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ANALYSIS

Nature-based solutions or green taxes? Riparian buffers prevent eutrophication more effectively than taxes on fertilizers

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ABSTRACT

Nutrient pollution from agricultural activities deteriorates water quality, biodiversity, and ecosystem functioning of interconnected terrestrial, aquatic and marine ecosystems. There are many policy instruments aiming to reduce the impact of nutrient eutrophication. However, their effectiveness is seldom compared. We assessed the environmental and economic performance of two policy instruments for controlling phosphorus diffuse pollution from agriculture into riverine systems: the implementation of riparian vegetation buffers and a phosphorus fertilizer tax. We used a spatial explicit model and integrated economic analysis to compare the cost-effectiveness and equity of both interventions using a representative watershed within the Rio de la Plata freshwater system of South America. We found that riparian vegetation buffers achieve substantial reductions in phosphorus exports from land to freshwater systems (51–61%), while a phosphorus fertilizer tax yields only marginal environmental benefits (less than 1% reduction in phosphorus exports to water). This contrasting environmental outcomes translate into marginal abatement costs that are approximately two to three orders of magnitude lower for riparian buffers than for a phosphorus fertilizer tax. Building on this comparison, we then explored a combined policy scheme in which riparian buffers costs are compensated through the revenue generated by a phosphorus fertilizer tax. This hybrid approach preserves the environmental effectiveness of riparian vegetation buffers while improving distributional outcomes and feasibility by reducing the burden imposed on farmers located near watercourses. Our findings suggest that complementing regulatory measures with targeted environmental taxes can offer a balanced and politically feasible strategy for addressing nutrient pollution in agricultural and ecological ecosystems.

1. Introduction

Nutrient pollution by excessive nitrogen and phosphorus use has altered the functioning and composition of terrestrial, freshwater and marine ecosystems worldwide (Handoh and Lenton, 2003; Poore and Nemecek, 2018; Rabotyagov et al., 2014; Richardson et al., 2023). Agricultural activities are major sources of diffuse nutrient enrichment of water, often due to excessive fertilizer application, poor fertilizer management practices, and the absence of strategies to effectively retain nutrients in the soil (Mekonnen and Hoekstra, 2018). Agricultural food production is responsible for 38% of global ocean acidification and 78% of global terrestrial eutrophication (Poore and Nemecek, 2018). Regionally, eutrophication reduces drinking water quality increasing health risks (Aubriot et al., 2017; Barreto et al., 2017), and leads to profound changes on nutrient cycling and ecological interactions that are difficult to reverse (Akinnawo, 2023; Sedyaaw et al., 2024).

Reducing nutrient input from agricultural lands into freshwater systems can be achieved by the establishment of riparian buffer zones (Luna Juncal et al., 2023). Riparian buffer zones are areas of natural or planted vegetation along the banks of waterways that filter out nutrients, sediments, and pollutants from land surface runoff before they enter the waterbody (Hill, 2019; Wang et al., 2020). These buffer zones can be highly effective at intercepting and retaining nutrients, reducing nutrient loads in rivers, lakes, and estuaries by up to 80% (Cole et al.,

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2020). Beyond nutrient retention, riparian zones can generate additional co-benefits such as bank stabilization, biodiversity habitat, and carbon storage (Zaimes and Iakovoglou, 2021). Nevertheless, riparian areas are frequently degraded or fragmented in agricultural landscapes, suggesting that policies aimed at conserving and expanding buffer zones could play an important role in water-quality management and the provision of other important functions (Zaimes et al., 2011; Zaimes and Iakovoglou, 2021).

Promoting the conservation and expansion of riparian buffer zones can be achieved through regulatory or incentive-based approaches. Governments may mandate riparian buffers without compensation (hereafter referred to as the non-compensated scheme) or provide financial incentives to landowners to encourage their adoption. While mandatory implementation may seem an effective straightforward approach, it can unfairly place the financial burden solely on farmers near watercourses and undermine intrinsic motivations to address environmental problems (Bakx et al., 2024; Barnes et al., 2013; Buckley et al., 2012). In contrast, financial incentives can distribute costs more equitably and, if they are correctly designed, foster a greater sense of environmental stewardship (Ramsdell et al., 2016).

Despite their effectiveness in mitigating eutrophication, riparian buffer should not be considered an "end of pipe" solution, as their nutrient retention capacity may saturate over time (Cole et al., 2020). Therefore, other complementary strategies should address nutrient overuse at its source (Luna Juncal et al., 2023; Paarlberg et al., 2025). Fertilizer taxes – commonly referred to as green or Pigouvian taxes– represents one such strategy, aiming to reduce the excessive nitrogen and phosphorus application by increasing input costs and incentivizing more efficient use However, their design is critical as excessively high tax rates may overburden farmers, negatively affecting food production and trigger political resistance from the agricultural sector (Finger and Pedersen, 2025; Rougoor et al., 2001). At the same time, earmarking tax revenues –that is, assigning them to a specific use rather than the general budget– to finance mitigation measures enhance the legitimacy and political feasibility of the intervention (Finger and Pedersen, 2025; Söderholm and Christiernsson, 2008).

Riparian buffers and fertilizer taxes have each been extensively analyzed in the scientific literature as individual policy instruments (Cole et al., 2020; Danlami, 2014; Liu et al., 2020; Viaud et al., 2004). However, assessing them as alternatives or complementary interventions to reduce nutrient pollution in water systems has rarely been attempted (Liu et al., 2020). Here we aim to bridge that gap. In this paper, we analyze and compare the cost-effectiveness of non-compensated riparian buffer zones and green taxes on phosphorus fertilizers, considering both as alternatives or complementary policy interventions to reduce nutrient pollution in agricultural watersheds. While both measures can reduce nutrient export to water, they differ in effectiveness and distributional impacts: non-compensated buffers concentrate the burden on farmers near waterways, whereas taxes distribute it among all fertilizer users across the watershed and may induce broader behavioral change (Bakx et al., 2024; Falconer, 1998; Goulder and Parry, 2008; Shortle and Horan, 2001).

Given the generally low price elasticity of fertilizer demand, we hypothesize that phosphorus fertilizer taxes may have more limited environmental effects than non-compensated riparian buffers (Al Rawashdeh, 2023; Lehtonen et al., 2008; Quddus et al., 2008). We further examine a policy design that uses fertilizer tax revenues to finances riparian buffers. Earmarking environmental tax revenues has been widely discussed as a strategy to improve the effectiveness, political acceptability by reinvesting funds in environmental protection measures rather than absorbed into general budgets (Carattini et al., 2018; Kallbekken and Sælen, 2011; Oates, 1995), and has been applied in water quality management support nutrient abatement and watershed protection (OECD, 2001; Söderholm and Christiernsson, 2008). Building on these experiences, this paper evaluates the effectiveness of using fertilizer taxation to finance riparian buffers in an agricultural watershed affected by diffuse nutrient pollution. We hypothesize that combining these instruments can reduce agricultural nutrient exports more effectively than each of them separately (Ewald et al., 2022), while improving the feasibility and long-term sustainability of buffer implementation through a stable funding mechanism.

2. Materials and methods

We used an integrated assessment model that combines the Soil and Water Assessment Tool (SWAT) with a phosphorus fertilizer demand function and economic secondary data. This approach enables us to assess the combined impact of the P fertilizer tax and riparian buffers on environmental outcomes. Below we describe in detail the main features of our methodological approach.

2.1. Study area

We applied the integrated assessement model (IAM) to a selected area within the Rio de la Plata, one of the largest estuaries in the world, with a drainage basin approximately 17% of South America's surface (Perillo et al., 1999). We selected one sub-basin of the Santa Lucía River catchment (Aguas Corrientes watershed) located in the southern part of Uruguay, which is composed of two main rivers: the Santa Lucía and the Santa Lucía Chico (Fig. 1). This watershed covers an area of 9090 km^2 and encompasses four administrative units (San José, Florida, Canelones, and Lavalleja). This region is particularly important because the drinking water treatment plant –located at the watershed outlet– supplies fresh water to more than 50% of Uruguay's population (Achkar et al., 2014).

