and forests, while the downstream lands are dominated by urban and agricultural areas (Figure 1).

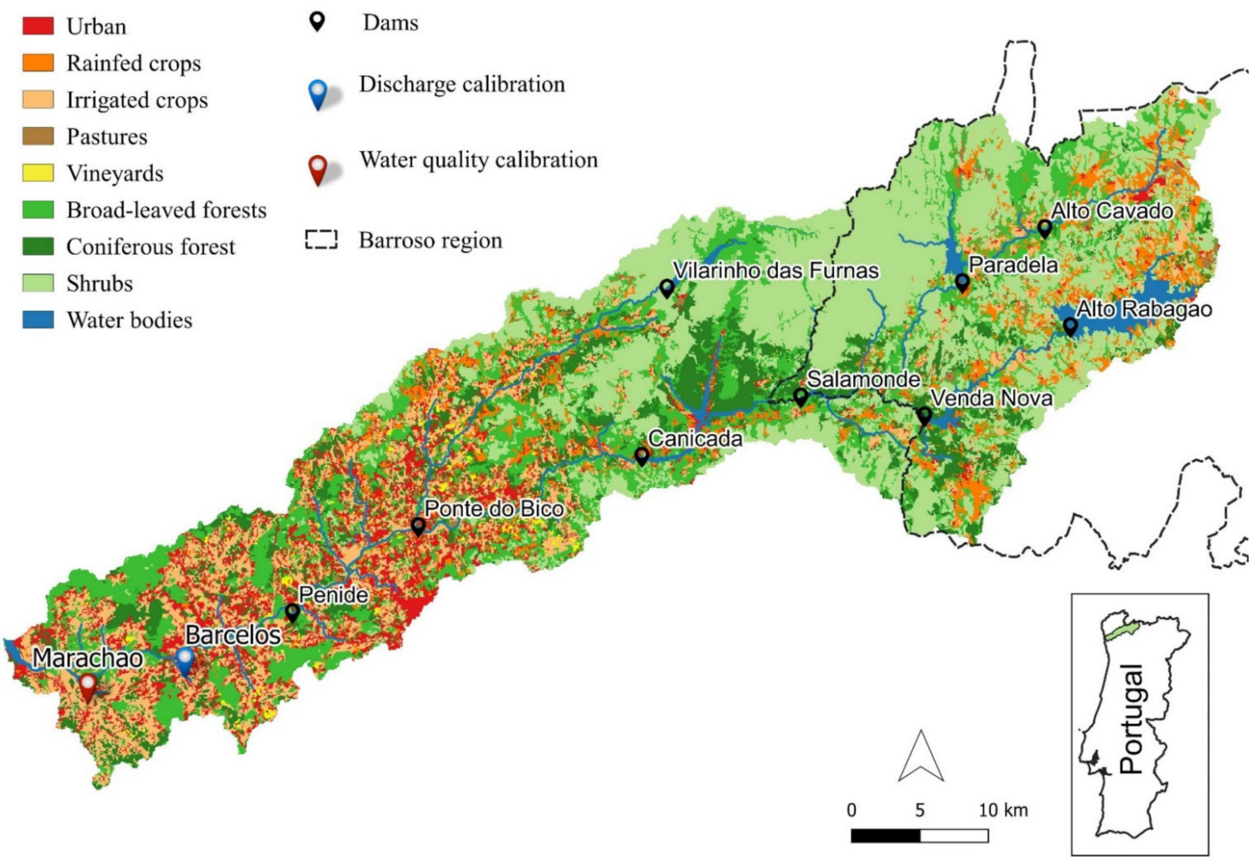


**Figure 1.** Location of the study area in the Cávado River Basin, land cover [21], calibration sites, and dams (SNIRH).

The upstream lands of the basin have a unique agricultural system recently distinguished by the Food and Agriculture Organization of the United Nations (FAO) as a Globally Important Agricultural Heritage System [22]. In the Barroso Agro-Sylvo-Pastoral System (Figure 1), livestock farming is the main agricultural activity and is carried out in extensive grazing systems using both permanent pastures and scrublands for beef cattle breeding [22]. Crops are mainly rainfed and cultivated in rotation with set-aside rye, potato, and maize, the most common crops in the region [23].

On the other hand, the agricultural activities in the downstream lands of the Cávado River basin are dominated by the intensive production of maize for silage and dairy, wherein 50% of the national dairy production occurs in the downstream lands of the Cávado and Ave (close to the Cávado) river basins [24]. Such a large portion of the national dairy production in a small region comes at the expense of intense farming systems, where extensive maize and grassland fields are needed to feed the cattle and where huge amounts of slurry and manure are produced and applied on arable lands as organic fertilizers [25].

This has increased water needs and the number of mineral fertilizers applied to improve crop yield, which in turn increased the export of nutrients and other contaminants to freshwater ecosystems [26].

The Cávado River basin is also affected by point discharges from urban and industrial activities and by hydromorphological alterations due to 9 dams (Figure 1). Consequently, the evaluation performed under the Water Framework Directive (WFD) revealed that the ecological status of 45% of river water bodies in the Cávado River basin was less than good [24].

### *2.2. Input Data and SWAT Setup*

River discharge, sediment, phosphorous, and nitrate export were simulated using the Soil and Water Assessment Tool (SWAT). SWAT is a physically based, semi-distributed, and continuous time-scale hydrological model that operates on a daily time step [27]. Model setup was carried out using SWAT2012 (rev. 670) in ArcSWAT 2012.10_5.21 interface for ArcGis [28]. The datasets used to run the SWAT model are available in Table S1 (supplementary material).

The Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global [29] was used to delineate the watershed, together with the stream network shapefile of the Water Framework Directive (WFD) [30], to force the model to create the same sub-basins as defined in the WFD. The sub-basins outlets were further adjusted to account for the calibration sites and to prevent the reservoirs from occupying more than one sub-basin.

A land cover map for mainland Portugal of 2010 [21], together with a soil map [20] and three slope classes (i.e., 0–10%, 10–25%, and >25%), were used to create the hydrological response units (HRUs). The soil classes were aggregated into 8 groups (Table S2, supplementary material), while the land covers were aggregated into 16 groups (Table S3, supplementary material). Parameterization of vegetation and soil was based on a previous study using SWAT in northwest Portugal [31], while management operations for each land cover were defined based on the literature [22,24,25].

