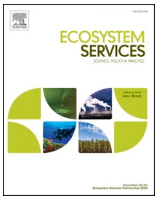
Ecosystem Services 79 (2026) 101853

Contents lists available at ScienceDirect

Ecosystem Services

journal homepage: www.elsevier.com/locate/ecoser



Full Length Article

Water purification ecosystem services in the Integrated Economic-Environmental Model (IEEM): An application to investing in water quality in Uruguay

Onil Banerjee[a,*], Martin Cicowiez[b], Kenneth J. Bagstad[c], Matías Piaggio[d], Renato Vargas[e], Pablo Kok[f]

[a] RMGEO Consultants Inc., 951 Regent Street, Suite 216, Fredericton, NB E3B-6Z2, Canada
[b] National University of La Plata, School of Economics, National University of La Plata, Calle 6 Between 47 and 48, 3rd Floor, Office 312, 1900 La Plata, Argentina
[c] Data Foundation, Washington, DC, USA, 20005, (formerly United States Geological Survey, Denver, CO 80225, USA
[d] South American Institute for Resilience and Sustainability Studies (SARAS), Los Teros esq. Cardenales, Bella Vista, CP 20200, Maldonado, Uruguay
[e] CHW Research, 27 Street 7-05 Zone 16, Alta Bosque, House 104, Guatemala City 01016, Guatemala
[f] Ministry of the Environment, National Directorate of Quality and Environmental Assessment, Juncal 1385, 8th Floor, Montevideo, Uruguay

ARTICLE INFO

Keywords:
Macroeconomic-Ecosystem Analytics
Integrated Economic-Environmental Modeling (IEEM)
Landscape management
Modeling and valuing regulating ecosystem services
Multiregional computable general equilibrium (CGE) modeling
Water purification ecosystem services

ABSTRACT

Increasingly, integrated macroeconomic-ecosystem service models inform policy design. We advance two relevant research frontiers: (i) incorporation of a new ecosystem service, water purification, into the integrated framework and (ii) development of subnational scale analysis. We develop a multi-regional Integrated Economic-Environmental Model (IEEM) and link changes in water quality to tourism demand and water treatment costs, capturing previously unquantified interactions between natural capital assets and economic performance. The multi-regional approach reveals trade-offs and inter-regional disparities in costs and benefits, enabling spatially explicit policy insights and equity considerations at a more granular level than previously possible. We demonstrate these innovations by applying IEEM to Uruguay's National Environmental Program for Sustainable Development. Results show that the Program would boost Gross Domestic Product and wealth by US$748.2 million and US$166.4 million, respectively and that the environmental and economic gains, including a 55 million ton-reduction in carbon emissions and a US$121 million increase in regulating ecosystem services, outweigh modest trade-offs in food provisioning services. Expost valuation of the carbon emissions avoided would result in a benefit of US$1.1 billion. The methods developed are replicable across countries for rapid, real-time policy evaluation for countries seeking to align economic development strategies with sustainability targets.

1. Introduction

A new suite of tools has emerged for public policy and investment analysis that integrates natural capital and ecosystem services (ES) enabling more robust policy assessments that account for impacts on the three dimensions of wealth and sustainable economic development: the economy, society and the environment (Banerjee et al., 2025a; Banerjee et al., 2020; Johnson et al., 2020; Valin et al., 2013; World Bank, 2025). One such modeling framework is the Integrated Economic-Environmental Modeling (IEEM) approach, which was first advanced in 2016 (Banerjee et al., 2016) and has since been applied to over 30 countries around the world.

This new class of models begins with, at its core, a recursive dynamic Computable General Equilibrium (CGE) model that statistically represents all economic sectors and the interactions between sectors and institutions. A number of natural capital assets and ES may be simulated with a CGE alone, including changes in land allocated to different uses, various provisioning ES that have market prices (e.g., food, fuel and fiber) and in specific scenarios, cultural ES related to tourism and recreation. Regulating ES, which generally do not have a market price, usually require a specialized treatment to capture policy impacts on the value of their future flows. These regulating services include water purification, water regulation, climate regulation and crop pollination ES (European Environment Agency, 2018), among others.