The region faces increasing nitrogen and phosphorus loads in the water caused by diffuse sources associated with current and past land use and agricultural practices (Barreto et al., 2017; Gorgoglione et al., 2020). The upper part of the basin is dominated by grassland-based production, primarily extensive cattle ranching, whereas the lower part, closer to the main watercourses, is characterized by agriculture and dairy farming, which involve more intensive land use and higher input requirements (Fig. 2). This pattern contributes to nutrient enrichment and eutrophication of water bodies, leading to recurrent algae and cyanobacteria blooms that are perceived as a serious problem for both freshwater and marine systems (Ciganda et al., 2024). In, 2013, a severe algae bloom triggered public alarm and prompted governmental institutions to implement an action plan with 12 measures to control and reduce nutrient pollution in the Santa Lucia River Basin (MVOTMA, 2013, MVOTMA, 2015).

One of the measures in this action plan, "Measure 8," involves establishing mandatory riparian buffer zones along major watercourses without any compensation. This measure designates 6436 ha for buffer strips where vegetation modification, land tillage, and agrochemical use are prohibited (MVOTMA, 2015). The buffer strips vary in width from 35 to 100 m, depending on the specific watercourse. In, 2018, the government proposed expanding Measure 8 to include smaller tributaries, but this proposal has not yet been enforced.

Riparian buffer zones in the Santa Lucía catchment present a diverse mosaic of land uses and vegetation cover types. A recent study characterizing riparian interfaces -defined as the area between 100 and 500 m from the watercourse centerline depending on stream order- reveals that these zones are composed of natural vegetation, cultivated areas, and artificial covers (Mary-Lauyé et al., 2023). Natural covers, which are the desired land cover under "Measure 8" of the national action plan, account for 68% of the riparian area in this region, slightly lower than the national average of 75%. Within these natural areas, herbaceous natural vegetation (natural grasslands) covers 40%, native forests represent 21%, wetlands cover 3%, and shrublands 1%. Cultivated areas, which include croplands, forest plantations, and fruit plantations, occupy 30% of the riparian zones in the Santa Lucía basin –significantly higher than the national mean of 22%– reflecting the region's intense agricultural

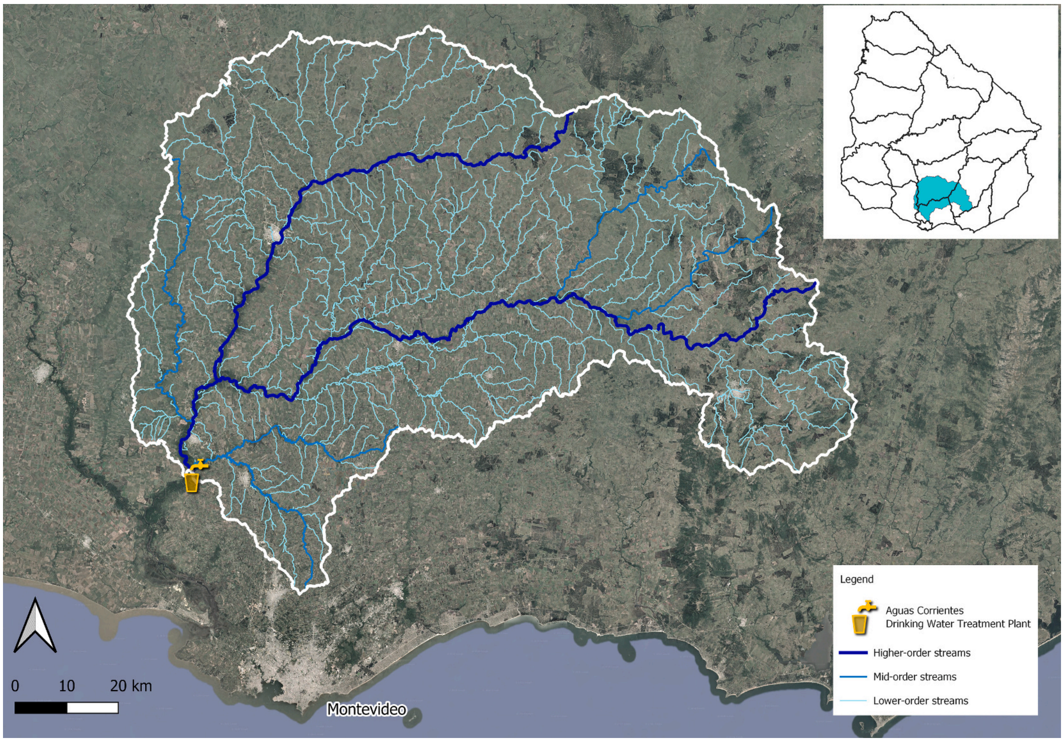

Fig. 1. Study area and hydrological context of the Santa Lucía River basin. The figure shows the location of the study area in Uruguay, including the boundary of the Santa Lucía watershed, major rivers, secondary tributaries, and lower-order streams. The location of the Aguas Corrientes drinking water treatment plant is indicated at the downstream outlet of the watershed.

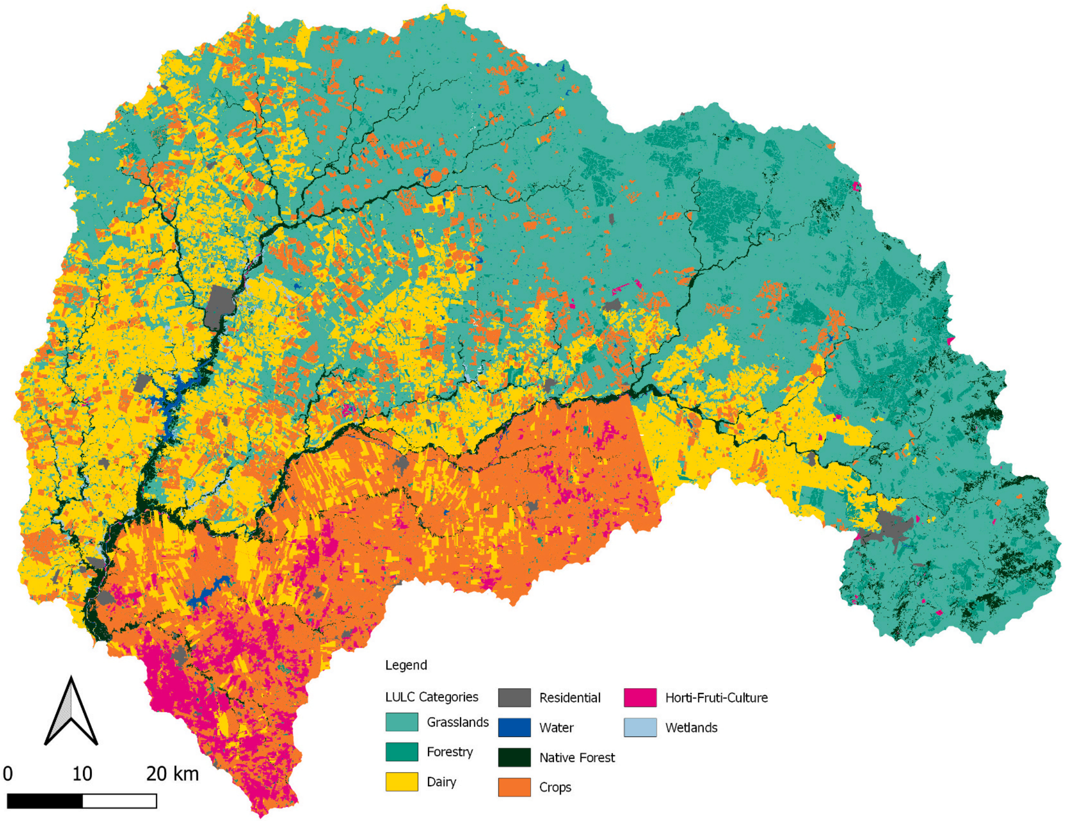

Fig. 2. Land use and land cover distribution within the study area. The map shows the spatial distribution of major land use and land cover categories across the study area. Grasslands dominate the upper catchment, where land use is primarily associated with extensive cattle grazing. In contrast, the middle and lower sections of the basin are characterized by more intensive land uses, including cropland and dairy systems, which are typically associated with higher fertilizer application rates and nutrient exports.

use. Artificial covers, including urban areas, artificial waterbodies, and quarries, constitute the remaining 2%.