Reservoirs were included in the model using data from SNIRH (National Water Resources Information System) and the Portuguese power company EDP [32]. Sixty-nine point sources were located in the Cávado River basin using the shapefiles of the wastewater treatment plants, industrial units, and aquiculture provided by the Portuguese Environment Agency (APA) and retrieved from SNIAmb. Data on nitrogen (NO3CNST and NH3CNST), phosphorous (MINPCNST), and volume discharged (FLOCNST) by each point source were retrieved from the attribute table of the shapefiles and from INSAAR (National Inventory of Water Supply and Wastewater Systems), and data per sub-basin were calculated in QGIS. Surface water abstractions were located using a shapefile from SNIG (National Geographic Information System), and the volume of water abstracted was retrieved from APA [33].

Data on mean daily precipitation and maximum and minimum daily temperature were retrieved from E-OBS [34] from 1970 to 2018. The loadeR and transformeR packages [35] were used to convert the climate data to the SWAT input format. Climate data from two weather stations from IPMA (Portuguese Institute for Sea and Atmosphere), one in the upstream and the other in the downstream part of the basin, were used together with E-OBS since it improved the model performance.

The spatial representation of precipitation and temperature in mountainous areas was improved by using ten elevation bands with a precipitation lapse rate of 1100 mm/km and a temperature lapse rate of −5 °C/km, according to Carvalho-Santos et al. [31].

The Hargreaves equation was used to estimate evapotranspiration since preliminary runs with Pennan–Monteith equation provided unsatisfactory results, probably related to the low quality of wind-speed data. Surface runoff was computed from daily precipitation using the curve number equation method (CN).

A 3-year warm-up period was used to reduce uncertain initial conditions. Additional methodological details regarding SWAT setup are available in Supplementary material S2 of supplementary material.

### *2.3. Discharge, Sediment, Phosphorous, and Nitrate Calibration*

Sensitive parameters in the soil (.sol), vegetation (.crop), and management databases (.mgt) were changed (Table 1) to improve SWAT outputs by land cover for leaf area index (LAI), evapotranspiration (ET) and total biomass (BIOM) when compared with expected values from the literature [23,36]. Additional methodological details are available in Supplementary material S3 of the supplementary material.

**Table 1.** Modified SWAT parameters by land cover to calibrate sediment and nutrient export.

| Parameter | Description | Calibrated (Initial Values) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RYE | CTSR | GRAP | ORCD | LAME | FOLH | RESI | INVA | MATO | ZDPV | URBAN |
| T_BASE | Minimum temperature for plant growth (°C) | - | - | - | - | 5 (12) | - | - | - | - | - | - |
| HVSTI | Harvest index for optimal growing conditions | - | - | 0.4 (0.02) | 0.3 (0.1) | - | - | - | - | - | - | - |
| BIO_LEAF | Fraction of tree biomass accumulated each year that is converted to residue each year | - | - | 0.4 (0.3) | 0.2 (0.3) | - | 0.02 (0.3) | 0.015 (0.3) | 0.02 (0.3) | - | - | - |
| BIO_E | Radiation use efficiency | - | - | - | - | - | 25 (15) | 16 (15) | 32 (22) | - | - | - |
| FRGRW1 | Fraction of the plant growing season corresponding to the first point on the optimal leaf area development curve | - | - | - | - | - | 0.01 (0.05) | - | - | - | - | - |
| FRGRW2 | Fraction of the plant growing season corresponding to the second point on the optimal leaf area development curve | - | - | - | - | - | 0.1 (0.4) | - | - | - | - | - |
| ALAI_MIN | Minimum leaf area index | - | - | - | - | 0.2 (0) | 3 (0.75) | - | - | - | - | - |
| USLE_P | Support practice factor | 0.5 (1) | 0.5 (1) | 0.6 (1) | 0.6 (1) | 0.5 (1) | 0.65 (1) | 0.65 (1) | 0.65 (1) | 0.6 (1) | 0.6 (1) | 0.65 (1) |
| USLE_C | Cover management factor | - | 0.1 (0.005) | 0.33 (0.1) | 0.05 (0.001) | - | 0.0015 (0.001) | 0.0015 (0.001) | 0.002 (0.1) | - | 0.005 (0.002) | - |

Note: RYE = non-irrigated arable land, CTSR = irrigated arable land, GRAP = vineyard, ORCD = orchard, LAME = pasture, FOLH = oaks, and other broadleaved trees, RESI = pine, INVA = eucalyptus, and other invasive plant species, MATO = Atlantic shrubland, ZDPV = baren rock and sparsely vegetated, URBAN = urban areas.

Land cover exports of sediments and nutrients were calibrated by changing USLE_K, USLE_P, and USLE_C parameters based on Panagos et al. [37], Panagos et al. [38], and Panagos et al. [39], respectively (Table 1). USLE_K was set to 0.02 based on the soil erodibility map of Europe developed by Panagos et al. [37].

The grain size of sediments (RES_D50) in Salamonde, Ponte de Bico, and Penide (Figure 1) was increased to 20, 30, and 30, respectively, to improve sediment calibration at the outlet of the basin and to set the dams trapping efficiency between 60% and 95%. The equilibrium sediment concentration (RES_NSED) in Ponte de Bico and Penide was also decreased from 1 to 0.9.

The nitrate and phosphorous settling rates in reservoirs (NSETLR, PSETLR) were changed to calibrate nitrate and phosphorous loads and the nutrient trapping efficiency of reservoirs. NSETLR was changed from 5.5 to 11 in Vilarinho das Furnas and 2.5 in Alto Rabagão reservoirs (Figure 1), respectively, while PSETLR was changed from 10 to 12 and 5, respectively.

The initial SCS runoff curve number for moisture condition was increased by 15 in the subbasins that flow into the Vilarinho das Furnas reservoir to increase the peak flow [40].