---

[*] Corresponding author.

E-mail addresses: onil@rmgeo.org (O. Banerjee), martin@depeco.econo.unlp.edu.ar (M. Cicowiez), ken.bagstad@datafoundation.org (K.J. Bagstad), matias.piaggio@gmail.com (M. Piaggio), renovargas@gmail.com (R. Vargas), pablo.kok@ambiente.gub.uy (P. Kok).

https://doi.org/10.1016/j.ecoser.2026.101853
Received 8 July 2025; Received in revised form 7 April 2026; Accepted 12 April 2026

2212-0416/© 2026 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

Some of these regulating services are considered intermediate services (i.e., they are themselves inputs into other ES) by conventional accounting frameworks and are frequently excluded from policy analysis due to the complexities involved in their measurement and valuation. Neglecting regulating ES, however, can undermine future ES supply given their role in supporting the provision of other ES as well as environmental quality (Mengist et al., 2020; Small et al., 2017; Sutherland et al., 2018). Furthermore, not valuing regulating ES in benefit-cost and other decision-making frameworks can lead to erroneous trade-offs, the undervaluation of natural capital assets and suboptimal decisions.

Including regulating ES in IEEM and other integrated frameworks is made possible by linking the IEEM with spatial land use-land cover (LULC) change and ES modeling (IEEM + ESM; Banerjee et al., 2020). To date, erosion, annual and seasonal water regulation, water purification, climate regulation, coastal protection and crop pollination ES have been integrated into IEEM, yielding results in terms of impacts on future ES flows in biophysical units. In our recent work, the linkage between service provision and human well-being has been established for erosion mitigation and crop pollination ES (Banerjee et al., 2024a; Banerjee et al., 2025b) which enables estimation of the value of marginal changes in service provision. Once this transmission pathway is established, we develop heuristics to capture the essence of the relationship between changes in regulating ES and economic agents. Heuristics for each transmission pathway identified enables the rapid deployment of IEEM + ESM to inform public policy and investment decisions in real-time.

In this paper, we develop transmission pathways between water purification ES and the economy and develop heuristics for their integration and implementation in IEEM + ESM. We demonstrate this approach by applying IEEM + ESM to the empirical analysis of Uruguay's National Environmental Program for Sustainable Development (NEPSD), a US$6 million investment loan from the Inter-American Development Bank to the Government of Uruguay. The overarching goal of NEPSD is to improve water quality through enhanced environmental monitoring and management systems, establishing riparian buffers and increasing the sustainability of livestock production systems. The Program focuses on priority watersheds in Uruguay, specifically, the Santa Lucia, Laguna del Sauce and Rio Negro watersheds.

This study advances the literature in two primary ways. First, we integrate water quality ES into the dynamic IEEM + ESM workflow, explicitly modeling the transmission pathways between biophysical changes, water treatment costs and tourism demand. Second, this study represents the first multi-regional application of IEEM + ESM, spatially disaggregated across Uruguay's 19 Departments. By resolving economic impacts at the sub-national level, this framework provides the granular evidence base necessary for designing regionally differentiated policies. As integrated assessment models evolve, the ability to capture spatially explicit ES feedbacks significantly amplifies the power of these tools, moving beyond national aggregates to offer more precise, localized insights needed for addressing increasingly complex policy questions.

In what follows, section 2 outlines the IEEM + ESM methodological framework. Section 3 details the NEPSD investment scenarios, followed by the analysis of results in Section 4. Finally, Section 5 synthesizes key findings, highlights methodological innovations and identifies future research directions for integrated economic-environmental modeling.