2.2. Assessing the effect of riparian buffer zones

We used the Soil and Water Assessment Tool (SWAT) to assess the effects of riparian buffer zones on nutrient exports from agricultural lands into adjacent riparian systems. SWAT is a hydrologic and water quality model that simulates the effects of land use and land management practices on water, sediment, and nutrient yields across watershed of varying size and complexity (Neitsch et al., 2011; Vigerstol and Aukema, 2011). The model is based on a set of physical and mathematical equations that describe the movement of water, sediment, and chemical constituents through the watershed, considering factors such as climate, topography, soils, land use, and management practices. SWAT can be used to quantify the impacts of different land use and management scenarios on water quality and quantity, as well as on crop yields. It is a widely used tool in the field of hydrology, agronomy, and environmental sciences. It has been used to evaluate the trade-offs between different land use and management options, to identify the most sustainable and cost-effective strategies for managing water resources, and to identify the potential impact of climate change on water resources. As of 2024, a total of 6562 scientific articles using the SWAT model have been published (Gassman et al., 2024).

SWAT's ability to simulate vegetation dynamics, soil interactions, and hydrological pathways, allows for a detailed assessment of how different riparian buffer configurations influence water quality parameters (Jiang et al., 2020; Lee et al., 2020; Moon et al., 2013). This tool can therefore be used to quantify both the reduction in nutrient exports, as they are retained by riparian vegetation and soils, and to estimate changes in nutrient concentrations downstream, providing insights into the buffering capacity of riparian zones in maintaining water quality. In summary, SWAT can elucidate the extent to which riparian buffers mitigate sediment transport and nutrient exports to water bodies. In this paper, we focus on the buffer capacity to reduce phosphorus exports at the watershed level. We specifically assessed phosphorus pollution since it is considered a critical limiting factor for algal growth and has been identified as a major issue in the Santa Lucia basin (Aubriot et al., 2017; Bennett et al., 2009; Schindler, 1977).

The SWAT model was calibrated using site-specific data from official national sources, including topography, climate, land use, soil characteristics, agricultural practices, and water quality indicators. For variables with limited data availability, a soft calibration approach was applied, drawing on national expert consultation and literature review. Observed data from six streamflow and five water quality monitoring stations were used to validate the model's performance in simulating hydrology, agricultural productivity, and nutrient concentrations. Model accuracy was assessed using standard performance metrics, including the Nash–Sutcliffe Efficiency (NSE), Kling–Gupta Efficiency (KGE), and Percent Bias (PBIAS), all of which met commonly accepted thresholds. A detailed description of the SWAT model calibration used in this paper can be found in Appendix A and in Mer et al. (2019).

Among the available methods to model riparian buffers using the SWAT model, we selected the vegetative filter strip (VFS) approach. This method simulates the effect of natural buffer vegetation in slowing runoff, allowing sediment and nutrient deposition before reaching water bodies (Lee et al., 2020; Neitsch et al., 2011). Compared to the simpler FILTERW method and the more complex REEM–SWAT coupling, VFS offers a practical balance between flexibility and simplicity (Ghimire et al., 2021; Ryu et al., 2011). Compared to FILTERW the VFS approach allows sub-watershed-level parameterization and is particularly effective for assessing the benefits of expanding buffer zones, aligning with our focus on evaluating buffer width rather than specific vegetation types or management practices. The VFS algorithm represents nutrient retention through removal efficiencies applied to surface runoff loads at each simulation time step, thereby accounting for within-period retention processes. However, it does not explicitly simulate cumulative nutrient accumulation or long-term saturation dynamics that could alter removal efficiency over time (White and Arnold, 2009).For readers interested in the technical aspects of the model configuration and parameters, detailed information is provided in Appendix A.

The effectiveness of riparian buffer and P fertilizer tax options is measured as reductions in phosphorus loads at the catchment level. Phosphorus loads are quantified as total subbasin inputs to the channel network, representing aggregated nutrient contributions from all Hydrologic Response Units (HRUs) prior to in-stream retention and transformation processes simulated by SWAT (Gassman et al., 2007; Neitsch et al., 2011).

2.3. Assessing the environmental impacts of phosphorus fertilizer taxation

The environmental effectiveness of a fertilizer tax depends on two key aspects. First, it hinges on how the tax affects fertilizer demand and application rates at farms. Second, it depends on the biophysical behavior of fertilizers in the soil and their transport through the landscape toward water bodies.

On the demand side, fertilizer taxes can reduce nutrient use through three main mechanisms: (i) the intensive margin, as farmers adjust application rates within existing cropping systems; (ii) the extensive margin, as land-use decisions shift in response to the relative cost of fertilizer-intensive activities; and (iii) the super-intensive margin, as farmers adopt more efficient fertilization technologies to lower input costs while maintaining productivity (Möhring et al., 2020). The magnitude of these responses varies across farmers, depending on production type (e.g., crops, pastures, fruit plantations), farm characteristics (e.g., size, technology, soil quality), and individual preferences (Pedersen et al., 2020). Although these mechanisms often interact and are difficult to disentangle in practice, their combined effect can be estimated using the price elasticity of demand for fertilizers. Elasticity of demand quantifies the responsiveness of fertilizer use to changes in fertilizer prices, measured as the percentage change in use resulting from a 1% change in fertilizer price (Pindyck and Rubinfeld, 2013).

On the biophysical side, reductions in fertilizer application do not necessarily lead to proportional decreases in water pollution. This is because the ultimate impact on nutrient loads is mediated by a range of biophysical processes that determine the fate and transport of nutrients from agroecosystems into water bodies. Key factors include soil properties, vegetation cover, topography, and the presence of riparian buffers or other nature-based solutions, all of which influence the retention, transformation, and movement of nutrients through runoff and leaching pathways (Lyu et al., 2021; Sharpley et al., 2013).

To manage this complexity, the analysis adopts a simplified approach. It assumes that farmers are homogeneous and all reduce fertilizer use by the same proportion—meaning they all reduce phosphorus fertilizer doses by the same proportion, as determined by the modeled tax and the estimated general price elasticity of demand. This assumption is consistent with both the watershed-scale focus of the analysis and the structure of the SWAT model, which represents average management practices by land use rather than individual farm-level decisions, allowing fertilizer application changes to be estimated using a general demand curve across the land-use map (Gassman et al., 2007). The resulting variation in fertilizer use is then incorporated into the SWAT model by adjusting phosphorus fertilizer input values (see Appendix A for more detailed information). This enables the model to simulate nutrient transport across the landscape, accounting for key biophysical characteristics such as soil properties, topography, and the presence of riparian buffer zones.

2.3.1. Phosphorus fertilizer demand function

To assess the effect of alternative phosphorus (P) fertilizer tax levels, it is necessary to estimate the price elasticity of demand for phosphorus fertilizers. Following a standard practice in the literature, fertilizer demand is represented using an isoelastic demand function, which allows the direct interpretation of the estimated price coefficient as a constat elasticity within the relevant range of prices and quantities (Pindyck and Rubinfeld, 2013). The general isoelastic demand function for phosphorus fertilizers is defined as:

$$Q_t = A.{P_t}^b.{X_t}^c$$

Where:

Q_t is the quantity or demand for fertilizer.