The Sequential Uncertainty Fitting (SUFI-2) algorithm [41] was used for semi-automated model calibration, validation, sensitivity, and uncertainty analysis in SWAT-CUP software version 5.2.1 [40]. The algorithm attempts to capture most of the observed data within the 95% prediction uncertainty (95PPU) of the model, calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling [41]. The goal is that the model result (95PPU) encloses most of the observations. The fit between observed and simulated values, expressed as 95PPU, is generally assessed by two indices, the P-factor and R-factor. The P-factor represents the percentage of observed data enclosed by the 95PPU, while the R-factor is the average width of the 95PPU divided by the standard deviation of the corresponding observed data [42]. P-factor $\geq$ 0.7 and R-factor $\leq$ 1.5 is recommended for calibrating river discharge, while P-factor $\geq$ 0.4 and R-factor $\leq$ 3 are recommended for calibrating sediments and nutrient loads [43].

SUFI-2 was used by performing up to 3 iterations, with 200 simulations each. The Nash–Sutcliffe (NS) was defined as the objective function, and the SWAT executable was updated to rev. 670. The parameters used for calibration were selected based on the literature [40,42,44,45], followed by a global sensitivity analysis. Calibration was performed at the outlet of the basin on a monthly time step from 1995 to 1997, and the calibrated parameter ranges were applied to observed data from 1998 to 2000 to build confidence in the calibrated parameters (i.e., validation). A 3-year warm-up period was used for calibration and validation to allow the parameters to reach an equilibrium after possible initialization biases. A sequential calibration of the variables was performed [45], starting with stream discharge, followed by sediments, total phosphorous, and nitrate.

### 2.4. Scenarios for Sustainable Agricultural Practices (SAPs)

The sustainable agricultural practices (SAPs) were selected based on the most effective SAPs in the literature [14,46,47], and those that most affect sediments and nutrients export in the basin. In this sense, the application of slurry and manure before spring and winter crops is a key driver of nutrient export in the basin, and therefore, the fertilizer application method, namely broadcast application and fertilizer incorporation, and the tillage operations were expected to be highly affect nutrient export.

We examined the effect of 2 fertilizer application methods (broadcast application and fertilizer incorporation), 3 tillage operations (conventional, conservation, and no tillage), and the implementation or not of filter strips to reduce sediments, nitrate, and phosphorous export (Figure 2). The scenarios combined the different sustainable agricultural practices to test individual and combined effects of SAPs, resulting in a total of 12 scenarios (Figure 2).

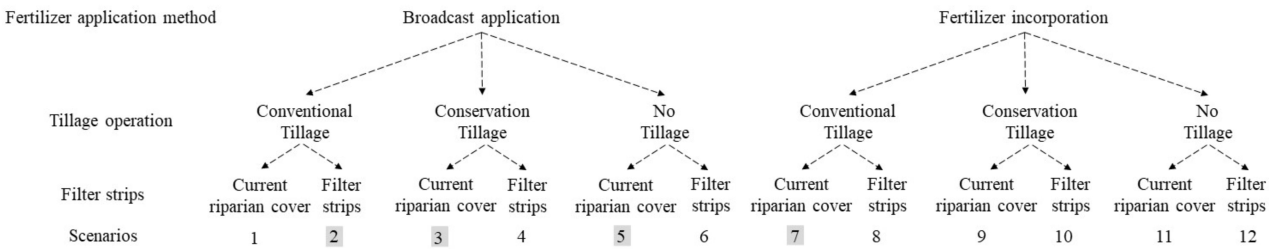


**Figure 2.** Selected scenarios to examine single and combined effects of sustainable agricultural practices on sediments, nitrate, and phosphorous export, considering 2 fertilizer application methods, 3 tillage operations, and the implementation of filter strips. The first scenario refers to the current agricultural practices in the basin, the scenarios in gray refer to the single effects of SAPs, while the other scenarios refer to the combined effects of SAPs.

The fertilizer application methods were simulated using the FRT_SURFACE parameter in SWAT, while the tillage operations were simulated by selecting the most appropriate tillage operation in the SWAT database, according to the mixing efficiency of the tillage operation (EFFMIX) and depth of mixing (DEPTIL) for Conventional, Conservation and No Tillage [46,47] (Table 2). The filter strips were defined based on the Portuguese plan for the Common Agricultural Policy 2023–2027 of the European Commission, which establishes the implementation of filter strips with varying widths for the agricultural areas close to water bodies according to the land slope [48]. Filter strips of varying widths were implemented in all Hydrological Response Units (HRUs) referring to agricultural areas within the riparian zone (Table 2), which was defined using the delineation of riparian zones from the Copernicus program [49].

**Table 2.** Model parameters used to represent sustainable and non-sustainable agricultural practices.

| Type of Agricultural Practice | Agricultural Practice | Where it was Implemented | How it was Implemented |
|---|---|---|---|
| Fertilizer application method | Broadcast application | Irrigated (CTRS) & Non-irrigated arable lands (RYE) | FRT_SURFACE = 1 |
| | Fertilizer incorporation | | FRT_SURFACE = 0.2 |
| Tillage operation | Conventional tillage | Irrigated (CTRS) & Non-irrigated arable lands (RYE) | TILLAGE_ID = 1 (Generic Fall Plowing Operation); EFFMIX = 0.95; DEPTIL = 150 |
| | Conservation tillage | | TILLAGE_ID = 3 (Generic Conservation Tillage); EFFMIX = 0.25; DEPTIL = 100 |
| | No tillage | | TILLAGE_ID = 4 (Generic No-till Mixing); EFFMIX = 0.05; DEPTIL = 25 |
| Filter strips | Current riparian cover | - | - |
| | Filter strip | All agricultural areas in riparian zone | If 0% < Slope < 10% then FILTERW = 3 m; If 11% < Slope < 25% then FILTERW = 10 m; If Slope ≥ 25% then FILTERW = 15 m; |

### 2.5. Statistical Analysis

The single and combined effect of fertilizer application method, tillage operation, filter strip, and precipitation on sediment, phosphorus, and nutrients export were examined using the Aligned Rank Transform (ART) test in R with the ARTool package [50]. The ART tests were followed by Aligned Ranked Transform Contrasts to conduct post hoc contrast tests [51]. The adjusted rank transform test (ART) is a non-parametric test to analyze interactions that is much more powerful than parametric tests when particular assumptions underlying the use of these tests are violated [52,53].