2. Methods overview

We applied the dynamic multiregional IEEM + ESM approach in scenario analysis to estimate NEPSD impacts on economic, social and environmental indicators (see Box 1 and Fig. 1 for the full IEEM + ESM workflow). IEEM + ESM takes a whole-of-economy approach where all economic sectors interact through supply and demand relationships and factor constraints (labor, manufactured capital and natural capital). At the core of IEEM is a recursive dynamic CGE model, long considered the workhorse of public policy analysis (Arrow, 2005; Jones, 1965; see Supplementary Information (SI) Section 1 for a detailed presentation of the IEEM + ESM methodology). CGE models are among the most well-documented models in the economics literature, which has developed over the last four decades.

We link IEEM with the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) ES suite of models (Natural Capital Project,

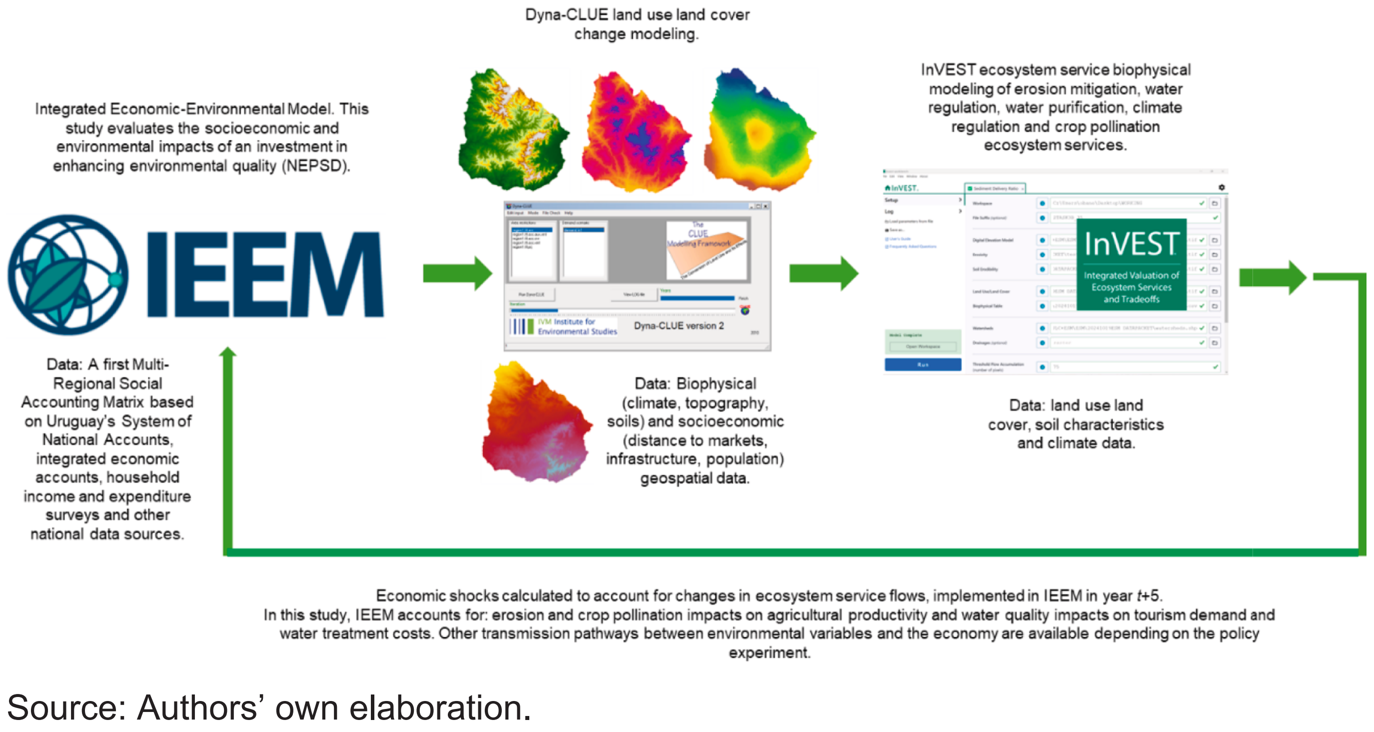


Fig. 1. Full IEEM + ESM workflow.
Source: Authors' own elaboration

2025), parametrized with national data and supplemented with global data sources. The ES models applied were the Sediment Delivery Ratio (erosion mitigation ES), Annual Water Yield (water regulation ES), Nutrient Delivery Ratio (water purification ES), Carbon Storage (climate regulation ES) and Crop Pollination ES models.