A is a constant >0.

P_t is the price of fertilizer.

X_t represent other explanatory variables such as price and/or production of agricultural commodities, income, and others. Taking the natural logarithm on both sides gives us an easy equation to handle econometrically.

$$ln(Q_t) = ln(A) + b.ln(P_t) + c.ln(X_t)$$

Moreover, the elasticity associated with eq. (3) is expressed as

$$\frac{\partial ln(Q_t)}{\partial ln\ (P_t)} = b = E_p$$

In this specification, the coefficient b directly represents the price elasticity of demand for phosphorus fertilizer (E_p). Empirical evidence consistently shows that demand of phosphorus as price inelastic, with elasticity values typically lying in the range $-1 < E_p < 0$. For example, reported phosphorus fertilizer demand elasticities range from -0.24 to -0.48 at the farm and national levels (Liu et al., 2020; Quddus et al., 2008) and are even lower in global estimates (Al Rawashdeh, 2023). This evidence anticipates that a green tax on P fertilizer need to be substantial to achieve meaningful reductions in fertilizer use.

Nevertheless, despite the relative high taxes rates required to influence fertilizer use, fertilizer taxes offer several advantages, including low administrative costs and the potential to generate revenue (Söderholm and Christiernsson, 2008; UNEP, 2020).

2.4. Data and econometric approach

Due to the absence of farm-level microdata for the region under study, our approach involves deriving elasticity estimates through a time-series model at the national level. Fertilizer consumption is measured as agricultural use of phosphorus fertilizer expressed in P_2O_5 (tons per year), while fertilizer prices are proxied by the average import price of phosphorus fertilizers (USD per ton). The dataset of observed historical data covering the period 1961–2020 and is compiled from (FAO, 2024) and (UN Comtrade, 2023) respectively.

Following standard practice, and previous studies (Al Rawashdeh, 2023; Quddus et al., 2008), we first use an Ordinary Least Squared (OLS) approach, including explanatory variables, such as crop prices, cultivated area and crop harvest. However, diagnostic tests revealed the presence of autocorrelation in the residuals, making this approach unsuitable (see Appendix B). Unit root tests indicated that the variables are integrated of mixed order, motivating the use of the Autoregressive Distributed Lag (ARDL) (Davidson and MacKinnon, 1993; Johnston and Dinardo, 1997; Pesaran and Shin, 1999).

Although ARDL models have been less commonly applied to estimate fertilizer demand elasticities, they have been extensively used to estimate price and income elasticities in other contexts with similar data constraints. In particular, the energy economics literature has applied on ARDL models with annual time-series data to estimate short- and long-run price elasticities for crude oil and electricity demand (Altinay, 2007; Sultan, 2010), supporting the suitability of this approach for elasticity estimation in contexts with limited data availability. The final econometric model specified in eq. (4)

$$ln\ Q_t = \alpha + \delta.ln\ Q_{t-1} + \beta.ln\ P_{t-1} + \varepsilon_t$$

where the dependent variable ($ln\ Q_t$) is the natural logarithm of agricultural use of nutrient phosphorus at the year t, and the explanatory variables are the natural logarithm of agricultural use of nutrient phosphorus at the year t-1 ($ln\ Q_{t-1}$) and the natural logarithm of the average import price of phosphorus fertilizers in the year t-1 ($ln\ P_{t-1}$). The error term for the year t (ε_t) captures the unobserved influences on fertilizer demand. The parameters α, β and δ are estimated econometrically, with β interpreted as the phosphorus fertilizers demand price elasticity. All estimations were conducted using Stata 17, employing robust standard errors where appropriate.

2.5. Integrated assessment model workflow

We combine the price elasticity of phosphorus fertilizer demand with the SWAT model to assess the cost-effectiveness of three policy schemes: (i) a Riparian Buffer Regulation (non-compensated), (ii) a Phosphorus Fertilizer Tax, and (iii) a Hybrid Policy (tax-funded riparian buffers). The analysis focuses on the economic burden these measures place on farmers in the study basin. For Riparian Buffer Regulation, we estimate the opportunity costs associated with setting aside land, while for the Phosphorus Fertilizer Tax, we evaluate the financial burden resulting from the increased cost of inputs.

The strategy we use to compare the cost-effectiveness of both alternative interventions is to assess the costs of Riparian Buffer Regulation for farmers, identify a tax rate that imposes a comparable economic burden, and compare both measures in terms of nutrient exports reduction and cost-effectiveness. An alternative strategy would be to compare both interventions based on achieving the same level of pollution reduction. This would involve assessing the impact of riparian buffers first and then selecting a tax rate that achieves an equivalent reduction in nutrient pollution. We chose to start with the first approach (assessing the impact of both measures given a comparable economic burden), and depending on the results, explore the latter. As it turns out, we later find that equaling the impact would require impractically high taxes, as discussed in Appendix C.

Based on these initial considerations, we establish a six-step workflow, summarized in Fig. 3. A brief overview is presented below; however, for a comprehensive description of the methodology, we refer the reader to Appendix C.

Step 1: We define three Riparian Buffer Regulation policy options, varying buffer width and location, compared to a baseline without riparian buffers implementation. These options are based on the regulatory framework established by the Santa Lucía Basin Action Plan and its proposed expansion (GNA and SNA, 2018). As depicted in Fig. 4, Option 1 corresponds to Measure 8 of the Action Plan; Option 2 represents an intermediate expansion; and Option 3 reflects the full extension proposed in, 2018.

Step 2: For the cost estimation, we focus on the opportunity cost of converting agricultural and livestock land uses into riparian buffers, excluding existing native forests cover which is already protected by law. We also consider fencing costs where livestock exclusion is necessary. We estimate opportunity costs using land use data (DIEA, 2021; MGAP, 2018) and rental values, while we annualize fencing costs over 7.5 years based on local market rates and discount rates (Balian et al., 2018). We assume passive regeneration of riparian vegetation, whereby riparian buffers establish naturally once land is excluded from production, without active planting or management. This approach is consistent with widely applied riparian restoration practices (Benayas et al., 2009; Sweeney and Newbold, 2014).

Step 3: As previously described, we determine the tax rate so that the total financial burden imposed on farmers is equivalent to the opportunity and fencing costs associated with riparian buffer implementation. The burden-equivalent phosphorus fertilizer tax rate was calculated using Excel's Goal Seek function. We therefore refer to Phosphorus Fertilizer Tax Option 1, 2, and 3 as the tax rates that generate a total