## 3. Results and Discussion

### 3.1. SWAT Calibration and Validation

The overall performance of the SWAT model was satisfactory for all variables, namely stream discharge, sediment, total phosphorous, and nitrate (Figure 3). The comparison between monthly observed and simulated data for the calibration period, considering the coefficient of determination ($R^2$), revealed that SWAT performance was good for sediment load ($0.65 \leq R^2 \leq 0.80$) and satisfactory for stream discharge ($0.70 \leq R^2 \leq 0.80$), phosphorous ($0.40 < R^2 < 0.65$), and nitrate loads ($0.30 < R^2 < 0.60$) [54] (Figure 3). The performance for the validation period was good for nitrate load ($0.60 \leq R^2 \leq 0.70$) and satisfactory for stream discharge ($0.70 < R^2 < 0.80$), sediment ($0.40 < R^2 < 0.65$) and phosphorus load ($0.40 < R^2 < 0.65$) [54] (Figure 3). The performance was generally satisfactory or good according to the Nash Sutcliffe efficiency (NSE) (i.e., NSE $\geq$ 0.55 for river discharge, NSE $\geq$ 0.45 for sediments, NSE $\geq$ 0.40 for phosphorous, NSE $\geq$ 0.35 for nitrate) [54], for both the calibration and validation periods, except for sediment loads (Figure 3). A lower performance for sediments could be expected, given the high number of dams in the basin and the limited data on sediment accumulation and dam operation. In any case, and despite the intense human intervention along the course of the river, the NSE values for sediments are still viewed as acceptable levels of performance [55] and satisfactory according to $R^2$ (Figure 3).

Point sources accounted for 35% and 25% of the total phosphorous and nitrogen loads in our model, respectively. However, point sources had to be simulated on equal daily intervals and therefore do not contribute much to the dynamics of nitrate and phosphorous loads to the river. Nutrient dynamics are mainly governed by the fate and transport of fertilizers in the soil, decomposition of organic matter, climate, and dams' operation and parameterization [40]. In highly managed watersheds, natural processes play a secondary role, and good model performance is often difficult to achieve even with detailed management data [40]. The Cávado River Basin is a highly managed watershed with very limited data on nutrient dynamics and dams' operations. However, the overall good performance of the model regarding nitrate and phosphorous loads (Figure 3) suggests that our model parameterization and calibration were able to capture the dynamics of nutrients in the basin.

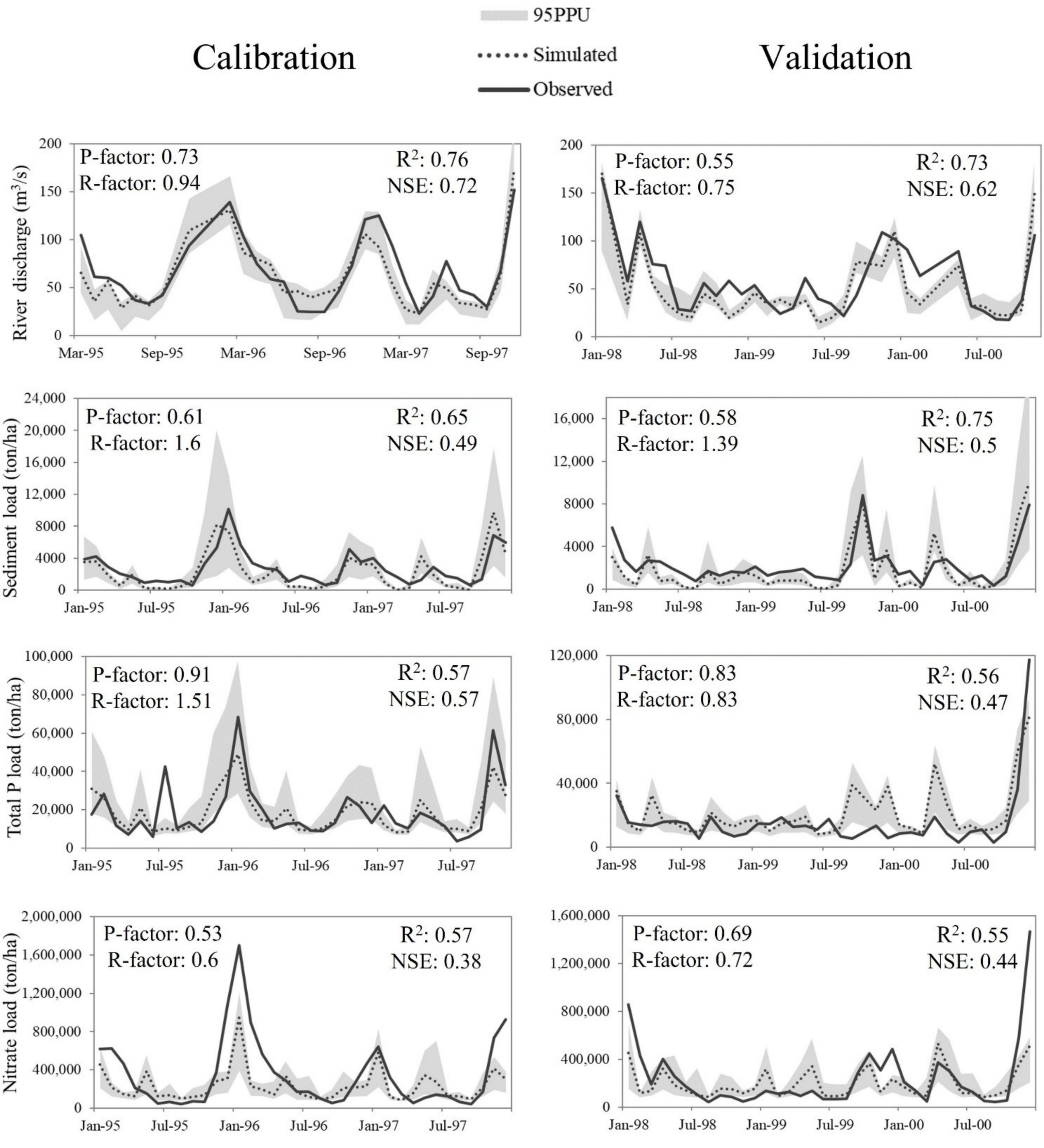


**Figure 3.** Monthly observed and simulated data at the basin outlet for river discharge, sediment, total phosphorous, and nitrate for calibration (1995–1997) and validation (1998–2000) of the SWAT model; 95PPU refers to the 95% prediction uncertainty of the model.