A distinguishing characteristic of IEEM + ESM is the consolidation of the following four features within a single, internally consistent analytical system: (i) IEEM integrates detailed environmental information through the United Nations System of Environmental-Economic Accounting (SEEA; United Nations et al., 2014), for those countries where accounts exist, to represent the economy and the environment in a comprehensive and inter-connected way, all consistent with the System of National Accounts (European Commission et al., 2009). Consistency with the National Accounts ensures robustness of estimates and credibility with decision-makers; (ii) the indicators IEEM generates are those demanded by policy makers including Gross Domestic Product (GDP), employment and poverty, but also metrics of wealth (Hamilton, 1999; Hamilton and Clemens, 1999), sustainability, natural capital stocks and ES supply. The concept of wealth we use is that of genuine savings, which is equivalent to net national savings adjusted for by changes in natural capital stocks and environmental quality; (iii) IEEM's environmental modeling modules capture the specific dynamics of natural capital-based sectors (forestry, agriculture, fisheries and mining) and; (iv) IEEM's linkage with LULC change and ES modeling enables estimation of spatially explicit impacts on LULC and the future flow of market and non-market ES.

In the dynamic IEEM + ESM approach applied in this study, changes in LULC arise from the establishment of riparian buffers, producing changes in the delivery of ES, which has consequences for the economy. In this workflow, economic shocks accounting for changes in erosion mitigation, crop pollination and water purification ES were estimated and implemented in IEEM iteratively in 5-year time steps. This approach enables estimation of the marginal value for these regulating ES, which do not have a market price.

In the implementation of the IEEM + ESM workflow, regulating ES are valued in monetary terms through a production function approach in the case of erosion mitigation and crop pollination ES, and through observed prices in the case of water purification services. These valuation methods are considered Tier 3 methods which, according to United Nations guidelines for ES Accounting, have the greatest accuracy and spatial resolution (NCAVES and MAIA, 2022; UN et al., 2024). At the time of publication, the dynamic multiregional IEEM + ESM workflow is the only modeling framework in the peer reviewed literature that integrates dynamic feedbacks between changes in ES and the economy in this way while maintaining consistency with a country's System of National Accounts.

2.1. *Integration of water purification ecosystem services*

We integrate water purification ES in the dynamic IEEM + ESM by accounting for water quality impacts on water-based recreational tourism demand and water treatment costs. In the sections that follow, we present an overview of the main features of the method while providing all relevant details in SI section 2.

2.1.1. *Water purification and tourism demand*

A major component of the NEPSD investment is the establishment of riparian buffers which are described in detail in section 3.3. These buffers are expected to positively impact water quality which is modeled and quantified using the InVEST Nutrient Delivery Ratio model. To account for the economic effect of improved water quality, we establish a transmission pathway between the economy represented by IEEM and the Nutrient Delivery Ratio model by relating water quality improvements with water-based recreational tourism demand.

Improvements in water quality will contribute to mitigating negative impacts on tourism demand in key coastal destinations in Uruguay, in particular, the coastal departments of Maldonado, Colonia, Montevideo, Canelones and Rocha. In the past, tourism demand has suffered due to episodes of poor water quality, for example, in the summer of 2019, the beaches of Montevideo, Canelones and Maldonado experienced cyanobacteria outbreaks, which negatively impacted tourism visitation and expenditure (Anido, 2021; Aubriot et al., 2020; Beltran, 2019; El Pais, 2019; Kruk et al., 2019). Riparian buffers mitigate the effects of excess nutrients leaching from farm fields and thus reduce the risk of future outbreaks such as that of 2019.