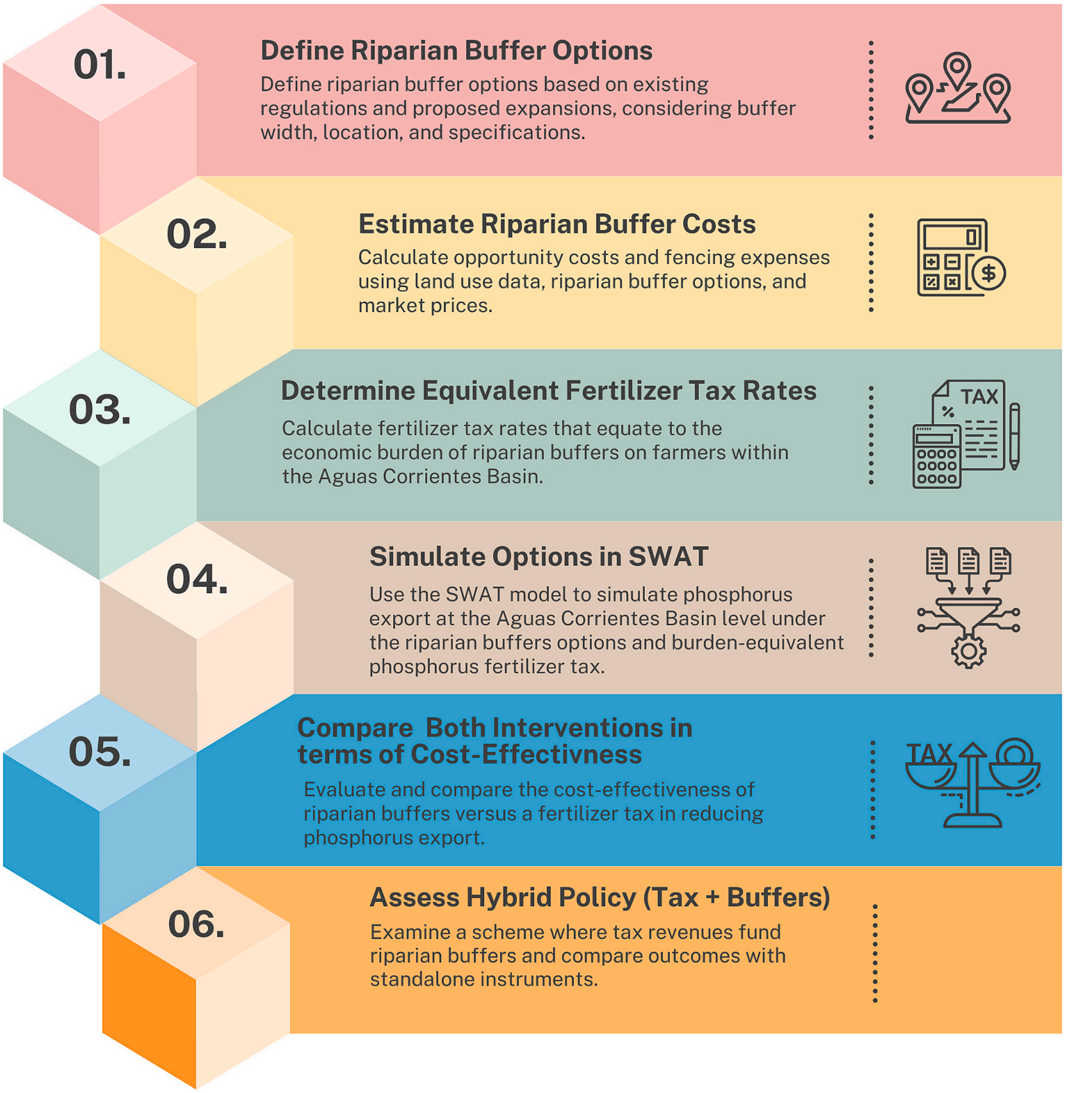

Fig. 3. Six-step methodological workflow used to compare alternative and complementary Riparian Buffer Regulation and Phosphorus Fertilizer Tax policy options.

financial burden equal to that of Riparian Buffer Regulation Option 1, 2, and 3, respectively.

Step 4: We simulate the effectiveness of the Riparian Buffer Regulation and Phosphorus Fertilizer Tax options in reducing phosphorus exports at the catchment scale using the SWAT model. We model the riparian buffer effectiveness by adjusting the Vegetative Filter Strip (VFS) parameters and simulate the impact of the P fertilizer tax by modifying fertilizer application rates in SWAT according to the estimated tax effects.

Step 5: We compare both interventions in terms of phosphorus export reduction and marginal abatement cost, providing insights into the relative cost-effectiveness of Riparian Buffer Regulation and a Phosphorus Fertilizer Tax under comparable economic burdens.

Step 6: We assess a Hybrid Policy scheme in which phosphorus fertilizer tax revenues finance riparian buffer costs for farmers. Revenues are redistributed as lump-sum payments (or tax credits) to landowners implementing buffers, fully covering opportunity and fencing (exclusion) costs. We assume no transaction costs, implying full and frictionless redistribution of revenues. We simulate this scheme in SWAT and compare its environmental effectiveness and distributional outcomes with standalone instruments.

2.6. *Suitability of phosphorus fertilizer tax as a funding mechanism for riparian buffers*

While effectiveness and cost-effectiveness are key criteria in assessing the suitability of a policy, as discussed in the previous section, there are other relevant considerations to determine policy success, such as social acceptability, administrative feasibility, and distributive and ethical implications (Falconer, 1998; Finger and Pedersen, 2025; Kallbekken and Sælen, 2011). This section compares two policy approaches that differ in the allocation of responsibilities and costs. One relies on mandatory, non-compensated riparian buffer implementation, while the other combines a uniform P fertilizer tax with a revenue-recycling scheme to fund riparian buffers.

The relative suitability of these two approaches is assessed by examining two main aspects: (i) impacts on food production, and (ii) distributional effects across farmers. The analysis combines results from the empirical case study with a qualitative assessment grounded in the environmental economics literature, providing a comprehensive evaluation of policy suitability beyond cost-effectiveness alone.

We assess the impact on food production by analyzing changes in land use and potential yield losses resulting from reduced fertilizer application following the introduction of the tax. Crop yield variations resulting from reduced fertilizer application are estimated using crop growth and yield algorithms embedded in the SWAT model.

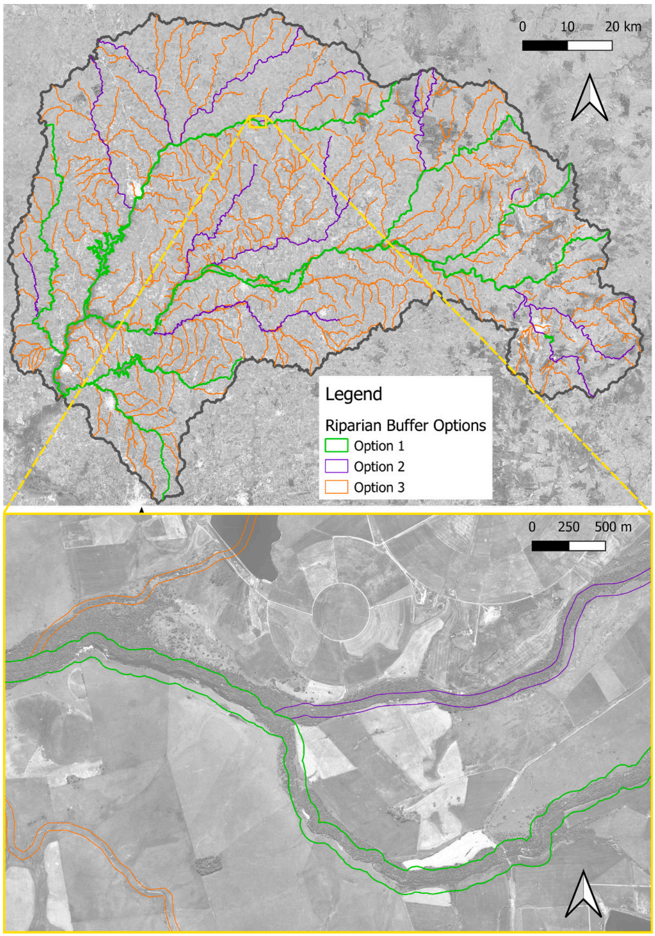

Fig. 4. Alternative riparian buffer options evaluated in the study. The figure illustrates three riparian buffer extension options based on stream order. Option 1 includes riparian buffers along high- and mid-order streams only. Option 2 builds on Option 1 adding mid-order streams and part of lower-order streams. Option 3 builds on Option 2 and extends riparian buffers to include all lower-order streams across the catchment.

