



# Mitigating water pollution in a Portuguese river basin under climate change through agricultural sustainable practices

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## Abstract

Sustainable agricultural practices have been extensively used to reduce water pollution; however, the effectiveness of these practices may be significantly affected by climate change. In this study, we assess the effectiveness of sustainable agricultural practices in reducing sediment and nutrient export to rivers under future climate conditions, using the Soil & Water Assessment Tool in a Portuguese river basin exposed to high levels of agricultural pollution. In our study, filter strips demonstrated a significant mitigation effect on sediment and nutrient increases under simulated climate change conditions, with maximum sediment export depletion reaching 65% and the highest nutrient export depletion observed at 35%. The implementation of multiple sustainable practices resulted in the highest depletions, with a notable 71% depletion in sediment export and a 35% depletion in nutrient export. Additionally, our research underscores the crucial role of filter strips and multiple sustainable agricultural practices in mitigating the projected rise in nutrient concentrations during summer, given the effect of climate change on river discharge. Further studies exploring sustainable agricultural practices across different climates and watersheds can improve our understanding of their effectiveness for adaptation to climate change.

**Keywords** Global warming · Best management practices · Filter strips · Diffuse pollution · SWAT

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## 1 Introduction

Agriculture is a major source of nutrients to water bodies that often causes water quality degradation and eutrophication of aquatic ecosystems (Evans et al. 2019). Water pollution from agricultural sources has worsened in many regions and some studies have pointed to agriculture as one of the main causes of water pollution globally, surpassing contamination from urban and industrial sources (FAO 2017). The contribution of agriculture to water pollution is likely to increase in the future due to population growth and climate change that can trigger food production intensification, expansion of agricultural land, and greater use of agricultural inputs (Evans et al. 2019). Reducing the impacts of agricultural water pollution is therefore essential to avoid additional environmental degradation undermining ecosystem health and human well-being.

Sustainable agricultural practices have been increasingly explored to reduce agricultural diffuse pollution and have shown to be valuable to improve water quality in streams and rivers (Mancuso et al. 2021). However, the effectiveness of sustainable agricultural practices depends on many factors, including the amount of nutrients applied, fertilization strategy, tillage practices, soil type, catchment topography, presence of natural or constructed buffers, and climate (Chaubey et al. 2010; EEA - European Environment Agency 2021). Moreover, changes in precipitation and temperature are expected to affect nutrient export by changing surface runoff and the rate of biological processes (Giri et al. 2020). Changes in atmospheric CO<sub>2</sub> concentration may also affect soil fixation and plant assimilation of nitrogen (N), and therefore N availability in soils (Ficklin et al. 2010). In this sense, climate change is likely to affect both the quantity and quality of inland waters, and the buffering capacity of sustainable agricultural practices.

The individual effect of climate change and sustainable agricultural practices on agricultural diffuse pollution has already been extensively studied (e.g., Malagó et al. 2019; Ockenden et al. 2017; Wang et al. 2018). However, few studies have examined the effectiveness of sustainable agricultural practices in reducing nutrient export under climate change (e.g., Giri et al. 2020; Wagena & Easton 2018). On one hand, an increase in extreme precipitation events may reduce the buffering capacity of sustainable practices, but, on the other hand, higher temperatures may increase denitrification and nutrient uptake by plants, which will then reduce nutrient export (Wagena et al. 2018).

Evaluating the effectiveness of sustainable agricultural practices under future climate conditions is essential for developing adaptation measures that can minimize the impact of climate change. However, adaptation is context-specific, and no single measure is equally effective across all regions and conditions (EEA - European Environment Agency 2021). Therefore, regional and basin scale studies are crucial to improve the planning and adaptation to climate change, despite their limited spatial scope.

In this study, we aim to examine the importance of sustainable agricultural practices in reducing sediment and nutrient export under different climate change scenarios, using the Cávado River basin (northwest Portugal) as a case study. This is, to the best of our knowledge, the first study examining the importance of sustainable agricultural practices under climate change in the Cávado River basin, one of the most important basins for dairy and corn production in Portugal. Additionally, this is one of the few studies exploring the combined effect of sustainable agricultural practices and climate change on sediment and nutrient export at a river basin scale. We hypothesize that sustainable agricultural practices will be critical to offset high surface runoff and nutrient export during winter, and low surface runoff associated with low discharge and high nutrient concentration during summer under climate change. This study is relevant for environmental and water managers to anticipate the impact that climate change can have on water quality, and to implement effective adaptation measures.

## 2 Materials and methods

### 2.1 Study area

The study was conducted in the Cávado River basin, in the northwest of Portugal, which covers an area of 1581 km<sup>2</sup>. The region has a Mediterranean climate with Atlantic influence, and an average annual precipitation of 1300 mm. The minimum and maximum temperatures are 3 °C and 29 °C, respectively, the highest temperatures occur from June to September, while the highest precipitation values are registered from October to April.

The basin's geology is mainly composed of granite, and the dominant soil types are Umbric Leptosols and Dydrtric Antrosols (Leitão et al. 2013). In the upstream lands of the basin, there is a distinctive agricultural system known as the Barroso Agro-Sylvo-Pastoral System, which was recently acknowledged by the Food and Agriculture Organization of the United Nations as a Globally Important Agricultural Heritage System (FAO - Food and Agriculture Organization of the United Nations 2018). Livestock farming is the major agricultural activity, and crops such as rye, potato, and maize are cultivated in rotation with set-aside. In the downstream lands of the Cávado River basin, intensive farming systems of maize for the dairy industry are dominant (DRAEDM – Direção Geral de Agricultura do Entre Douro e Minho (General Directorate of Agriculture of Entre Douro e Minho), 2007). This system involves extensive maize fields and the production of large amounts of slurry and manure, which are used as organic fertilizers on arable lands (DRAEDM – Direção Geral de Agricultura do Entre Douro e Minho (General Directorate of Agriculture of Entre Douro e Minho), 2007). This agricultural practice has contributed to diffuse pollution in the basin and has led to the degradation of river water bodies, with 45% of water bodies having a lower than good ecological status under the Water Framework Directive (APA – Portuguese Environment Agency 2016). The water bodies' degradation is also caused by point discharges from urban and industrial activities and hydromorphological alterations from 9 dams present in the basin (APA – Portuguese Environment Agency 2016).

### 2.2 Hydrological and water quality modeling

The hydrological and water quality parameters analyzed include river discharge, sediment, phosphorous, and nitrate export. The selection of sediments, nitrate, and phosphorus as primary indicators in our study stems from several key justifications. Firstly, the choice is grounded in the availability of comprehensive observed data specifically for these water quality parameters within the Cávado River basin. These datasets not only facilitate robust model calibration and validation but also align with the practical constraints of data availability. Furthermore, sediments, nitrate, and phosphorus are identified as critical contributors to water pollution from agricultural sources in the study region (APA - Portuguese Environment Agency 2012). Nitrate and phosphorus, being essential nutrients in agriculture, are commonly associated with fertilizers and are pivotal for crop growth (Evans et al. 2019). Simultaneously, sediments, primarily arising from soil erosion, are intimately linked to agricultural land management practices (Evans et al. 2019). Focusing on these indicators enables a targeted assessment of the impact of sustainable agricultural practices on the most significant sources of water pollution in the watershed.

To simulate river discharge, sediment, phosphorous, and nitrate export, we employed the Soil & Water Assessment Tool (SWAT). SWAT is a hydrological model that operates on a daily time step, which is physically based, semi-distributed, and operates on a continuous time scale (Arnold et al. 2013). The SWAT model was set up using SWAT2012 (rev. 670) in ArcSWAT 2012.10\_5.21 interface for ArcGis (Winchell et al. 2013).

The watershed was delineated by using the Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global (USGS - United States Geological Survey 2018) and the stream network shapefile of the Water Framework Directive (WFD) (SNIAMB – National Environmental Information System 2018) (Table 1). We used this to ensure that the model created sub-basins that were consistent with the ones defined in the WFD. The outlets of these sub-basins were further adjusted to account for the calibration sites and avoid the reservoirs occupying more than one sub-basin.

To create the hydrological response units (HRUs), we utilized a land cover map for mainland Portugal of 2010 (DGT – National Territory Directorate, 2010), a soil map (Leitão et al. 2013), and three slope classes (i.e., 0–10%, 10–25%, and > 25%) (Table 1). The vegetation and soil parameters were based on a prior study that employed SWAT in northwest Portugal (Carvalho-Santos et al. 2016). The management operations for each land cover were designed based on the literature (APA – Portuguese Environment Agency 2016; DRAEDM – Direção Geral de Agricultura do Entre Douro e Minho (General Directorate of Agriculture of Entre Douro e Minho), 2007; FAO - Food and Agriculture Organization of the United Nations 2018).