The predictive model uncertainty was assessed using the P-factor and R-factor with the goal of reducing the uncertainty band and enclosing as many observations as possible. Results reveal that more than 50% of the observed data were enclosed by the 95PPU band for all variables and time periods, except for sediments load during the validation period, and the width of the uncertainty band was generally low (R-factor < 1.5) (Figure 2). The P-factor and R-factor in our study are similar to those reported in the literature [45,56,57].

### *3.2. Single and Combined Effects of Sustainable Agricultural Practices*

Sediment export was affected by the tillage operation, the presence of filter strips, and the amount of precipitation (Table 3). Phosphorous export was mostly affected by the fertilizer application method and the presence of filter strips, while nitrate export was mainly affected by the fertilizer application method, the tillage operation, the presence of filter strips, and the amount of precipitation (Table 3). There was no interaction among the sustainable agricultural practices regarding the effects on sediments, phosphorous, and nitrate export ($p$-value > 0.05).

**Table 3.** Results of the adjusted rank transform test (ART) about the effects of the fertilizer application method, tillage operation, filter strips, and precipitation on sediments, phosphorous, and nitrate export. Only the variables with a significant effect (i.e., $p$-value < 0.05) are presented. df refers to degrees of freedom. F-value is the ratio of the between-group and within-group variation.

| Dependent Variable | Effect | df | F | *p*-Value |
|---|---|---|---|---|
| Sediment export | Tillage operation | 2 | 3.83 | 0.02 |
| | Filter strips | 1 | 11.7 | 0.0006 |
| | Precipitation | 3 | 4.36 | 0.005 |
| Phosphorous export | Fertilizer application method | 1 | 6.45 | 0.01 |
| | Filter strips | 1 | 24.6 | <0.0001 |
| Nitrate export | Fertilizer application method | 1 | 7.6 | 0.006 |
| | Tillage operation | 2 | 3.2 | 0.04 |
| | Filter strips | 2 | 41.4 | <0.0001 |
| | Precipitation | 3 | 8.8 | <0.0001 |

#### 3.2.1. Effectiveness of Sustainable Agricultural Practices in Reducing Sediment Exports

The transfer of sediment from land to the ocean by rivers is a key pathway of material transport on Earth, and it is crucial to the functioning of inland and coastal ecosystems [58]. On the other hand, land clearance and land use change can increase sediment loads that destroy in-stream habitats and reduce reservoirs storage capacity, while the construction of dams can decrease sediment loads to the oceans that are key for the evolution of deltas and other coastal landforms [59]. The sediment loads entering the Atlantic Ocean from the Cávado River basin might be lower than expected due to the presence of 9 dams (Figure 1). However, an increase in sediment load may impair the in-stream habitat upstream of the dams and reduce the reservoir storage capacity. In addition, soil loss brings negative impacts on soil fertility, carbon stocks, biodiversity, and overall crop production [60].

Our study shows that implementing both filter strips and no-tillage practices can substantially reduce sediment export (Figure 4). Sediment export was mostly affected by the presence of filter strips (Table 3), and the effect was more pronounced around June (i.e., late spring, beginning of summer) (Figure 4). Sediment export was also reduced when adopting conservation tillage or no-tillage practices (Figure 4). This was expected because conventional tillage reduces the stability of soil structure and residue cover and consequently increases erosion and sediment losses in runoff [61]. The highest monthly (−69%) and annual (−42%) depletions of sediment export were achieved when both filter strips and no-tillage practices were implemented (Figure 4). However, there were no differences between conservation tillage and no-tillage regarding sediment export (Aligned Ranked Transform Contrasts test, $p$-value > 0.05).