Distributional effects are analyzed at the level of Rural Property Units (RPUs) using official cadastral data, treating each RPU as an individual production bearing the costs of intervention. Using QGIS geometry algorithms, we identify the RPUs affected under each scheme and estimate the corresponding cost per property. Further details on the calculation procedures are provided in Appendix D. We further asses distributional effects by land use type. Affected RPUs are classified according to their dominant land use (cropping, dairy, grasslands, forestry, and horticulture), and for each policy option we calculate the share of total affected area by category see Appendix D. This allow us to compare how the financial burden is allocated across production systems with different expected contributions to nutrient pollution.

3. Results

3.1. Phosphorus fertilizer demand price elasticity

Table 1 presents the estimation results of the ARDL model described in Section 2.3.1, based on 58 annual observations.

The coefficient on the lagged quantity of phosphorus fertilizer use is positive and statistically significant ($\delta = 0.375, p < 0.01$), indicating persistence in fertilizer consumption over time. This suggests that current fertilizer use is partly determined by past use levels.

Table 1
Results of the autoregressive distributed lag model estimating phosphorus fertilizer demand.

Variable	Coefficient	Robust Std. Error	t-statistic	*p*-value
$ln\ Q_{t-1}$	0.3750	0.1073	3.58	0.001
$ln\ P_{t-1}$	−0.3384	0.1128	−3.00	0.004
α	4.7590	1.0059	4.73	0.000

Note: The dependent variable is the natural logarithm of agricultural phosphorus fertilizer use (P_2O_5). Robust standard errors are reported to account for heteroskedasticity. The estimated coefficient on the lagged fertilizer price represents the short-run price elasticity of phosphorus fertilizer demand. Number of observations = 58. Adjusted R^2 = 0.42.

The coefficient on the lagged fertilizer price is negative and statistically significant ($\beta = -0.34, p < 0.01$). This coefficient represents the short-run price elasticity of demand for phosphorus fertilizers, implying that a 1% increase in fertilizer prices leads to an average reduction of approximately 0.34% in fertilizer use in the subsequent period. The estimated elasticity confirms that phosphorus fertilizer demand is price inelastic.

Overall model performance is satisfactory, with an adjusted R^2 of 0.42. Diagnostic tests reported in Appendix B indicate no evidence of residual autocorrelation, while heteroskedasticity was addressed through the use of robust standard errors.

3.2. Riparian buffer regulation vs phosphorus fertilizer tax

We found that as riparian buffer implementation expands, both the total area covered and the associated costs increase substantially across the three options considered. In Option 1, buffers cover 3289 ha (0.4% of the basin), with an average annual burden of USD 570,000. Option 2 extends the buffer area to 5639 ha (0.6%), raising the annual burden to USD 966,000. Option 3, which represents the most ambitious implementation, covers 19,088 ha (2.1%) and results in an annual burden of USD 3.69 million. These results show that large-scale implementation significantly amplifies the financial demands, particularly through higher opportunity and cattle exclusion costs (see Table 2).

The phosphorus fertilizer tax rates required to generate a financial burden equivalent to the costs of riparian buffer implementation are:

- **Option 1**: 0.7% tax rate (equivalent to USD 570,000/year)
- **Option 2**: 1.1% tax rate (equivalent to USD 966,000/year)
- **Option 3**: 4.4% tax rate (equivalent to USD 3.69 million/year)

Table 2
Riparian buffer characteristics, costs, and equivalent phosphorus fertilizer tax rates for the three options considered.

Variable	Option 1	Option 2	Option 3
Riparian buffer area (ha)	3289	5639	19,088
% of Aguas Corrientes Basin area	0.4%	0.6%	2.1%
Opportunity costs (thousand USD year^{-1})	421	669	2283
Opportunity cost ha^{-1} (USD ha^{-1} year^{-1})	128	119	120
Perimeter (Km)	1661	2692	8932
Cattle exclusion costs (thousand USD year^{-1})	149	296	1411
Average burden of intervention (thousand USD year^{-1})	**570**	**966**	**3694**
Burden equivalent phosphorus fertilizer tax (%)	**0.7%**	**1.1%**	**4.4%**

Note: Each option corresponds to a different spatial extent of riparian buffer implementation based on stream order, with increasing buffer coverage from Option 1 to Option 3. The equivalent phosphorus fertilizer tax rate represents the uniform tax required to generate the same total annual burden as riparian buffer implementation under each option.

The results obtained from the SWAT model simulations reveal a clear contrast in the effectiveness of the two interventions: Riparian Buffer Regulation achieves substantial reductions in phosphorus exports to water at significantly lower costs per unit of phosphorus abated, while the Phosphorus Fertilizer Tax is markedly less effective as a standalone mitigation measure. The results are summarized in Table 3.

Riparian buffers resulted in substantial reductions in phosphorus exports across all options. As buffer areas expanded from 3289 ha in Option 1 to 19,088 ha in Option 3, phosphorus exports decreased by 51%, 52%, and 61%, respectively, compared to the baseline. The associated marginal abatement costs ranged from USD 412 per ton in Option 1 to USD 2202 per ton in Option 3, reflecting declining marginal effectiveness of nutrients captures -the nutrient capture increases ten percentual points (51% to 61%) while the area increases between five and six-fold.

In contrast, the Phosphorus Fertilizer Tax led to only modest environmental improvements. Despite increasing tax rates –0.7% in Option 1, 1.1% in Option 2, and 4.4% in Option 3— fertilizer demand declined by just 0.2% to 1.6%, resulting in phosphorus export reductions of less than 0.6% vs baseline. The marginal abatement costs for the tax were markedly higher, ranging from USD 464,348 to USD 252,889 per ton of phosphorus export reduced.

When the Hybrid Policy Scheme (tax-funded riparian buffers) was implemented under Option 3, phosphorus exports decreased to 1050 ton/year, representing a total reduction of 1683 ton/year (−61.6%) (see Table 4). The combined reduction was marginally smaller than the sum of the individual effects, suggesting limited synergistic or additive benefits in terms of nutrient export from the simultaneous implementation of both interventions.

3.3. *Feasibility of an phosphorus fertilizer tax*

The feasibility analysis reveals that using a fertilizer tax as a funding mechanism to finance riparian buffers has a modest impact on food production. It also reduces the financial burden on individual landowners adjacent to watercourses by distributing the cost more broadly across the agricultural sector.

As shown in Table 5, the phosphorus fertilizer tax applied under Option 3 (4.4%) reduced yields across all crops. Pasture showed the largest decline (0.57% in annual biomass yield), while yield changes for grass, soybean, corn, and wheat were all below 0.1%.

Regarding distributional effects across farmers, Table 6 shows that the Riparian Buffer Regulation concentrates the intervention's burden on a smaller group of landowners, resulting in higher average annual costs per RPU—rising from USD 259 in Option 1 to USD 372 in Option 3. In contrast, under the Hybrid Policy scheme, the burden is shared across over 28,000 RPUs, with average contributions ranging from USD 20 to USD 131. The cost per hectare follows a similar pattern, dropping from USD 6.9 in Option 3 in the Riparian Buffer Regulation to USD 5.9 under the Hybrid Policy scheme. These results indicate that the Hybrid Policy scheme spreads the burden more widely, reducing the financial impact on individual landowners.

Table 4
Phosphorus export reductions under alternative policy interventions for the most extensive riparian buffer option (option 3), relative to the baseline.

Intervention	Phosphorus (P) Exports Option 3 (Ton/Year)	Reductions vs. Baseline	% variation
Riparian Buffers	1055	−1677	−61.4%
P fertilizer Tax	2718	−15	−0.5%
Riparian Buffers + P fertilizer Tax	1050	−1683	−61.6%

Note: Results correspond to the most extensive riparian buffer option. Baseline phosphorus exports are 2732 t year^{-1}. The combined intervention reflects the simultaneous implementation of riparian buffers and the phosphorus fertilizer tax calibrated to the same economic burden.

Table 5
Crop yields under baseline conditions and under the phosphorus fertilizer tax for Option 3 (tax rate = 4.4%), and percentage change relative to baseline.