Cyanobacteria outbreaks pose a significant danger for both local populations and tourists. Exposure to cyanobacteria can affect the nervous system and cause skin irritation, diarrhea and vomiting (Aguilera et al., 2018). Climate change is expected to increase the intensity and frequency of these outbreaks (O'Neil et al., 2012; Paerl and Huisman, 2008) and thus measures to reduce leaching from farm fields are a high priority for maintaining water quality standards and mitigating negative impacts on Uruguay's tourism industry.

In our implementation of IEEM, the business-as-usual scenario incorporates the negative impacts of poor water quality on tourism demand and expenditure. With the implementation of NEPSD, the creation of riparian buffers will reduce the volume of phosphates and nitrates that run-off from farm fields and other non-point sources of pollution that reach waterways. NEPSD also includes measures to improve the sustainability of agricultural practices in the priority watersheds, which are expected to lead to the more rational application of fertilizers and improved livestock management and consequently, less harmful run-off.

To formalize the relationship between water quality and tourism demand, we reviewed the relevant literature (Aminu et al., 2015; Breen et al., 2018; Dorevitch et al., 2015, 2011; Egan et al., 2009; Freeman, 1995; Keeler et al., 2015; Lee and Lee, 2015; Vesterinen et al., 2010; Wade et al., 2010). Econometric studies of this nature specific to Uruguay were not available at the time of publication of this study. To estimate a tourism demand function with water quality as an independent variable, we follow the travel cost model developed in Breen, Curtis and Hynes (2018). This model is particularly well-suited to the present policy context since it is a multi-site study and includes variables for which information exists in our case of the priority watersheds in Uruguay.

The model estimated in Breen, Curtis and Hynes (2018) takes the form presented in equation (1).

$$\ln\lambda_i = \beta_0 + \beta_1 \bullet x_{1i} + \beta_2 \bullet x_{2i} + \beta_{wq} \bullet x_{wq} + \beta_{wqD_m} \bullet (D_m \bullet x_{wq}) \tag{1}$$

Where:

λ_i is the number of tourist visit days.

$\beta_{1\ldots n}$ are model coefficients.

x_{1i} is a vector of individual and site-specific variables.

D_m is a dummy variable for a specific type of recreational activity.

To account for changes in tourism demand for a unit change in water quality, we estimate an economic shock to implement in IEEM. In the Breen et al. (2018) model, we focus on the variables related to the type of recreational activity and water quality. While the authors consider various water quality variables, our application of the Nutrient Delivery Ratio model provides estimates of the volume of phosphates and nitrates reaching waterways. In the absence of visitor preference survey data from Uruguayan waterways, we solve equation (2) for the change in the length of stay of water sports enthusiasts arising from a change in the level of phosphates present in the water as described in equation (2). We selected the water sports category as the representative behavioral proxy because it isolates the sensitivity of users engaging in direct water immersion activities which accurately captures the avoidance behavior of Uruguay's dominant sun and sand tourists who are constrained primarily by the health risks of direct contact with toxic cyanobacteria blooms in the water (Aubriot et al., 2020).

Specifically, we estimate the change in water quality, Δx_{wq}, arising

Box. 1. IEEM ESM methods Summary.

The IEEM + ESM modeling workflow implemented in this study is comprised of two models that interact through the transfer of data and results from one model to another. The first model is IEEM which is constructed based on a country's National Accounts, the internationally accepted framework for measuring economic activity and development, usually combined with other sources of statistical data on the economy, government and households. In this application, a multiregional Social Accounting Matrix underpins IEEM, which is a statistical representation of all sectors and transactions in an economy at the Departmental level as well as land-use dynamics for the base year. IEEM is used to generate a business-as-usual projection of the economy in the absence of any new public policies and investments. Policy scenarios are then implemented in IEEM which represent the key components of NEPSD.