The reservoirs were added to SWAT using data from SNIRH (National Water Resources Information System) and the Portuguese power company EDP (EDP - Portuguese Power Company 2019) (Table 1). The point sources of pollution were located in the Cávado River basin using the shapefile of the wastewater treatment plants provided by the Portuguese Environment Agency (APA) and SNIAMB (Table 1). The data on nitrogen (NO<sub>3</sub>CNST and NH<sub>3</sub>CNST), phosphorous (MINPCNST), and volume discharged (FLOCNST) by the point sources were obtained from the shapefile of the wastewater treatment plants and from INSAAR (National Inventory of Water Supply and Wastewater Systems). To locate the surface water abstractions, a shapefile from SNIG (National Geographic Information System) was employed, while the APA - Portuguese Environment Agency (2012) was consulted to obtain the volume of water abstracted (Table 1).

To improve the spatial representation of precipitation and temperature in mountainous areas, we used 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. (2016).

The curve number equation method (CN) was employed to simulate surface runoff. The Hargreaves equation was used to simulate evapotranspiration, since the Penman–Monteith equation was found to provide unsatisfactory results, most likely because of the low quality of wind-speed data. To mitigate the impacts of uncertain initial conditions, a warm-up period of 3 years was used.

SWAT has already been applied in the Cávado River basin to assess the effect of climate change on hydropower generation (Ramião et al. 2023), and the effect of sustainable agricultural practices on sediment, phosphorous, and nitrate export (Ramião et al. 2022). Additional methodological details on the SWAT setup are available in Ramião et al. (2023) and Ramião et al. (2022).

### 2.3 Model calibration and validation

SWAT outputs by land cover for leaf area index (LAI), evapotranspiration (ET), and total biomass (BIOM) were first compared with values from the literature (ICNF – National Institute for Nature Conservation and Forests 2015; Tereso et al. 2011), to calibrate the model by changing sensitive parameters in the soil (.sol), vegetation (.crop), and management databases (.mgt). The SWAT parameters USLE\_K, USLE\_P, and USLE\_C were

**Table 1** SWAT data variables used in model setup, calibration, and validation. Retrieved from Ramião et al. (2022)

Variables	Source	Description
DEM	NASA Shuttle Radar Topography Mission (SRTM)	1 Arc-Second Global Land Elevation Map
Stream network	SNIAmb	Stream network according to the Water Framework Directive (WFD)
Land cover	DGT	COS 2010 (land use map), 1 ha (minimum mapping unit). Classes were aggregated into seven main cover classes
Soil	Leitão et al. (2013)	Soil Ecological Value of Mainland Portugal, 1:50,000. Classes were aggregated into seven main soil classes
Precipitation and temperature	E-OBS	Mean daily precipitation (mm), maximum and minimum daily temperature (°C) from E-OBS gridded dataset, from 1970 to 2018
Climate (other variables)	SNIRH	Hourly values from 2003 to 2017 were converted to daily values of solar radiation (MJ), relative humidity (%), and wind speed (m/s) from climate 3 climate stations
River discharge	SNIRH	Daily observations of river discharge ( $\text{m}^3 \text{s}^{-1}$ ) at 1 hydrometric station. Calibration period: 1980–1982; validation: 1983–1985
Water flow-in to reservoirs	SNIRH	Daily observations of water flow-in ( $\text{m}^3 \text{s}^{-1}$ ) to 6 reservoirs. Calibration period: 2004–2006; validation: 2015–2017
Reservoirs	SNIRH, EDP	Location and input data for reservoirs
Water abstraction	SNIG, APA	Location of surface water abstractions and volume of water abstracted

Reprinted from Ramião et al. (2022)

also changed according to Panagos et al. (2014), Panagos et al. (2015a), and Panagos et al. (2015b), respectively, to calibrate land cover exports of sediments and nutrients.

To enhance sediment calibration at the outlet of the basin, and to set the dam trapping efficiency between 60 and 95%, the grain size of sediments (RES\_D50) of Salamonde, Ponte do Bico, and Penide was increased to 20, 30, and 30, respectively, and the equilibrium sediment concentration (RES\_NSED) was decreased from 1 to 0.9 in Ponte do Bico and Penide. To improve phosphorous and nitrate calibration, the nutrient settling rates in reservoirs (NSETLR, PSETLR) were changed in two reservoirs.

A semi-automated model calibration and validation were then performed using SWAT-CUP software version 5.2.1 (Abbaspour et al. 2015), with the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al. 2004). The semi-automated calibration was performed using up to three iterations, with 200 simulations each, and the Nash–Sutcliffe (NS) as the objective function. The SWAT executable was previously updated to rev. 670.

A global sensitivity analysis was used to select the most sensitive parameters from those previously chosen in the literature (Abbaspour et al. 2015, 2007; Molina-Navarro et al. 2017; Shrestha et al. 2016). The model was calibrated from 1995 to 1997 at the outlet of the river basin, and then validated from 1998 to 2000, to establish trust in the accuracy of the calibrated parameters (i.e., validation). The output parameters were calibrated sequentially (Shrestha et al. 2016), starting by stream discharge, followed by sediments, total phosphorous, and nitrate.

SWAT had already been calibrated and validated in the Cávado River basin for river discharge, sediment, phosphorous, and nitrate export (Ramião et al. 2022). Additional calibration details are available in Ramião et al. (2022).

## 2.4 Climate projections

In this study, we used the same methodology applied by Ramião et al. (2023) to assess the climate change impacts on the Cávado River basin using SWAT. The climate projections were based on daily data of precipitation (pr), minimum and maximum 2-m air temperature (tasmin, tasmx), near-surface relative humidity (hurs), surface downwelling short-wave radiation (rsds), and near-surface wind speed (sfcWind). These data were obtained from the EUROCORDEX project at a resolution of 0.11° for two time periods, 1976–2005 and 2031–2060, under two different Representative Concentration Pathways (RCP4.5 and RCP8.5) scenarios. The decision to include these scenarios was driven by a strategic consideration of both worst-case and more plausible future conditions. Four regional climate models (RCMs) were used to simulate these variables, and their performance was evaluated based on statistical measures of goodness-of-fit between the simulated and observed data in the Cávado River basin. Statistical goodness-of-fit measures were calculated in R using the hydroGOF package (Zambrano-Bigiarini 2014), while EURO-CORDEX and E-OBS data were analyzed in R using climate4R packages (Iturbide et al. 2019).

A bias correction method was applied to the simulated data using E-OBS as a reference dataset. This was done using the linear scaling method, where the difference between the observed and simulated means was considered for temperature, and the quotient between the observed and simulated means was considered for precipitation. The carbon dioxide concentrations used in the simulations were based on the IPCC – Intergovernmental Panel on Climate Change (2013) values for historical and future periods under different scenarios.

The maximum consecutive 5-day precipitation (Rx5day) was calculated in R using the climate4R.climdex package (Iturbide et al. 2019). Rx5day is one of the climate extremes

indices defined by the Expert Team on Climate Change Detection and Indices (Karl et al. 1999), used to examine changes in extreme precipitation under climate change.

## 2.5 Sustainable agricultural practices

The importance of sustainable agricultural practices (SAPs) in reducing sediment and nutrient export under climate change was examined considering two fertilizer application methods (broadcast application and fertilizer incorporation), along with two tillage operations (conventional and conservation) and the implementation of filter strips. Fertilizer incorporation, conservation tillage, and the implementation of filter strips were considered sustainable agricultural practices, while the current management practices in the basin comprise broadcast application of manure, conventional tillage, and no filter strips. We selected sustainable agricultural practices (SAPs) that have been shown in the literature to be effective in reducing sediment and nutrient export in agricultural basins, and based on a previous study assessing the effectiveness of SAPs in the Cávado River basin (Ramião et al. 2022). The effect of each SAP was examined individually, and with all SAPs implemented simultaneously, since it has been found that the highest average combined depletion of sediment, phosphorus, and nitrate export was achieved when fertilizer incorporation, conservation tillage, and filter strips were implemented simultaneously (Ramião et al. 2022). The simulations were conducted by integrating the specified climate change scenarios (1976–2005 and 2031–2060 under RCP4.5 and RCP8.5) with the sustainable agricultural practices examined. This integrated approach allowed us to assess the combined effects of changing climatic conditions and sustainable agricultural practices on sediment and nutrient export dynamics.