Crop	Baseline (t ha^{-1})	Option 3 (t ha^{-1})	Change vs. baseline (%)
Corn	3040	3040	−0.02%
Soybean	3561	3560	−0.03%
Wheat	2224	2223	−0.02%
Sorghum	3173	3170	−0.08%
Oats	1643	1642	−0.05%
Pasture*	6746	6707	−0.57%

Note: Results correspond to the phosphorus fertilizer tax calibrated to match the economic burden of the most extensive riparian buffer implementation (Option 3). Pasture yield is expressed in terms of annual dry matter production, while crop yields are expressed as harvested grain.

In terms of land use across production systems (Table 7), the Riparian Buffer Regulation places a larger share of the burden on grassland areas (up to 52% in Option 3). In contrast, the Hybrid Policy scheme shifts the burden toward cropping, dairy, and horticulture –land uses more closely associated with phosphorus pollution than grasslands. Under this scheme, crop land accounts for 30% of the affected area, dairy for 32%, and horticulture for 5%, compared to lower shares under the non-compensated scheme.

4. Discussion

We found that the (non-compensated) Riparian Buffer Regulation is a significantly more effective intervention than a Phosphorus Fertilizer Tax in reducing diffuse nutrient pollution to watercourses. The modeled Riparian Buffer Regulation options yielded phosphorus export

Table 3
Comparison of riparian buffer and phosphorus fertilizer tax options relative to the baseline.

Metric	Baseline	Option 1	Option 2	Option 3
Average burden of intervention (thousand USD year^{-1})	**–**	**570**	**966**	**3.694**
Riparian Buffers				
Buffer area (ha)	–	3289	5639	19,088
Phosphorus (P) exports (t year^{-1})	2732	1349	1315	1055
Δ P exports vs baseline (%)	–	−51%	−52%	−61%
Marginal abatement cost of Riparian Buffers (USD/ t of P export reduced)		**412**	**681**	**2202**
P fertilizer tax				
P fertilizer tax rate (%)	–	0.7%	1.1%	4.4%
P fertilizer demand change after tax (%)	–	−0.2%	−0.4%	−1.6%
Phosphorus exports after tax (t year^{-1})	2732	2731	2729	2718
Δ P exports vs baseline (%)	–	0.0%	−0.1%	−0.5%
Marginal abatement cost of P Fertilizer Tax (USD/ t of P export reduced)		**464,348**	**259,298**	**252,889**

Note: Options 1–3 correspond to increasing spatial extents of riparian buffer implementation based on stream order. For each option, the phosphorus fertilizer tax rate is calibrated to generate the same total annual economic burden as riparian buffer implementation. Baseline values represent current conditions without additional policy intervention.

Table 6

Distribution of costs across rural properties under non-compensated riparian buffers and phosphorus fertilizer tax–funded buffer alternatives.

	Number of payers (Rural Property Units)	Average burden per payer (USD per Rural Property Unit)	Agricultural area of payers (ha)	Average burden per ha (USD ha^{-1})
Riparian Buffer Regulation (non-compensated)				
Option 1	2203	259	121,913	4.7
Option 2	3434	281	215,920	4.5
Option 3	9933	372	535,434	6.9
Hybrid Policy (tax-funded riparian buffers)				
Option 1	28,182	20	621,390	0.9
Option 2	28,182	34	621,390	1.6
Option 3	28,182	131	621,390	5.9

Note: Options 1–3 correspond to increasing spatial extents of riparian buffer implementation based on stream order. Under the Hybrid Policy scheme, all Rural Property Units with agricultural land contribute to the intervention, whereas under the Riparian Buffer Regulation only properties intersecting riparian buffer areas bear the costs.

Table 7

Land use composition of affected Rural Property Units affected under non-compensated riparian buffers and by phosphorus fertilizer tax–funded riparian buffers.

Variable	Riparian Buffer Regulation – Option 1	Riparian Buffer Regulation – Option 2	Riparian Buffer Regulation – Option 3	Hybrid Policy
Area of affected RPUs (ha)	121,913	215,920	535,434	621,390
Land uses within affected RPUs (%)				
Grasslands	43%	51%	52%	31%
Crops	25%	22%	20%	30%
Forestry	3%	4%	5%	2%
Dairy	27%	23%	22%	32%
Horti-Fruit	1%	1%	1%	5%

Note: Under the Riparian Buffer Regulation options, affected Rural Property Units are those intersecting buffer areas. Under Hybrid Policy (tax-funded riparian buffers) scheme, affected Rural Property Units include all properties with agricultural land uses contributing to fertilizer demand. Options 1–3 correspond to increasing spatial extents of riparian buffer implementation based on stream order.

reductions ranging from 51% to 61%. These estimations are comparable to those found in SWAT simulations performed by Jiang et al. (2020), who reported phosphorus reductions of 51–55% with 30-m buffers in agricultural systems. These estimations are consistent with a meta-analysis of 35 studies on riparian buffer effectiveness that found an average phosphorus removal of 54.5% (95% CI: 46.1–61.6%), with efficiency varying considerably under different conditions such as vegetation buffer width (most between 2 and 30 m), vegetation type (trees and/or grass), slope, and soil characteristics (Tsai et al., 2022). These findings highlight riparian buffers as a robust strategy for improving water quality and reducing phosphorus runoff in agricultural landscapes worldwide.

In contrast, given our estimated price elasticity of fertilizer demand (−0.34), a 1% Phosphorus Fertilizer Tax would reduce fertilizer demand by only 0.34% at both regional and national levels. Indeed, empirical evidence suggests that phosphorus fertilizer demand is relatively price inelastic, with elasticities typically below 0.5 in absolute value (Finger, 2012; Liu et al., 2020; Quddus et al., 2008). This implies that achieving significant reductions in fertilizer use would require substantial increases in fertilizer tax rates, likely beyond politically feasible levels. Furthermore, even when fertilizer application is reduced at the farm level, the impact on nutrient exports to water bodies is further attenuated by the landscape's filtering capacity (Tittonell, 2021), which dampens the effect of an already small tax. Taken together, these findings suggest that the marginal reductions in fertilizer use induced by a standalone phosphorus tax have a limited effect on the reduction on the amount of nutrients reaching watercourses –ranging from −0.1% to 0.8% in the modeled options-, especially when compared to the more direct and substantial benefits of implementing the Riparian Buffer Regulation.

Our modeling exercise assumes the tax is applied to the quantity of fertilizer purchased by agricultural producers. While this represents a common approach, future research could explore alternative tax designs –such as those based on nutrient balances at the production unit level, which may better target excessive phosphorus application and potentially enhance the environmental effectiveness of phosphorus taxation. Another challenge is the assumption that the phosphorus fertilizer tax is applied at the regional level, within a single river basin, which may pose administrative difficulties. Nevertheless, as a theoretical exercise, the analysis aimed to illustrate potential outcomes under ideal conditions. In practice, an alternative approach would be to implement the policy through existing administrative units (national or subnational level). Additionally, the partial equilibrium framework used here only captures changes at the intensive margin and does not account for broader economic interactions such as crop switching or input substitution. More comprehensive approaches –such as computable general equilibrium models or full cost-benefit analyses– would help capture these complex dynamics and provide a more complete evaluation of Phosphorus Fertilizer Tax performance.

When comparing cost effectiveness of Riparian Buffer Regulation in terms of cost per ton of phosphorus export reduction, Option 3 -representing 19,088 ha along water courses of all sizes- was found to be almost five times more expensive than Option 1, which included 3289 ha of buffers along the main watercourses. This results challenge the prevailing recommendation to prioritize buffer implementation along lower-order streams in upper watershed areas (Aubriot et al., 2017; Maher Hasselquist et al., 2021; Naiman and Décamps, 1997; Saunders et al., 2002). Although prior modeling of riparian buffer with SWAT suggest effectiveness plateaus beyond 50 m of width, Option 3 applied 25-m buffers to lower-order streams (Sirabahenda et al., 2020).