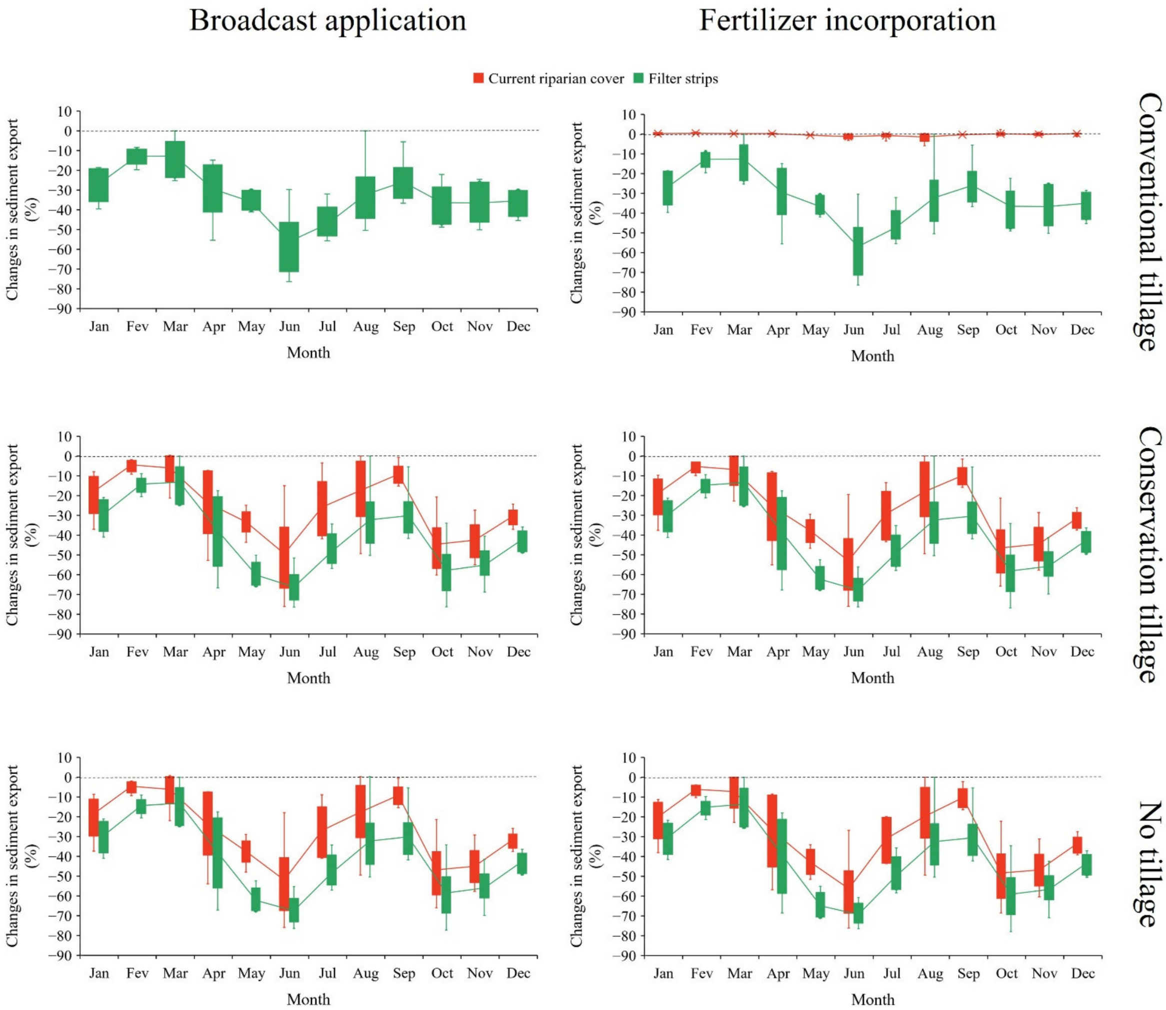


**Figure 4.** Percentage of change in monthly average sediment export under different sustainable agricultural practices. Percentage of change regarding the baseline scenario, with a broadcast application of fertilizer, conventional tillage, and current riparian cover (i.e., no filter strips).

### 3.2.2. Effectiveness of Sustainable Agricultural Practices in Reducing Nutrients Exports

Filter strips are known to have an important ecological role in reducing nutrient exports by providing resistance to water flow and promoting the deposition of suspended particulates and plant uptake [62,63]. The efficiency of filter strips in reducing water pollution depends on many factors, including the filter's width, plant species, soil type, slope, and climate [64]. Filters width is critical to the reduction capacity of filter strips; however, optimum width depends on site-specific characteristics, such as soil type, slope, or vegetation structure and composition [65]. The efficiency of filter strips generally increases with the width, but it does not increase linearly, with benefits tailing off above 10 m width [66,67]. Widening filter strips beyond necessary can be economically unfeasible and increase resistance to adoption [68]. Although often installed with a fixed width, filter strips of varying widths can be beneficial due to the uneven nutrient loading distribution throughout the watersheds and the interaction with other effect factors [69]. For instance, filter strips in higher slope lands might require larger widths to reduce increased runoff velocities [64]. The Portuguese plan for the Common agricultural policy 2023–2027 establishes the implementation of filter strips of varying widths for the agricultural areas close to water bodies [48]. Our study suggests that this proposal can reduce annual sediment export by 32%, phosphorous export by 14%, and nitrate export by 19%, despite recommending filter strips to just 3.9% of the basin area. Prioritizing key areas for water pollution, such as riparian zone, can enhance the effectiveness of sustainable agricultural practices by allowing the reduction of water pollution without requiring large-scale interventions.

In our study, the capacity of filter strips to reduce phosphorous export was more pronounced around May and October after manure fertilization (Figure 5), while the capacity to reduce nitrate export was more pronounced around January, May, and October (Figure 6). An increased effect of filter strips around May and October was expected due to the importance of manure application to nutrient export in the basin. An increased effect of filter strips on nitrate export around January was probably related to the high precipitation during this month throughout the modeling period and the dominance of surface runoff to N losses. Nitrate is not attracted to or adsorbed by soil particles and therefore is highly susceptible to both leaching and surface runoff [70]. Unlike nitrogen, phosphorous combines with other ions to form a number of insoluble compounds that precipitate and reduce their solubility, and phosphorus export is mostly related to surface runoff and sediment export [71]. The variability of phosphorous export was found to be lower in the presence of reservoirs [72], which was likely related to the higher trapping efficiency of particulate matter. In our study, the trapping efficiency of phosphorous in reservoirs was higher than the trapping efficiency of nitrate. This may explain the lower effect of filter strips on phosphorous export during high precipitation months (e.g., January) since the export of phosphorous might be already decreased by the barrier effect of the reservoirs.