The FRT\_SURFACE parameter in SWAT was used to simulate the different fertilizer application methods, while the mixing efficiency of the tillage operation (EFFMIX) and depth of mixing (DEPTIL) was used to simulate the different tillage operations (Dechmi and Skhiri 2013; Tuppad et al. 2010). Filter strips were implemented in all agricultural areas within the riparian zone, which was defined by applying the riparian zones from the Copernicus programme (Copernicus programme, 2015). The width of the filter strips was defined according to the Portuguese plan for the Common Agricultural Policy 2023–2027 of the European Commission that involves installing filter strips of different widths in agricultural areas near water bodies, depending on the land slope (GPP – Planning Policy and General Administration Office 2021). When the slope was lower than 10% the filter strips should have 3-m width, when the slope was between 11 and 25% the filter strips should have 10-m width, and when the slope was equal or higher than 25% the filter strips should have 15-m width. Additional methodological details regarding SAP implementation in SWAT can be found in (Ramião et al. 2022).

## 3 Results and discussion

### 3.1 SWAT calibration and validation

SWAT has already been calibrated and validated for river discharge, sediment, phosphorus, and nitrate export in the Cávado River basin (Ramião et al. 2022), with an overall good performance of the model for all variables, considering both the Nash Sutcliffe efficiency (NSE) and the coefficient of determination ( $R^2$ ) (Moriasi et al. 2015) (Table 2). To address uncertainties, we considered the 95% prediction uncertainty (95PPU) band. Over 50% of observed data fell

**Table 2** Goodness-of-fit statistics (NSE,  $R^2$ ) for river discharge, sediment, phosphorous, and nitrate calibration and validation, considering monthly data from 1995 to 1997 for calibration and 1998 to 2000 for validation. The  $P$ -factor represents the percentage of observed data enclosed by the 95PPU, while  $R$ -factor is the average width of the 95PPU divided by the standard deviation of corresponding observed data

	River discharge		Sediments		Phosphorous		Nitrate	
	Calibration	Validation	Calibration	Validation	Calibration	Validation	Calibration	Validation
NSE	0.72	0.62	0.49	0.5	0.57	0.47	0.38	0.44
$R^2$	0.76	0.73	0.65	0.75	0.57	0.56	0.57	0.55
$P$ -factor	0.73	0.55	0.61	0.58	0.91	0.83	0.53	0.69
$R$ -factor	0.94	0.75	1.6	1.39	1.51	0.83	0.6	0.72

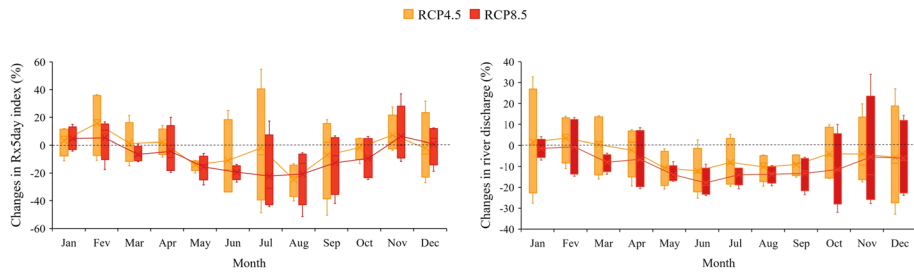
within this band for most variables and temporal periods (Table 2,  $P$ -factor). The  $R$ -factor, indicating the width of the uncertainty band, consistently remained below 1.5, underlining the precision of our model predictions. The  $P$ -factor and  $R$ -factor, representing the percentage of observed data within the 95PPU and the average width of the 95PPU relative to observed data standard deviation, respectively, aligned with findings in the literature (Nkiaka et al. 2018; Rocha et al. 2015; Shrestha et al. 2016), reinforcing the reliability of our calibration.

The calibration of the SWAT model for the Cávado River basin adheres to a well-established and widely accepted approach in hydrological modeling, aligning with standard practices (Abbaspour et al. 2015). However, the challenge arises when attempting to extend the application of calibrated models to predict responses under future climate scenarios, especially in the context of climate change (Majone et al. 2022). This endeavor involves extrapolating beyond the historical range, introducing uncertainties, particularly when the model encounters conditions significantly different from those observed during calibration (Duethmann et al. 2020). Factors such as changes in precipitation, temperature extremes, and other climatic variables may deviate significantly from historical patterns, challenging the reliability of the calibrated model for accurate projections into the future (Majone et al. 2022). Acknowledging these complexities is crucial for interpreting climate change impacts based on the calibrated model and emphasizes the need for ongoing research to enhance the reliability of future projections.

### 3.2 Precipitation, evapotranspiration, and river discharge under climate change

Precipitation in the Cávado River basin is expected to decrease, on average, 3.7% in 2031–2060 under RCP4.5, while potential evapotranspiration is expected to increase, on average, 5% in 2031–2060 under RCP4.5 (Ramião et al. 2023). Higher reductions in precipitation and more pronounced increments in evapotranspiration are expected under RCP8.5 (Ramião et al. 2023). Changes in precipitation and potential evapotranspiration are projected to differ across the year, with precipitation having the highest depletions during the summer, when potential evapotranspiration is projected to have the highest increments (Ramião et al. 2023). Furthermore, the maximum consecutive 5-day precipitation will increase during most of the winter and decrease during the summer (Fig. 1), which will then likely increase surface runoff and nutrient export during the rainy season, and decrease the dilution capacity of rivers during the dry season (Giri et al. 2020; Qiu et al. 2020). This is supported by an increase in river discharge from January to March, and a decrease during the rest of the year, especially during the summer under RCP8.5 (Fig. 1).





**Fig. 1** Change in 30-year average Rx5day (Maximum consecutive 5-day precipitation) and river discharge in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios. The boxplots display the dispersion among four regional climate models

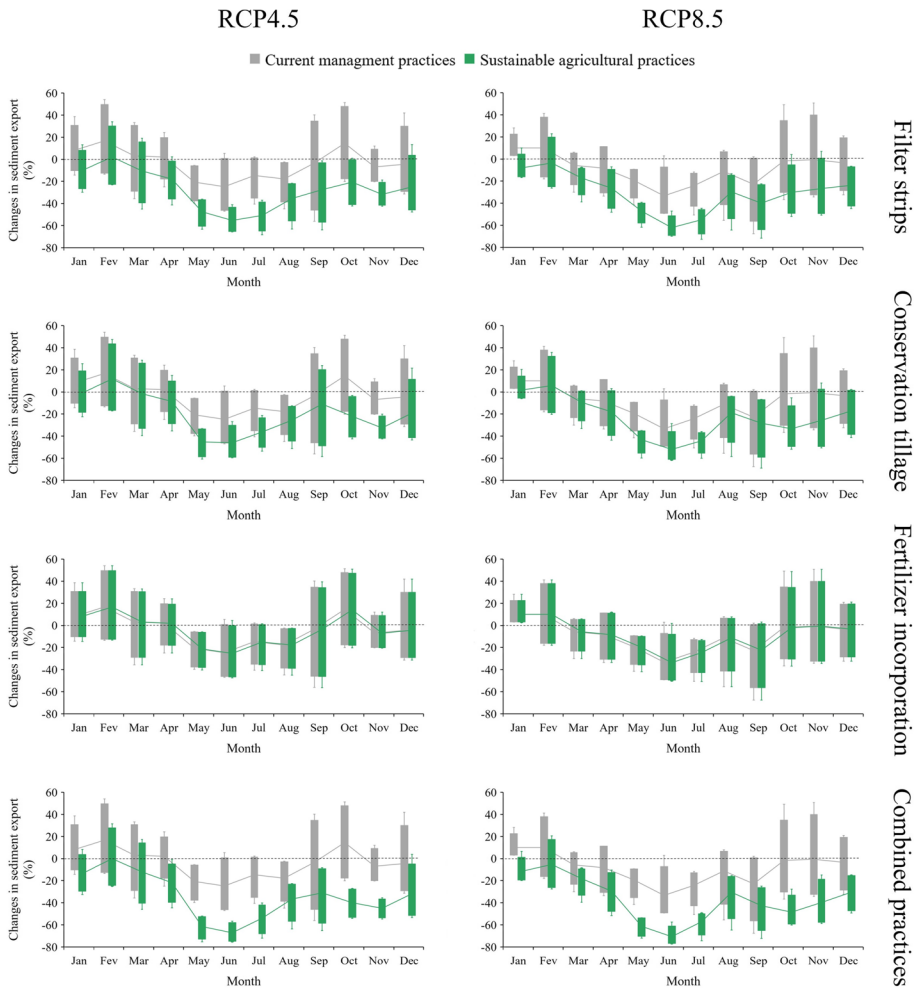
Several studies have already predicted lower river discharge under future climate conditions, including in Portugal and the entire Mediterranean region (Fonseca & Santos, 2019; Lionello & Scarascia, 2018). The Cávado River basin is expected to be less affected by climate change than the basins in the southern region; however, high discharge depletions during the summer, when water demand is higher and is likely to increase, may aggravate the water stress problems, and degrade the water quality due to a low dilution capacity.