Linked to IEEM are the InVEST erosion mitigation, crop pollination, water purification, water regulation and carbon storage ES models. ES model runs calculate changes in future ES flows for each policy scenario with respect to the business-as-usual scenario. These results are summarized at the level of Uruguayan Department and are used to calculate economic shocks that account for changes in ES flows, which are subsequently implemented in IEEM to generate the final results presented in section 4. In most previous IEEM applications (Banerjee et al., 2024b, 2023, 2022), the bridge between IEEM and the spatial ES modeling is made through a LULC change model, which spatially allocates change in demand for land across the landscape (see Fig. 1). In this application, the major LULC change arises through the establishment of riparian buffers with known spatial locations. For this reason, maps representing this LULC change, which are a key variable input into the ES modeling, are instead generated through the application of a Geographic Information System (GIS; ArcGIS 3.3.0) and standard analytical tools within the GIS, without the need for an LULC change model's land allocation algorithm.

from the implementation of riparian buffers (i.e. the BUFFER scenario described in section 3.3) with the Nutrient Delivery Ratio Model. We use the business-as-usual (BASE) LULC map and a scenario-generated map (BUFFER LULC map) representing the buffers established through NEPSD as inputs and the main variables of change in the Nutrient Delivery Ratio model which calculates the amount of nitrates and phosphates that are exported to waterways. The difference between the BUFFER and BASE model runs is the NEPSD-driven change in the volume of nutrients reaching waterways.

$$\Delta\lambda_i = \beta_{wq} \bullet \Delta x_{wq} + \beta_{wqD_m} \bullet (D_m \bullet \Delta x_{wq}) \quad (2)$$

We use the following coefficients and data from Breen et al. (2018)[1]

β_{wq} = -18.61.

β_{wqD_m} = -9.231.

x_{wq} = 0.038.

D_m = 1.

The implementation of riparian buffers resulted in a 1.46% and 0.58% reduction in nitrates and phosphates, respectively. We use the average of these two results (1.02%) and calculate that $\Delta x_{wq} = -0.000387108$.[2]

To estimate the impact of this 1.02% improvement in water quality (Δx_{wq} = -0.000387108) on the length of stay of water sports enthusiasts, we calculate:

$$\begin{aligned}\Delta\lambda &= -18.61 \bullet 0.00038710 + (-9.231 \bullet 0.00038710)\\ &= -0.010777473 \quad (3)\end{aligned}$$

As shown in equation (3), a 1.02% improvement in water quality would result in a 0.01078-day increase in length of stay.

The next step in calculating an economic shock to implement in IEEM is to calculate the average length of stay of tourists and their average per person per day expenditure; these were calculated as 6.15 days and US $79.47 per person per day, respectively. Considering the average length of stay and tourism expenditure and the 1.02% improvement in water quality, the 0.01078-day increase in length of stay would increase the average length of stay from 6.150 days to 6.161 days. On an annual basis, this would imply a US$2,789,383 increase in tourism demand arising from the improvement in water quality attributable to NEPSD. This is one of the two transmission pathways developed to link water quality improvements with economic outcomes. The second transmission pathway, described in the section that follows, relates water quality to water treatment costs.

2.1.2. *Water purification and water treatment costs*

The carefully designed implementation of riparian buffers can positively impact water quality (Chaplin-Kramer et al., 2016) which can result in the reduction of water treatment costs. With cleaner water reaching water treatment facilities, the variable costs of chemical treatment are reduced. In establishing this transmission pathway between water quality, water treatment costs and economic outcomes in IEEM, we focus on water turbidity. To estimate changes in the volume of sediments reaching Uruguay waterways, again the difference in turbidity between the BASE and BUFFER LULC maps, we implement the InVEST Sediment Delivery Ratio model. Turbidity is the volume of suspended sediments in water and is commonly used as an indicator of overall water quality.