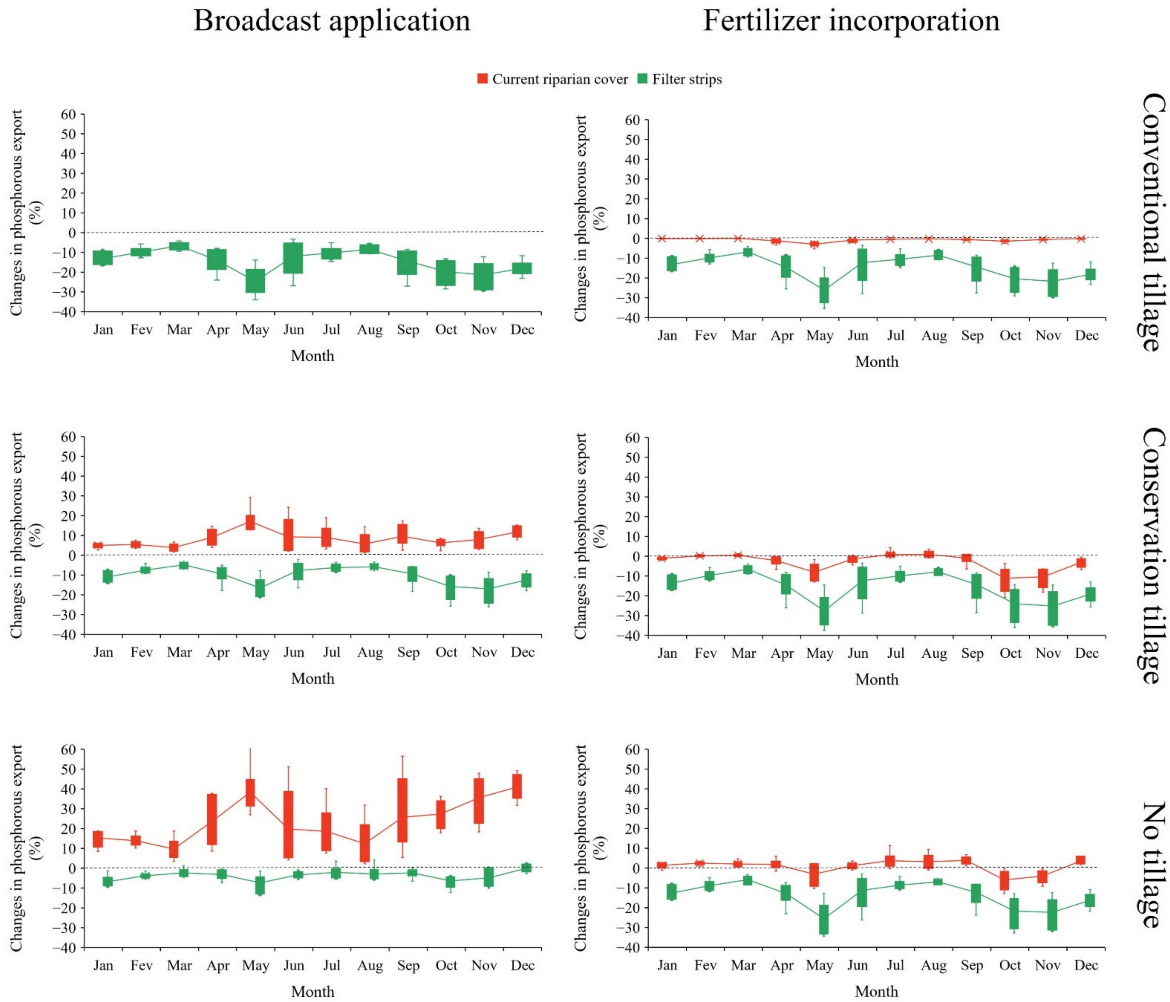


**Figure 5.** Percentage of change in monthly average phosphorous export under different sustainable agricultural practices. Percentage of change regarding the baseline scenario, with broadcast application of fertilizer, conventional tillage, and current riparian cover (i.e., no filter strips).

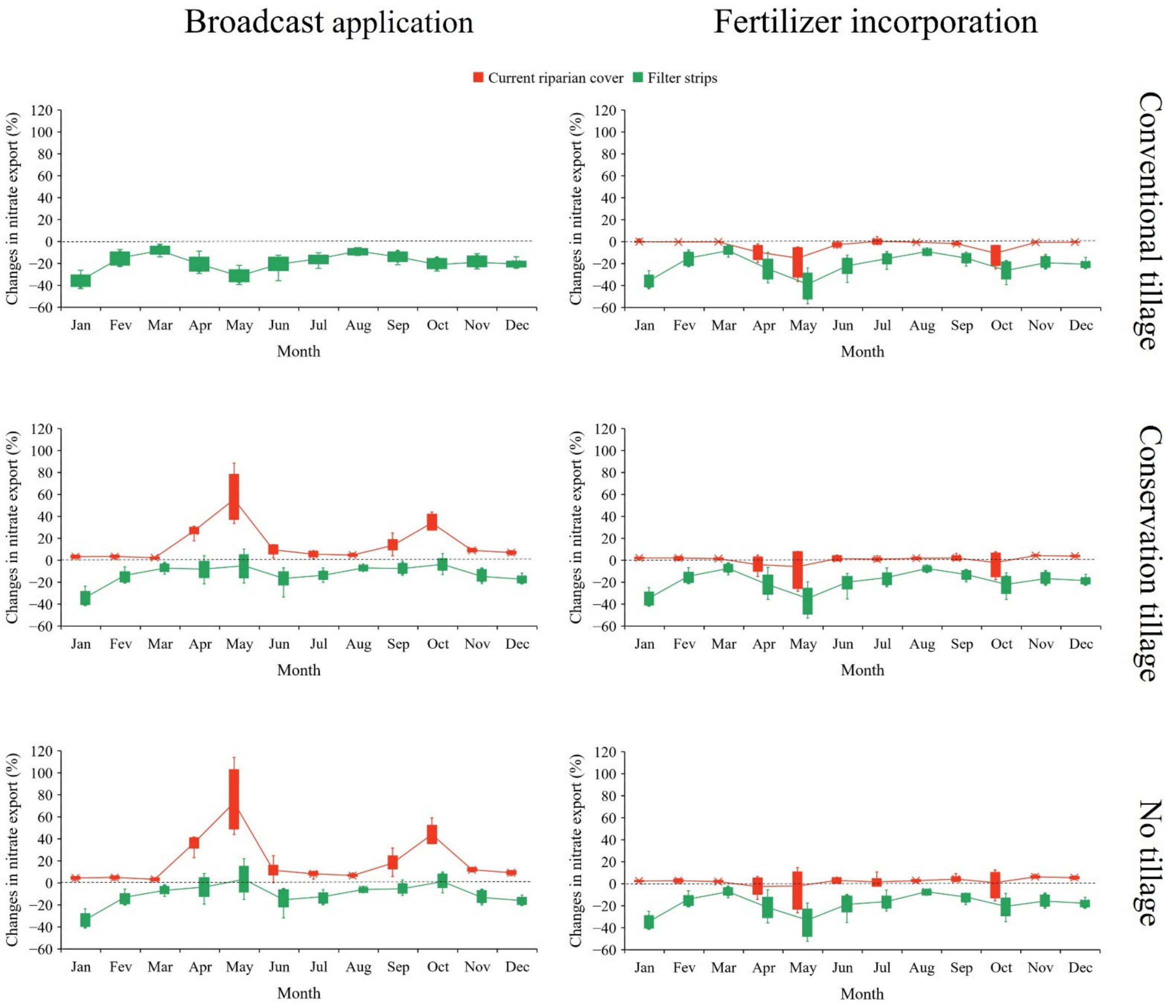


**Figure 6.** Percentage of change in monthly average nitrate export under different sustainable agricultural practices. Percentage of change regarding the baseline scenario, with broadcast application of fertilizer, conventional tillage, and current riparian cover (i.e., no filter strips).