### 3.3 Sediment export under climate change and sustainable agricultural practices

Sediment export is expected to increase from January to April, and to decrease during summer under RCP4.5 (Fig. 2). Previous studies have already predicted an increase in sediment export under climate change during the rainy season, due to an increase in precipitation that leads to soil loss, and/or an increase in river discharge that exacerbates stream bank erosion (Giri et al. 2020; Qiu et al., 2020a). The lower sediment export observed during the summer, especially under RCP8.5 (Fig. 2), can probably be related to the lower surface runoff and river discharge.

Our study shows that sustainable agricultural practices will be important to control sediment export under climate change (Fig. 2). Filter strips, conservation tillage, and the combination of the three studied sustainable agricultural practices will decrease sediment export under future climate scenarios (Fig. 2), avoiding sediment increments during the rainy season, and exacerbating sediment depletions during the dry season (Fig. 2). The highest sediment depletions under both RCP4.5 and RCP8.5 were achieved when multiple sustainable agricultural practices were implemented simultaneously, followed by filter strips, and conservation tillage (Fig. 2). Higher sediment depletions with multiple sustainable agricultural practices were already reported by many studies, including for the Cávado River basin (Ramião et al. 2022), but our study highlights that these practices can also result in considerable sediment depletions under the influence of climate change.

Filter strips are expected to reduce sediment export since they provide resistance to water flow and promote the deposition of suspended particulates (Gumiero et al. 2011; Li et al. 2016). Previous studies have suggested that climate change may reduce the effectiveness of filter strips in reducing sediment export, by increasing precipitation and decreasing the residence time of concentrated runoff flowing across filter strips (Qiu et al. 2020). However, our study shows that filter strips can still be important to offset sediment increments during the rainy season due to forecast increase in rainfall erosivity (Panagos et al.



**Fig. 2** Percentage of change in monthly 30-year average sediment export in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios, and three sustainable agricultural practices, filter strips, conservation tillage, and fertilizer incorporation, plus the combination of such practices. The boxplots display the dispersion among four regional climate models

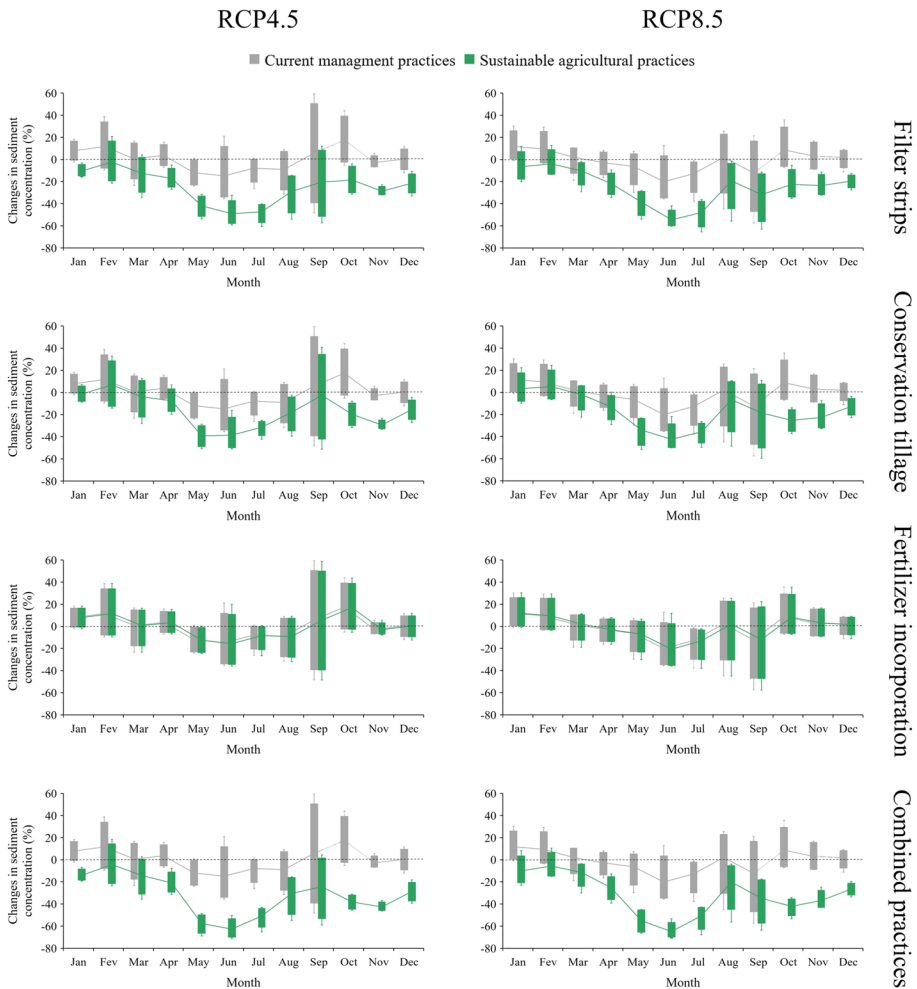
2017), and to exacerbate sediment depletion during the summer under climate change predictions (Fig. 2).

Conservation tillage was also found to augment sediment depletions under climate change, mostly during the months following crop plantation (i.e., May to July) (Fig. 2). Conservation tillage was expected to increase sediment depletion, since conventional tillage is known to reduce the stability of soil structure and residue cover, while increasing erosion and sediment losses (Maguire et al. 2011).

Changes in sediment concentration will likely follow changes in sediment export (Fig. 3), probably because sediment export is highly related to precipitation and surface runoff that also affects river discharge (Qiu et al. 2020). The effects of sustainable

agricultural practices on sediment concentration have closely followed the same pattern as sediment export (Fig. 3).

Our study shows that filter strips, conservation tillage, and multiple sustainable agricultural practices will allow the reduction of sediment export under future climate conditions (Fig. 2), which will be crucial to avoid reservoir sedimentation and the destruction of in-stream habitats. In addition, avoiding soil erosion is critical to maintain soil health and productivity as a guarantee of the sustainable food-system production (Pozza and Field 2020).



**Fig. 3** Percentage of change in monthly 30-year average sediment concentration in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios for three sustainable agricultural practices plus the combined practices (filter strips, conservation tillage, and fertilizer incorporation simultaneously). The boxplots display the dispersion among four regional climate models

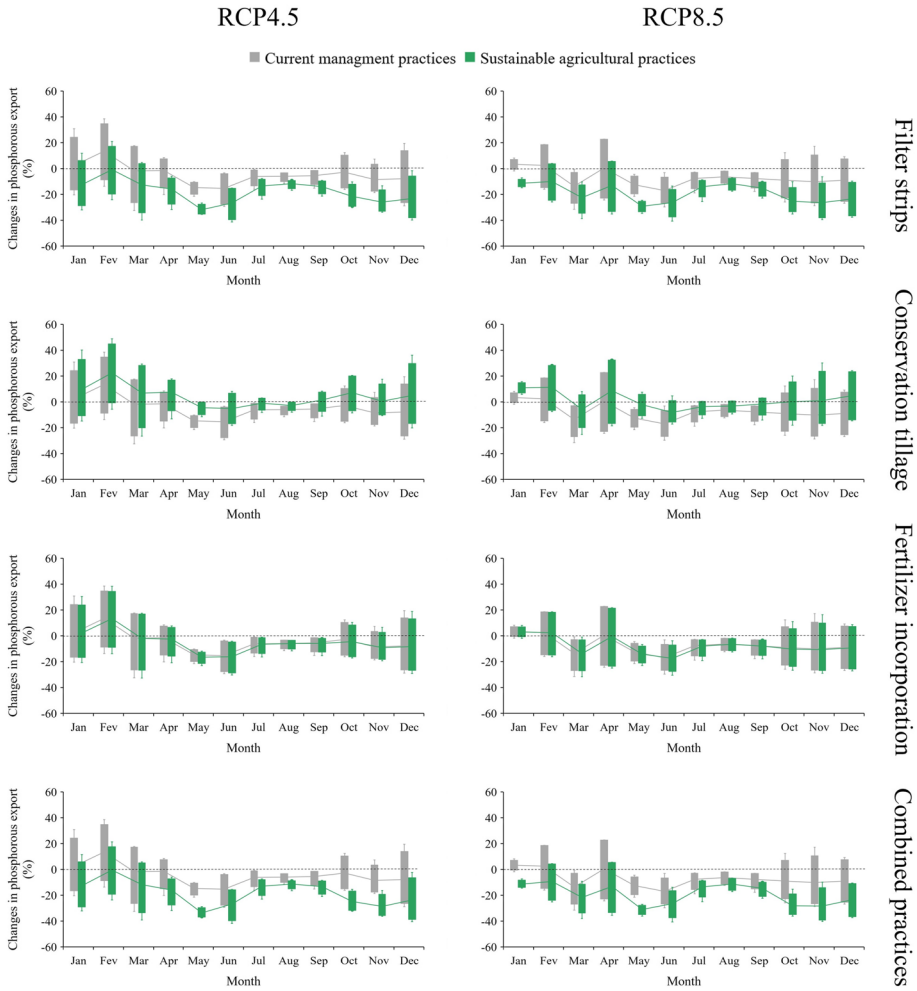
### 3.4 Nutrient export and concentration under climate change and sustainable agricultural practices