Water treatment facilities aim to eliminate turbidity (Danelon et al., 2021) which simultaneously eliminates many other pollutants, including organic components and nutrients beyond certain thresholds (EPA, 1999). Gianessi et al. (1981) estimated that soil erosion from crops and pasture lands account for about 68% of the suspended sediments found in waterways. The NEPSD Program includes measures to enhance erosion mitigation ES through the establishment of buffers and improved crop and pastureland management.

In the absence of empirical evidence from Uruguay on the relationship between erosion and water treatment costs, we reviewed the international literature. Elsin et al. (2010) estimated the costs avoided due to an increase in the quality of raw water used as an input into eight water treatment facilities in the Neuse River Basin in North Carolina, USA. The authors performed a benefits transfer from the producer's perspective to relate changes in water quality to water treatment costs. Their study used the findings of Dearmont et al. (1998), Forster et al. (1987), Holmes (1988) and Murray and Forster (2001), which found that a 1% change in turbidity would affect water treatment costs by between 0.07% and 0.4%. Piaggio and Siikamäki (2021) estimated that the contribution of forests to purifying water in Costa Rica was approximately US$9.50 per hectare. The authors also found that reducing turbidity by 1% would decrease the amount of aluminum

---

[1] Although the interaction term in Breen et al. (2018) lacks statistical significance, we retain the point estimate to avoid the implicit and theoretically inconsistent assumption of the complete absence of a behavioral response to toxic blooms which is consistent with methodological best practices (The White House, 2023; United States Environmental Protection Agency, 2024).

[2] We chose to average nitrogen and phosphorus in light of the Uruguayan evidence which has shown that cyanobacteria blooms are driven by high concentrations of both nitrogen and phosphorus (see Ferrari et al. 2011 for more).

sulfate used in water treatment plants by 0.005%, thus reducing variable water treatment costs.

Given the limited data available for the Uruguayan case, we use the regression model developed in Forster et al. (1987) to calculate the economic shock to implement in IEEM to relate changes in water quality to water treatment costs. Equation (4) describes the relationship between the annual variable water treatment cost (independent variable) and the volume of water treated, the average retention time, the average daily reduction in turbidity and soil erosion as explanatory variables.

$$c = a0 \bullet s^{a1} \bullet r^{a2} \bullet t^{a3} \bullet e^{a4} \tag{4}$$

Where:

c is the average daily variable treatment cost in United States Dollars.
s is the average daily volume of water treated in thousands of gallons.
r is the average water retention time in days.
t is the average daily reduction in turbidity.
e is the annual level of soil erosion in tons per acre.
$a1,\ a2,\ a3$ and $a4$ are the regression coefficients.

Estimating the logarithmic form of equation (4) gives:

$$\log c = -0.562 + 0.657 \bullet (\log s) + 0.14 \bullet (\log r) + 0.119 \bullet (\log t) + 0.406 \bullet (\log e) \tag{5}$$

With the logarithmic form of the model, the interpretation of the coefficients is straightforward. The coefficient on water quality, proxied for by turbidity, indicates that annual water treatment costs would be reduced by 0.4% for each 1% reduction in soil erosion. Since we are interested in the relative change in water treatment costs with respect to a change in soil erosion, in the absence of data for Uruguay, we assume similar values for the variables $s,\ r$ and t in equation (5) following Forster et al. (1987).

To calculate the change in soil erosion arising from the implementation of riparian buffers, we implement the Sediment Delivery Ratio model with the BUFFER and BASE LULC maps as the key variables of change. The difference in the results of these two model runs is the NEPSD-driven change in soil erosion. Specifically, the resulting difference between the BUFFER and BASE LULC was a 4.69% reduction in soil loss attributable to the implementation of the NEPSD riparian buffers. Following from equation (5), a 4.69% reduction in soil erosion would thus result in a 1.88% reduction in the annual variable water treatment costs. This is the shock implemented in IEEM to account for changes in water treatment costs resulting from the impact of NEPSD on water quality.