Pollutant removal by filter strips is expected to be higher during the summer due to higher vegetation density and lower runoff intensity [13], which could also explain the highest nutrient reductions around May and June (Figures 4–6). However, the filter strip algorithm we used in SWAT has some limitations since it does not consider the effects of flow concentration, and it considers the same filtering efficiency for sediment and all nutrient forms [70], even though different filtering efficiencies have been observed for soluble and particulate nutrients [73]. The most recent algorithm distinguishes soluble from particulate nutrients; however, it requires input data for each HRU regarding the drainage area to filter strip area ratio, the fraction of the field drained by the most heavily loaded 10% of the filter strip, and the fraction of the flow through the most heavily 10% of the filter strip that is fully channelized [70], which was not feasible to implement in 800 HRUs. A simpler and more accurate algorithm to simulate the effect of filter strips in SWAT would improve the usefulness of the model.

Moving from conventional to conservation and no-tillage was found to increase phosphorous and nitrate export when broadcast application was used unless filter strips were implemented (Figures 5 and 6). Tillage increases soil erosion and sediment export; however, it also reduces the availability of nutrients to surface runoff by incorporating most of the manure on the soil surface [61,74]. Conventional tillage has more pronounced effects on soil erosion and nutrient incorporation due to higher mixing depth and efficiency [70].

This might explain the reduction of sediment export and the increase in nutrient export when moving from conventional to conservation and no-tillage (Figures 4–6).

The tillage operation had less effect on phosphorous and nitrate export when fertilizers were previously incorporated into the soil (Figures 5 and 6), probably because fertilizer incorporation removes the potential for the direct transfer of nutrients to runoff [61]. Fertilizer incorporation also decreases $NH_3$ volatilization and then odor problems of manure and slurry application [12]. Fertilizer incorporation can also increase nitrate leaching relative when compared to broadcast application [75]; however, shallow fertilizer injection was found to reduce $NH_3$ emissions without consistently increasing nitrate leaching [12]. Furthermore, fertilizer incorporation has a lower impact on soil stability relative to nutrient incorporation by tillage, and therefore, the potential for sediment export and P losses over the long term due to higher erosion is generally lower with fertilizer incorporation [74].

The highest monthly (−27.7%) and annual (−15.4%) reductions in phosphorous export were achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously (Figure 5). However, the highest monthly and annual reductions of phosphorous export were very similar among the scenarios with fertilizer incorporation and filter strips but different tillage operations (−26.1% and −14.7% for conventional tillage, and −25.6% and −13.8% for no-tillage) (Figure 5).

The same pattern was observed for nitrates, where the highest monthly (−38.8%) and annual (−20.9%) reductions of nitrate export were also achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously (Figure 6). Likewise, for phosphorous export, the highest monthly and annual reductions of nitrate export were very similar among the scenarios with fertilizer incorporation and filter strips but different tillage operations (−34.7% and −19% for conventional tillage, and −34.5% and −18.3% for no-tillage) (Figure 6).

The main effect of tillage on nutrient export is related to nutrient incorporation into the soil and subsequent reduction in nutrient export via surface runoff, but our results suggest that as long as nutrients are previously incorporated into the soil, the type of tillage operation has little effect on nutrient exports. However, once nutrients are correctly incorporated into the soil, conventional tillage is expected to increase nutrient exports relative to other tillage practices due to higher soil erosion and surface runoff of particulate nutrients [64,74].

#### 3.2.3. Combination of Practices Allowing the Highest Reductions of Both Sediments and Nutrients

The highest average combined reduction of sediment, phosphorus, and nitrate export was achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously (−25.2%). This was expected because filter strips had the strongest effect on both sediment and nutrient export, while conservation tillage reduced sediment export (Figure 4) without increasing nutrients when manure was previously incorporated (Figures 5 and 6). The combined reduction of sediment, phosphorus, and nitrate was, however, quite similar to when fertilizer incorporation, no-tillage, and filter strips were implemented simultaneously (−24.7%). Soil tillage provides some benefits such as soil aeration, manure, and fertilizer incorporation, seedbed preparation, and weed suppression [76], meaning that eliminating tillage practices may increase nutrients export when fertilizers are not previously incorporated and increase the dependence on herbicides to remove undesirable weeds. Our study shows that the optimally combined reduction of sediment, phosphorus, and nitrate export was achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously, suggesting that tillage practices might be changed from conventional to conservation rather than eliminated to balance the positive effect on other practices.

Despite the evidence of the benefits of adopting sustainable agricultural practices, a range of factors can hamper its adoption, including the non-perceived benefit to farmer livelihoods and the increased initial costs [77,78]. Even when sustainable agricultural practices are known to be profitable over the long term, farmers may not be capable of financing their initial costs. The adoption of sustainable agricultural practices will then require additional scientific evidence, but also smart policy measures supporting farmers' education and economic subsidies that will allow the adoption of sustainable agricultural practices over non-sustainable solutions [79].

## 4. Conclusions

Sustainable agricultural practices will be critical to increase global food production without compromising water quality and ecosystem health. Our study shows that sustainable agricultural practices can substantially reduce sediments and nutrient export to a river basin, especially the implementation of filter strips. We found that the implementation of filter strips of varying width for the agricultural areas close to water bodies, as proposed by the Portuguese plan for the Common Agricultural Policy 2023–2027, can reduce annual sediment exports by 32%, phosphorous exports by 14%, and nitrate exports by 19%, despite recommending filter strips to just 3.9% of the basin area. Prioritizing key areas for water pollution can therefore improve the effectiveness of sustainable agricultural practices by allowing to reduce water pollution without requiring large-scale interventions. Our findings also show that the highest depletions for single and combined pollutants were achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously, suggesting that multiple sustainable practices may be needed to achieve higher depletions of sediments and nutrient export. However, since the effect of sustainable agricultural practices depends on site-specific conditions, such as soil type, slope, and climate, additional studies on sustainable agricultural practices are needed to explore the effect of combined measures, and especially the interaction between measures, across a range of climate and watershed characteristics, as well as the performance of sustainable agricultural practices in dealing with challenges related to climate change.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14233962/s1, Supplementary material S1: Table S1. SWAT data variables for model setup and calibration/validation; Table S2. Soil classes used in SWAT; Table S3. Land-cover classes used in SWAT; Supplementary material S2 and Supplementary material S3.

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