Phosphorous export is expected to increase from January to February, and to decrease during the rest of the year, under both RCP4.5 and RCP8.5 (Fig. 4). Changes in phosphorous export under climate change scenarios are similar to changes in sediment export (Figs. 2 and 4), probably because phosphorous is mainly transported in its particulate form and phosphorous attached to sediments is often the main pathway of phosphorous export (Qiu et al. 2020; Serpa et al. 2017).

Changes in nitrate export due to climate change are expected to be similar to changes in phosphorous export (Figs. 4 and 5). However, phosphorous increases are expected to be higher than nitrate increases, and nitrate export is likely to decrease during the entire year under RCP8.5 (Figs. 4 and 5). Differences between changes in phosphorous and nitrate export under climate change may be related to differences in their preferential transport pathways. In this sense, phosphorous export is mainly transported in its particulate form and it is highly related to changes in surface runoff (Molina-Navarro et al. 2014; Serpa et al. 2017), meaning that more pronounced effects of climate change on surface runoff may be translated into higher phosphorous increments during the winter and higher depletions during the summer (Fig. 4). This is consistent with previous findings in nearby river basins, where nutrients that are mainly mobilized in particulate forms had lower exports during the summer under climate change predictions, due to the simultaneous decrease in runoff and sediment yield (Molina-Navarro et al. 2014; Serpa et al. 2017).

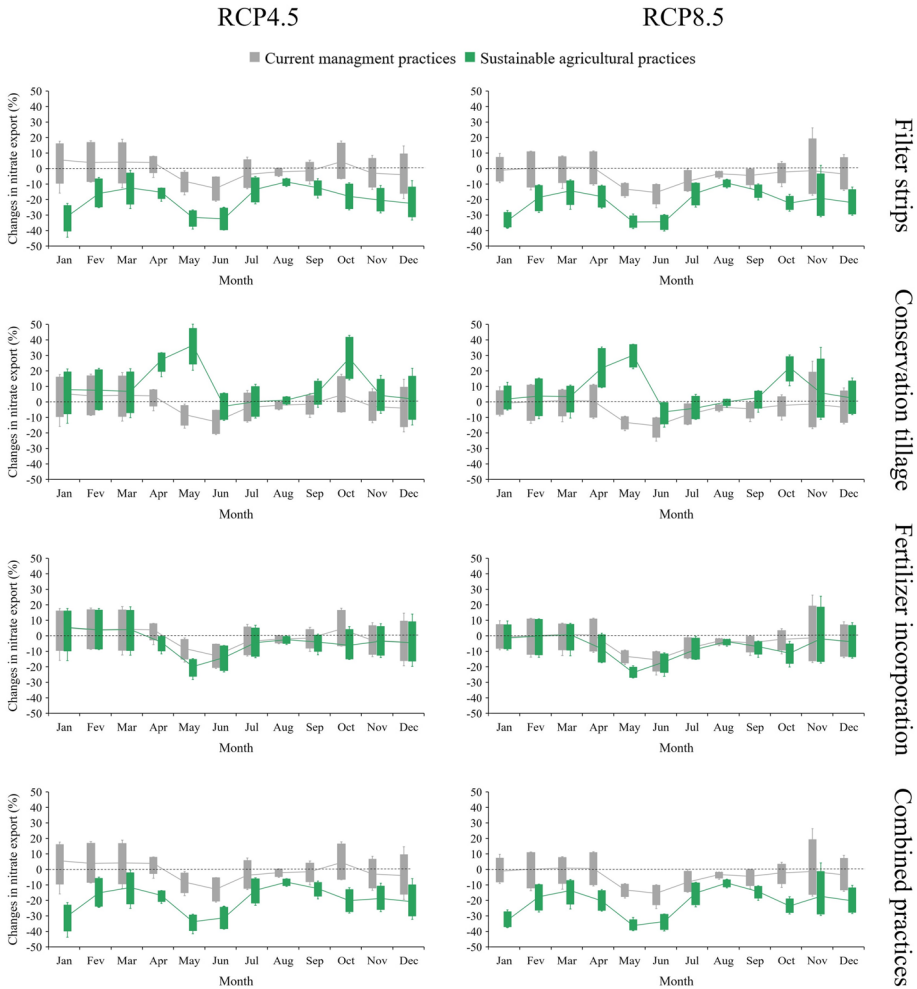
Filter strips and multiple sustainable agricultural practices will avoid nutrient increments during the rainy season and exacerbate nutrient depletions during the rest of the year, especially around May and October, after manure fertilization (Figs. 4 and 5). Filter strips were the most important individual practice reducing both sediments and nutrients under climate change (Figs. 2, 4, and 5). Previous studies have already reported a key role of riparian forests in reducing sediment and nutrient export to rivers, and their importance as an adaptation measure to climate change (Giri et al. 2020; Wagena and Easton 2018). However, the efficiency of filter strips in reducing water pollution depends on many factors, including the amount of precipitation and air temperature that are likely to change in the future. Our study shows that the proposal of the Portuguese plan for the Common Agricultural Policy 2023–2027, that establishes the implementation of filter strips of varying widths for agricultural areas close to water bodies, will help to avoid sediment and nutrient increments under future climate conditions. Furthermore, filter strips will help to reduce sediment and nitrate increments up to 18% and 35% (Figs. 2 and 6, RCP4.5), respectively, while only requiring management interventions in 3.9% of the basin area, showing that prioritizing key areas for water pollution, such as riparian zones, can play a crucial role in mitigating the impacts of climate change without requiring large scale interventions (Xu and Bosch 2019).

Moving from conventional to conservation tillage will exacerbate nutrient increments during the rainy season and reduce nutrient depletions during the rest of the year (Fig. 4). Unlike phosphorous, conservation tillage will lead to very high increments of nitrate during the spring and autumn after manure application (Figs. 4 and 5). This was probably related to the higher content of nitrogen in manure, combined with its higher solubility (Serpa et al. 2017). Conservation tillage had already been found to increase nutrient export when broadcast application of fertilizers was used, probably because conventional tillage reduces the availability of nutrients to runoff by incorporating most of the manure on the



**Fig. 4** Percentage of change in monthly 30-year average phosphorous export in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios, and four sustainable agricultural practices. Combined practices refer to the implementation of filter strips, conservation tillage, and fertilizer incorporation simultaneously. The boxplots display the dispersion among four regional climate models

soil surface (Ramião et al. 2022). Climate change may aggravate the effect of conservation tillage on nutrient export by increasing precipitation intensity and surface runoff. However, the tillage operation had lower effect on nutrient export when fertilizers were previously incorporated into the soil (Ramião et al. 2022), since fertilizer incorporation removes the potential for the direct transfer of nutrients to runoff (Maguire et al. 2011), which may explain the highest nutrient depletions when multiple sustainable practices were implemented (Fig. 4). Therefore, fertilizer incorporation when using conservation tillage will be even more important under climate change. Furthermore, fertilizer incorporation when conventional tillage is also used will have little to non-effect on nutrient export under climate change (Figs. 4 and 5), probably because conventional tillage already reduces the availability of nutrients to surface runoff (Ramião et al. 2022). However, since