Three complementary explanations may explain this apparent discrepancy. First, land-use patterns within the catchment may play an important role. As shown in Fig. 2 and Table 7, the expansion of buffers under Option 3 occurs predominantly in grassland-dominated areas, which are generally associated with lower fertilizer inputs and lower nutrient export rates than cropland and dairy systems. As a result, additional buffer area may yield diminishing marginal benefits in terms of phosphorus retention when implemented in these less intensive upstream areas. Second, nutrient transport dynamics may differ by stream order. In lower-order streams, nutrient travel distances and contributing source areas may be smaller, potentially reducing the marginal effectiveness of additional buffer area compared to buffers located along higher-order streams that intercept cumulative upstream loads. Third, the observed results may partly reflect how riparian buffers are represented in the SWAT model. In this study, buffers are modeled as a proportion of total sub-basin area using generalized vegetative filter strip parameters, which may limit the spatial resolution needed to accurately capture the efficiency of narrow, hydrologically targeted buffers along lower-order streams. SWAT version used does not allow for fine-scale, site-specific buffer placement across the landscape and implicitly assumes uniform buffer configurations within each sub-basin. Moreover, recent evidence indicates that hydrologically adapted and spatially targeted riparian buffers can achieve comparable or even higher nutrient retention at lower opportunity costs than fixed-width buffers (Tiwari et al., 2016; Cole et al., 2020). Taken together, these findings suggest that the lower cost-effectiveness observed for Option 3 may reflect implementation design and modeling constraints rather than an inherent inefficiency of targeting lower-order streams. Future work should therefore explore spatially targeted buffer designs to further improve cost-effectiveness and the efficient use of public funds for conservation practices.

Conserving and expanding riparian vegetation faces several ecological and social challenges. Although native riparian forests are the most effective filters of phosphorus loads from agricultural lands (Calvo et al., 2024), they are currently confined to narrow bands across Uruguay and the Campos region of South America (Bernardi et al., 2016). These forests can potentially expand on adjacent productive grasslands but this is prevented by cattle browsing (Holmgren et al., 2024) and therefore only occurs where cattle densities have been significantly reduced (Bernardi et al., 2019). Expansion of riparian forests as a nature based solution to improve water quality will therefore depend on people's perceptions on landscapes and the role of trees in them (Holmgren and Scheffer, 2017).

Beyond environmental effectiveness, the success of agri-environmental policies depends critically on social acceptance and on how costs and benefits are distributed among stakeholders. Even environmentally effective measures may face resistance when perceived as unfair or when they impose disproportionate burdens on specific groups (Bjørnåvold et al., 2023; Carattini et al., 2018; Dresner et al., 2006; Klenert et al., 2018). In the context of agricultural nutrient pollution, these considerations are particularly relevant, as policies directly affect farmers' production decisions, incomes, and potentially food supply. Evaluating policy suitability therefore requires moving beyond environmental outcomes to consider distributive effects and alignment with equity considerations and the polluter pays principle (Finger and Pedersen, 2025; OECD, 2001).

Our results indicate that combining riparian buffers implementation with a phosphorus fertilizer tax can be a powerful strategy to increase adoption by compensating landowners for the costs associated with riparian buffer zones. This Hybrid Policy scheme provides a stable and predictable source of public revenue while redistributing costs across the agricultural sector, without significantly altering food production (See Table 5). The modest crop yield response (reductions below 0.6%) to reduced phosphorus application may suggest that crop production in the study area is determined by existing soil phosphorus levels rather than by annual fertilizer inputs. This pattern is consistent with empirical evidence from the Santa Lucía Basin (Barreto et al., 2017) and with findings reported for systems characterized by phosphorus accumulation (Rutan and Steinke, 2021). Under these conditions, a P fertilizer tax could function as a viable fiscal instrument for financing environmental interventions such as riparian buffers, while exerting limited effects on agricultural production in intensive margin.

Coupling a phosphorus fertilizer tax with riparian buffer implementation also generates three key co-benefits that strengthen the equity and political feasibility of the measure. First, it helps broaden the cost base of riparian buffers implementation by redistributing the financial responsibility more evenly among producers across the basin, alleviating the burden that would otherwise fall disproportionately on landowners near watercourses (Bakx et al., 2024; Pohjanmies et al., 2019).

Second, the tax improves alignment with the polluter pays principle. While (non-compensated) Riparian Buffer Regulation place the financial burden on landowners adjacent to watercourses regardless of their actual contribution to nutrient pollution –these areas are predominantly covered by natural grasslands, which generally provide beneficial nutrient filtration services (Tittonell, 2021). In contrast, a Hybrid Policy (tax-funded riparian buffers) scheme shifts the cost to phosphorus consumers, primarily crop producers and dairy farmers, who have been identified as the main contributors to phosphorus pollution in the Santa Lucía Basin (Aubriot et al., 2017). Although not all fertilizer users contribute equally to nutrient pollution, as nutrient losses vary with application methods, cover cropping, and soil management, assuming polluters are relatively evenly distributed across the basin, this Hybrid Policy scheme ensures a more equitable allocation of environmental responsibilities.

Third, this approach can increase the political acceptability of the phosphorus fertilizer tax. Taxes on agricultural inputs often face resistance from farmers, particularly when seen as an additional cost without direct benefits (Finger and Pedersen, 2025). However, this opposition can be mitigated through earmarking, whereby tax revenues are reinvested into the sector (Söderholm and Christiernsson, 2008). When producers see tangible improvements -such as financial support for buffer implementation or funding for sustainable practices- the tax is more likely to be perceived as fair and purposeful (Kallbekken and Sælen, 2011; Söderholm and Christiernsson, 2008). This helps reconcile agricultural production with environmental protection objectives, thereby strengthening long-term policy support (Bakx et al., 2024; OECD, 2001).

More broadly, our analysis suggests that addressing diffuse nutrient pollution requires a policy mix rather than a choice between standalone instruments. Moreover, just as riparian buffers should not be treated as an end-of-pipe solution, neither should tax-funded riparian buffers. Between riparian buffers and fertilizer taxes lies a spectrum of additional interventions -such as the promotion of nutrient management practices, the adoption of cover crops, and the use of improved fertilization technologies- that should be considered within an integrated policy framework aimed at reducing nutrient pollution (Liu et al., 2020). Thus, while this study presents a viable strategy to address nutrient pollution, future work should explore the complementarities with other instruments and strategies, as well as the integration of other financing mechanisms to support more effective and equitable solutions.

5. Conclusions

This paper underscores the importance of moving beyond single-policy approaches when addressing diffuse phosphorus pollution in agricultural landscapes. While a phosphorus fertilizer tax alone is unlikely to produce significant reductions in nutrient runoff, their strategic value lies in their ability to mobilize resources and reallocate the costs of environmental interventions more equitably. In contrast, riparian buffers emerge as a far more impactful intervention, offering substantial nutrient retention benefits. However, when not compensated, they concentrate the burden of implementation on a smaller group of farmers -particularly those located near watercourses- which raises equity concerns and may create financial and political barriers to large-scale adoption. The findings of this study suggest that the real potential lies in combining these instruments. A well-designed hybrid policy approach can enhance the effectiveness of riparian buffer policies, not only by securing funding, but also by improving fairness among stakeholders. Overall, this analysis highlights the need for integrated policy tools that account for both the biophysical dynamics of nutrient retention and the socioeconomic realities of land use. Effective agricultural water quality policy must go beyond cost-effectiveness to also uphold principles of environmental integrity and equitable distribution of responsibilities and benefits.

CRediT authorship contribution statement

Guillermo Sena: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Francisco Alpízar:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Magdalena Borges:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Miguel Carriquiry:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Milena Holmgren:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary materials

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Data availability

Data will be made available on request.

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