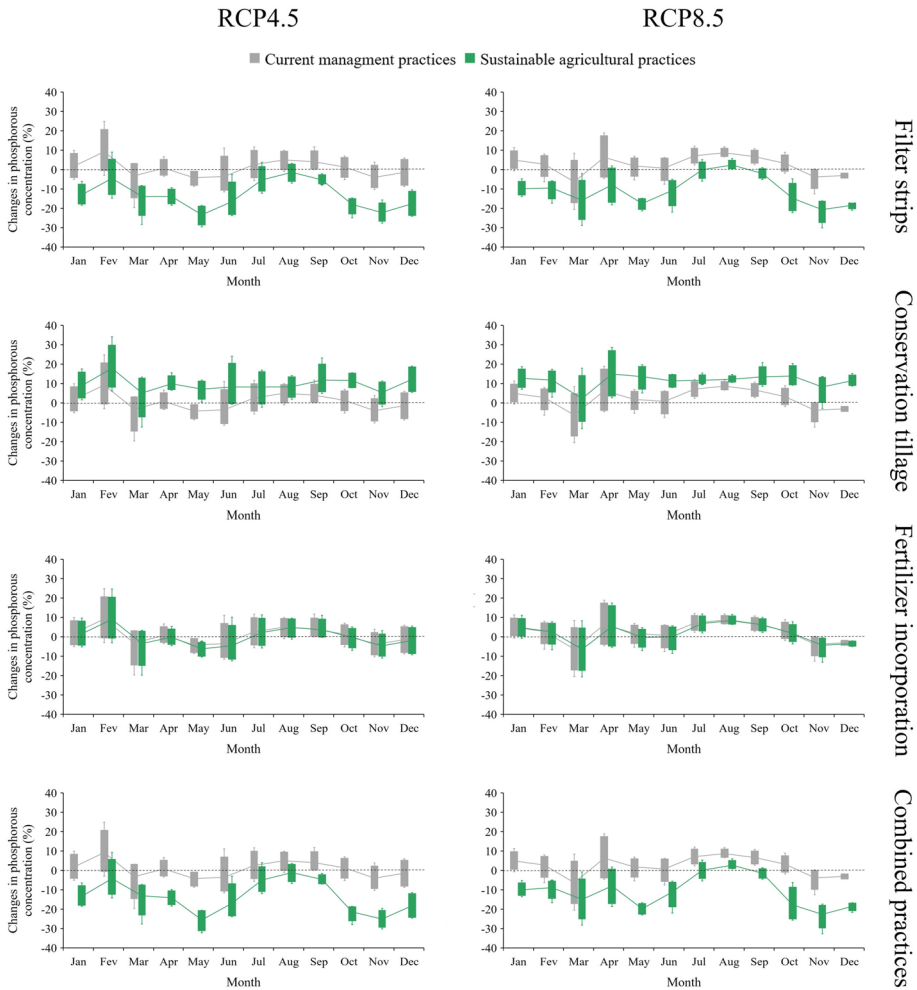


**Fig. 5** Percentage of change in monthly 30-year average nitrate export in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios, and four sustainable agricultural practices. Combined practices refer to the implementation of filter strips, conservation tillage, and fertilizer incorporation simultaneously. The boxplots display the dispersion among four regional climate models

conventional tillage increases sediment export (Fig. 2), combining conservation tillage with fertilizer incorporation will allow the reduction of both sediment and nutrient export under climate change.

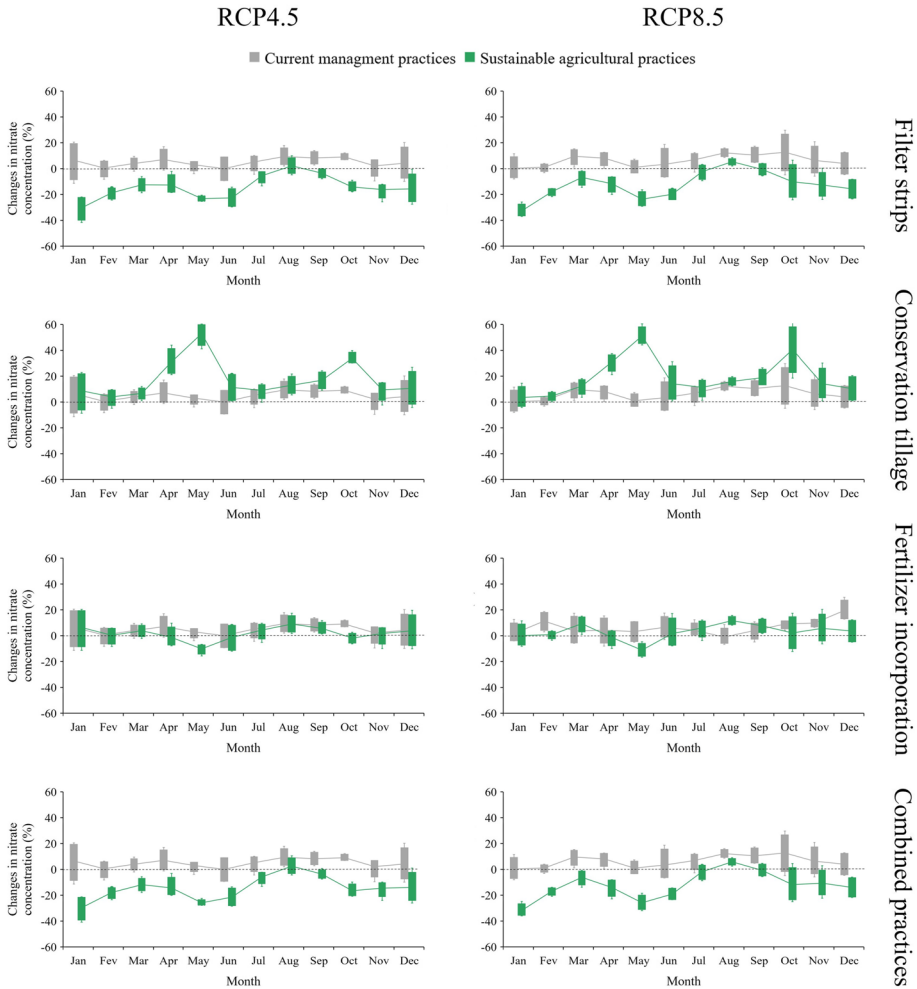
Lower nutrient export during the summer under climate change (Figs. 4 and 5) does not necessarily mean an improvement of surface water quality, since lower precipitation and river discharge are likely to reduce the water dilution capacity (Serpa et al. 2017). In fact, our study shows that despite reducing nutrient export (Figs. 4 and 5), climate change is expected to increase nutrient concentration during the summer, when river discharge is likely to have the highest depletions (Figs. 6 and 7).

Filter strips and the combination of all sustainable agricultural practices will also be crucial to mitigate higher nutrient concentration during the summer (Figs. 6 and 7), while



**Fig. 6** Percentage of change in monthly 30-year average phosphorous concentration in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios, and four sustainable agricultural practices. Combined practices refer to the implementation of filter strips, conservation tillage, and fertilizer incorporation simultaneously. The boxplots display the dispersion among four regional climate models

with respect to nutrient export, these sustainable practices are only expected to exacerbate nutrient depletions (Figs. 4 and 5). Even though pollutant loads are generally used to assess the performance of sustainable agricultural practices, pollutant concentration is often used to evaluate water quality due to its biological significance (Serpa et al. 2017; Wagena and Easton 2018). Considering that climate change is expected to affect both nutrient export and river discharge, and that changes in nutrient export may not reflect changes in nutrient concentration (Figs. 4, 5, 6, and 7), an effective reduction of nutrient export by sustainable practices may not ensure lower nutrient concentration under future climate conditions.



**Fig. 7** Percentage of change in monthly 30-year average nitrate concentration in 2031–2060 relative to 1976–2005, under RCP4.5 and RCP8.5 scenarios, and four sustainable agricultural practices. Combined practices refer to the implementation of filter strips, conservation tillage, and fertilizer incorporation simultaneously. The boxplots display the dispersion among four regional climate models

### 4 Conclusions

Sustainable agricultural practices have been increasingly used to reduce diffuse pollution and as an adaptation measure to climate change. However, changes in precipitation and temperature can impact the effectiveness of sustainable agricultural practices in reducing sediments and nutrients under future climate conditions. Our study shows that filter strips will mitigate sediments and nutrients increases under climate change, while conservation tillage combined with broadcast application of manure will mitigate sediment but exacerbate nutrient export. The highest reductions in both sediments and nutrients under climate change will be achieved when combining certain sustainable agricultural practices, namely filter strips,



conservation tillage, and fertilizer incorporation, suggesting that multiple sustainable practices will be needed to achieve higher benefits. Considering that the effect of sustainable agricultural practices depends on site-specific conditions, additional studies exploring the effect of different measures across a range of climate and watershed characteristics will allow to improve our understanding about the effectiveness of sustainable agricultural practices and therefore our adaptation to climate change. Moreover, the lessons drawn from this study offer valuable insights for other basins facing similar water pollution issues. The effectiveness of sustainable agricultural practices in mitigating sediment and nutrient export, as demonstrated in the Cávado River basin, provides a template for adaptation measures in comparable regions. By understanding the nuanced interactions between climate, land use, and sustainable practices, scientists and policymakers in other basins can tailor strategies to address their specific water quality challenges, fostering a more comprehensive and context-specific approach to diffuse pollution management. Acknowledging that the potential benefits or trade-offs of these sustainable agricultural practices may extend beyond the scope of our analysis, encompassing other pollutants not explicitly investigated in this study, emphasizes the need for future research to delve into assessing the broader impacts on water quality parameters beyond sediments and nutrients. This ongoing exploration will provide valuable insights into the multifaceted consequences of sustainable agricultural practices, further enhancing our understanding of their environmental implications.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Ethics approval** This research does not involve Human Participants and/or Animals.

**Competing interests** The authors declare no competing interests.

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## References

- Abbaspour KC, Johnson CA, Van Genuchten MT (2004) Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zone J* 3:1340–1352. <https://doi.org/10.2113/3.4.1340>

- Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J Hydrol* 333:413–430. <https://doi.org/10.1016/j.jhydrol.2006.09.014>
- Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Kløve B (2015) A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. *J Hydrol* 524:733–752. <https://doi.org/10.1016/j.jhydrol.2015.03.027>
- APA - Portuguese Environment Agency (2012) Plano de Gestão da Região Hidrográfica do Cávado, Ave e Leça (First River Basin Management Plan of the Water Framework) [WWW Document]. <https://www.apambiente.pt/agua/1o-ciclo-de-planeamento-2010-2015>. Accessed 6.1.2022
- APA - Portuguese Environment Agency (2016) Plano de Gestão da Região Hidrográfica do Cávado, Ave e Leça (RH2) (Second River Basin Management Plan of the Water Framework) [WWW Document]. <https://www.apambiente.pt/agua/2o-ciclo-de-planeamento-2016-2021>. Accessed 6.1.2022
- Arnold JG, Kiniry JR, Srinivasan R, Williams JR, Haney EB, Neitsch SL (2013) SWAT 2012 input/output documentation. Texas Water Resources Institute. <https://swat.tamu.edu/media/69296/swat-io-documentation-2012.pdf>
- Carvalho-Santos C, Nunes JP, Monteiro AT, Hein L, Honrado JP (2016) Assessing the effects of land cover and future climate conditions on the provision of hydrological services in a medium-sized watershed of Portugal. *Hydrol Process* 30:720–738. <https://doi.org/10.1002/hyp.10621>
- Chaubey I, Chiang L, Gitau MW, Mohamed S (2010) Effectiveness of best management practices in improving water quality in a pasture-dominated watershed. *J Soil Water Conserv* 65:424–437. <https://doi.org/10.2489/jswc.65.6.424>
- Copernicus programme (2015) Delineation of Riparian Zones [WWW Document]. <https://land.copernicus.eu/local/riparian-zones/riparian-zones-delineation?tab=metadata>. Accessed 5.1.2022
- Dechmi F, Skhiri A (2013) Evaluation of best management practices under intensive irrigation using SWAT model. *Agric Water Manag* 123:55–64. <https://doi.org/10.1016/j.agwat.2013.03.016>
- DGT - National Territory Directorate (2010) Carta de Uso e Ocupação de solo - 2010 (Land use and land cover map - 2010) [WWW Document]. <https://snig.dgterritorio.gov.pt/>. Accessed 11.1.2018
- DRAEDM - Direção Geral de Agricultura do Entre Douro e Minho (General Directorate of Agriculture of Entre Douro e Minho) (2007) Plano de ordenamento da bacia leiteira primária do Entre Douro e Minho (Management plan of the dairy basin of Entre Douro e Minho) [WWW Document]. <https://portal.drapnorte.gov.pt/>. Accessed 3.1.2022
- Duethmann D, Blöschl G, Parajka J (2020) Why does a conceptual hydrological model fail to correctly predict discharge changes in response to climate change? *Hydrol Earth Syst Sci* 24:3493–3511. <https://doi.org/10.5194/hess-24-3493-2020>
- EDP - Portuguese Power Company (2019) Declaração ambiental 2019, Aproveitamentos Hidroelétricos da EDP Produção, Direção centro de produção Cávado-Lima (Environmental Declaration 2019. EDP Hydroelectric Plants, Cávado-Lima Production Center) [WWW Document]. <https://portugal.edp.com/pt-pt/sustentabilidade-1>. Accessed 3.1.2019
- EEA - European Environment Agency (2021) Water and agriculture: towards sustainable solutions — European Environment Agency [WWW Document]. <https://www.eea.europa.eu/publications/water-and-agriculture-towards-sustainable-solutions>. Accessed 2.1.2020
- Evans AE, Mateo-Sagasta J, Qadir M, Boelee E, Ippolito A (2019) Agricultural water pollution: key knowledge gaps and research needs. *Curr Opin Environ Sustain* 36:20–27. <https://doi.org/10.1016/j.cosust.2018.10.003>
- FAO - Food and Agriculture Organization of the United Nations (2018) Barroso Agro-Sylvo-Pastoral System [WWW Document]. <https://www.fao.org/giahs/giahsaroundtheworld/designated-sites/europe-and-central-asia/barroso-agro-sylvo-pastoral-system/detailed-information/en/> (accessed 6.1.21)
- FAO - Food and Agriculture Organization of the United Nations, 2017. Water pollution from agriculture: a global review, FAO y IWMI.
- Ficklin DL, Luo Y, Luedeling E, Gatzke SE, Zhang M (2010) Sensitivity of agricultural runoff loads to rising levels of CO<sub>2</sub> and climate change in the San Joaquin Valley watershed of California. *Environ Pollut* 158:223–234. <https://doi.org/10.1016/j.envpol.2009.07.016>
- Fonseca AR, Santos JA (2019) Predicting hydrologic flows under climate change: the Tâmega Basin as an analog for the Mediterranean region. *Sci Total Environ* 668:1013–1024. <https://doi.org/10.1016/j.scitotenv.2019.01.435>
- Giri S, Lathrop RG, Obropta CC (2020) Climate change vulnerability assessment and adaptation strategies through best management practices. *J Hydrol* 580:124311. <https://doi.org/10.1016/j.jhydrol.2019.124311>
- GPP - Planning Policy and General Administration Office (2021) Relatório sobre o Plano Estratégico da PAC de 2021 (Report on the strategic plan of the Common agricultural policy) [WWW Document]. [https://www.gpp.pt/images/PEPAC/PEPAC\\_Submetido/PEPAC\\_30122021.pdf](https://www.gpp.pt/images/PEPAC/PEPAC_Submetido/PEPAC_30122021.pdf). Accessed 2.1.2021

- Gumiero B, Boz B, Cornelio P, Casella S (2011) Shallow groundwater nitrogen and denitrification in a newly afforested, subirrigated riparian buffer. *J Appl Ecol* 48:1135–1144
- ICNF – National Institute for Nature Conservation and Forests (2015) 6º Inventário Florestal Nacional (6th National Forest Inventory) [WWW Document]. URL <https://www.icnf.pt/api/file/doc/c8cc40b3b7ec8541>. Accessed 3.1.2020
- IPCC – Intergovernmental Panel on Climate Change (2013) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1535
- Iturbide M, Bedia J, Herrera S, Baño-Medina J, Fernández J, Frías MD, Manzanar R, San-Martín D, Cimadevilla E, Cofiño AS, Gutiérrez JM (2019) The R-based climate4R open framework for reproducible climate data access and post-processing. *Environ Model Softw* 111:42–54. <https://doi.org/10.1016/j.envsoft.2018.09.009>
- Karl TR, Nicholls N, Ghazi A (1999) Clivar/GCOS/WMO workshop on indices and indicators for climate extremes workshop summary. In: *Weather and Climate Extremes*. Springer, pp 3–7
- Leitão M, Cortez N, Pena SB (2013) Valor Ecológico do Solo de Portugal Continental (Soil Ecological Value of Mainland Portugal) [WWW Document]. <http://epic-webgis-portugal.isa.ulisboa.pt/> (accessed 11.1.18)
- Li Y, Shao X, Sheng Z (2016) Field experiments on reducing pollutants in agricultural-drained water using soil-vegetation buffer strips. *Polish J. Environ, Stud*, p 25
- Lionello P, Scarascia L (2018) The relation between climate change in the Mediterranean region and global warming. *Reg Environ Chang* 18:1481–1493. <https://doi.org/10.1007/s10113-018-1290-1>
- Maguire RO, Kleinman PJA, Dell CJ, Beegle DB, Brandt RC, McGrath JM, Ketterings QM (2011) Manure application technology in reduced tillage and forage systems: a review. *J Environ Qual* 40:292–301. <https://doi.org/10.2134/jeq2009.0228>
- Majone B, Avesani D, Zulian P, Fiori A, Bellin A (2022) Analysis of high streamflow extremes in climate change studies: how do we calibrate hydrological models? *Hydrol Earth Syst Sci* 26:3863–3883. <https://doi.org/10.5194/hess-26-3863-2022>
- Malagó A, Bouraoui F, Pastori M, Gelati E (2019) Modelling nitrate reduction strategies from diffuse sources in the Po River Basin. *Water (Switzerland)* 11. <https://doi.org/10.3390/w11051030>
- Mancuso G, Bencrediuto GF, Lavrić S, Toscano A (2021) Diffuse water pollution from agriculture: a review of nature-based solutions for nitrogen removal and recovery. *Water (switzerland)* 13:1–22. <https://doi.org/10.3390/w13141893>
- Molina-Navarro E, Andersen HE, Nielsen A, Thodsen H, Trolle D (2017) The impact of the objective function in multi-site and multi-variable calibration of the SWAT model. *Environ Model Softw* 93:255–267. <https://doi.org/10.1016/j.envsoft.2017.03.018>
- Molina-Navarro E, Trolle D, Martínez-Pérez S, Sastre-Merlín A, Jeppesen E (2014) Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. *J Hydrol* 509:354–366. <https://doi.org/10.1016/j.jhydrol.2013.11.053>
- Moriasi DN, Gitau MW, Pai N, Daggupati P (2015) Hydrologic and water quality models: performance measures and evaluation criteria. *Trans ASABE* 58:1763–1785. <https://doi.org/10.13031/trans.58.10715>
- Nkiaka E, Nawaz NR, Lovett JC (2018) Effect of single and multi-site calibration techniques on hydrological model performance, parameter estimation and predictive uncertainty: a case study in the Logone catchment, Lake Chad basin. *Stoch Environ Res Risk Assess* 32:1665–1682. <https://doi.org/10.1007/s00477-017-1466-0>
- Ockenden MC, Hollaway MJ, Beven KJ, Collins AL, Evans R, Falloon PD, Forber KJ, Hiscock KM, Kahana R, MacLeod CJA, Tych W, Villamizar ML, Wearing C, Withers PJA, Zhou JG, Barker PA, Burke S, Freer JE, Johnes PJ, Snell MA, Surridge BWJ, Haygarth PM (2017) Major agricultural changes required to mitigate phosphorus losses under climate change. *Nat Commun* 8. <https://doi.org/10.1038/s41467-017-00232-0>
- Panagos P, Ballabio C, Meusburger K, Spinoni J, Alewell C, Borrelli P (2017) Towards estimates of future rainfall erosivity in Europe based on REDES and WorldClim datasets. *J Hydrol* 548:251–262. <https://doi.org/10.1016/j.jhydrol.2017.03.006>
- Panagos P, Borrelli P, Meusburger K, Alewell C, Lugato E, Montanarella L (2015a) Land use policy estimating the soil erosion cover-management factor at the European scale. *Land Use Policy* 48:38–50. <https://doi.org/10.1016/j.landusepol.2015.05.021>
- Panagos P, Borrelli P, Meusburger K, Van Der Zanden EH, Poesen J, Alewell C (2015b) ScienceDirect Modelling the effect of support practices (P-factor) on the reduction of soil erosion by water at European scale. *Environ Sci Policy* 51:23–34. <https://doi.org/10.1016/j.envsci.2015.03.012>

- Panagos P, Meusburger K, Ballabio C, Borrelli P, Alewell C (2014) Science of The total environment soil erodibility in Europe : a high-resolution dataset based on LUCAS. *Sci Total Environ* 479–480:189–200. <https://doi.org/10.1016/j.scitotenv.2014.02.010>
- Pozza LE, Field DJ (2020) The science of soil security and food security. *Soil Secur* 1:100002. <https://doi.org/10.1016/j.soisec.2020.100002>
- Qiu J, Shen Z, Hou X, Xie H, Leng G (2020) Evaluating the performance of conservation practices under climate change scenarios in the Miyun Reservoir Watershed. *China Ecol Eng* 143:105700. <https://doi.org/10.1016/j.ecoleng.2019.105700>
- Ramião JP, Carvalho-Santos C, Pinto R, Pascoal C (2023) Hydropower contribution to the renewable energy transition under climate change. *Water Resour Manag* 37:175–191. <https://doi.org/10.1007/s11269-022-03361-4>
- Ramião JP, Carvalho-Santos C, Pinto R, Pascoal C (2022) Modeling the effectiveness of sustainable agricultural practices in reducing sediments and nutrient export from a river basin. *Water*. <https://doi.org/10.3390/w14233962>
- Rocha J, Roebeling P, Rial-Rivas ME (2015) Assessing the impacts of sustainable agricultural practices for water quality improvements in the Vouga catchment (Portugal) using the SWAT model. *Sci Total Environ* 536:48–58. <https://doi.org/10.1016/j.scitotenv.2015.07.038>
- Serpa D, Nunes JP, Keizer JJ, Abrantes N (2017) Impacts of climate and land use changes on the water quality of a small Mediterranean catchment with intensive viticulture. *Environ Pollut* 224:454–465. <https://doi.org/10.1016/j.envpol.2017.02.026>
- Shrestha MK, Recknagel F, Frizenschaf J, Meyer W (2016) Assessing SWAT models based on single and multi-site calibration for the simulation of flow and nutrient loads in the semi-arid Onkaparinga catchment in South Australia. *Agric Water Manag* 175:61–71. <https://doi.org/10.1016/j.agwat.2016.02.009>
- SNIAMB – National Environmental Information System (2018) Massas de água superficiais Rios de Portugal continental (surface water bodies rivers of mainland Portugal) [WWW Document]. <https://sniamb.apambiente.pt/> (accessed 11.1.18)
- Tereso J, Honrado J, Pinto A, Rego F (2011) Florestas do Norte de Portugal: História, Ecologia e Desafios de Gestão (Forests of Northern Portugal: History, Ecology and Management Challenges). InBio - Rede de Investigação em Biodiversidade e Biologia Evolutiva, Porto
- Tuppad P, Kannan N, Srinivasan R, Rossi CG, Arnold JG (2010) Simulation of agricultural management alternatives for watershed protection. *Water Resour Manag* 24:3115–3144. <https://doi.org/10.1007/s11269-010-9598-8>
- USGS - United States Geological Survey (2018) Shuttle radar topography mission 1 arc-second global [WWW Document]. <https://doi.org/10.5066/F7PR7TFT>. Accessed 5.1.2019
- Wagena MB, Collick AS, Ross AC, Najjar RG, Rau B, Sommerlot AR, Fuka DR, Kleinman PJA, Easton ZM (2018) Impact of climate change and climate anomalies on hydrologic and biogeochemical processes in an agricultural catchment of the Chesapeake Bay watershed, USA. *Sci Total Environ* 637–638:1443–1454. <https://doi.org/10.1016/j.scitotenv.2018.05.116>
- Wagena MB, Easton ZM (2018) Agricultural conservation practices can help mitigate the impact of climate change. *Sci Total Environ* 635:132–143. <https://doi.org/10.1016/j.scitotenv.2018.04.110>
- Wang Y, Bian J, Zhao Y, Tang J, Jia Z (2018) Assessment of future climate change impacts on nonpoint source pollution in snowmelt period for a cold area using SWAT. *Sci Rep* 8:2402. <https://doi.org/10.1038/s41598-018-20818-y>
- Winchell M, Srinivasan R, Di Luzio M, Arnold J (2013) ArcSWAT interface for SWAT2012. Res. Center, Texas AgriLife Res. Coll. Stn, Blackl
- Xu Y, Bosch DJ (2019) Meeting water quality goals by spatial targeting of best management practices under climate change 173–184. <https://doi.org/10.1007/s00267-018-01133-8>
- Zambrano-Bigiarini M (2014) hydroGOF: goodness-of-fit functions for comparison of simulated and observed hydrological time series. R package version 0.3-8. Zenodo [code] 10. <https://github.com/hzambbran/hydroGOF>

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