3. Scenario generation

This section outlines the scenarios developed to evaluate the economic and environmental impacts of Uruguay's NEPSD Program. To provide a clear roadmap of the analytical framework, Table 1 presents a high-level overview of the baseline and policy scenarios, summarizing the primary objectives and key variables affected in each. The subsequent subsections describe the watersheds where interventions occur, the anticipated ecosystem services impacts, the NEPSD theory of change and the key characteristics of each of the scenarios.

In this application, we develop and implement scenarios in IEEM + ESM that represent the key components of NEPSD’s two specific objectives, to: (i) strengthen the Ministry of Environment’s strategic planning, evaluation, control and environmental monitoring functions; and (ii) improve the integrated management of priority watersheds, with an emphasis on reducing agricultural and other non-point pollution loads. Fig. 2 presents the locations of the priority watersheds, namely, the Santa Lucia, Laguna del Sauce and Rio Negro watersheds. Many of the activities and investments related to the first objective involve institutional strengthening, which we apply in our first investment scenario. For the second objective, our application focuses on the establishment of riparian buffers along waterways in the three priority watersheds and the implementation of more sustainable livestock production systems. Fig. 3 presents the NEPSD theory of change with an emphasis on the Program components that are central to this study.

Table 1
IEEM + ESM scenario overview.

Scenario	High-Level Description	Key Elements / Variables Changed
BASE	The counterfactual reference scenario representing the future trajectory of Uruguay’s economy until 2050 in the absence of any new large public policies and investments.	Imposes historical macroeconomic trends and the same GDP growth rate across all Departments. Serves as the reference point to which all other policy scenarios are compared.
INVEST	Captures the direct public investments associated with the NEPSD program.	Simulates the public expenditure required for enhanced environmental monitoring and management systems. The total size of investment is US$6 million across all scenarios described below.
GOVCAP	Simulates NEPSD’s first objective, focusing on the institutional strengthening and capacity-building aspects of the Program.	Simulates the institutional strengthening and capacity building aspects of the Program (US$1.2 million).
BUFFER	Simulates the establishment of riparian buffers to mitigate nutrient runoff and enhance water purification ecosystem services.	Establishes 30-meter buffers (15 m on each side of major waterways) in the three priority watersheds. Converts areas identified as uncompliant and/or non-forested into forested buffers, withdrawing this land from agricultural production (US$3 million).
SILVOPAST	Targets water quality improvements through the adoption of sustainable silvopastoral practices.	Models interventions aimed at increasing the sustainability of livestock production systems to reduce nutrient leaching from farm fields (US$1.8 million).
COMBI	A comprehensive scenario assessing the full, simultaneous implementation of the NEPSD components.	Integrates the INVEST, GOVCAP, BUFFER, and SILVOPAST shocks simultaneously to evaluate the synergistic macroeconomic and spatial ecosystem service impacts through 2050.

Source: Authors’ own elaboration.

3.1. *Background on The Santa Lucia, Laguna del Sauce and Rio Negro watersheds*

The Santa Lucia, Laguna del Sauce and Rio Negro watersheds are important for both rural areas and urban centers in Uruguay. All three watersheds have experienced major changes in land use, with the establishment of monoculture forest plantations affecting water regulating and other ES (Torremorell et al., 2021). Eutrophication and algal blooms have been the most significant water quality issues in all three watersheds. The Santa Lucía watershed (13.4 thousand km^2) located in Uruguay’s south is the primary source of potable water for Montevideo, the nation’s capital, with a total population of approximately 1.384 million people in 2024. Over the last two decades, the Santa Lucia watershed has experienced intense LULC change with clearing for intensive crop production (mostly soybean) and an increasing number of cattle feedlots and dairy operations, all of which have had important impacts in the basin (DIEA, 2018; MGAP, 2015). Consequently, water contamination has become a serious health risk, especially for the drinking water supply of Montevideo. Episodes of contamination have since arisen requiring increased government expenditure in water

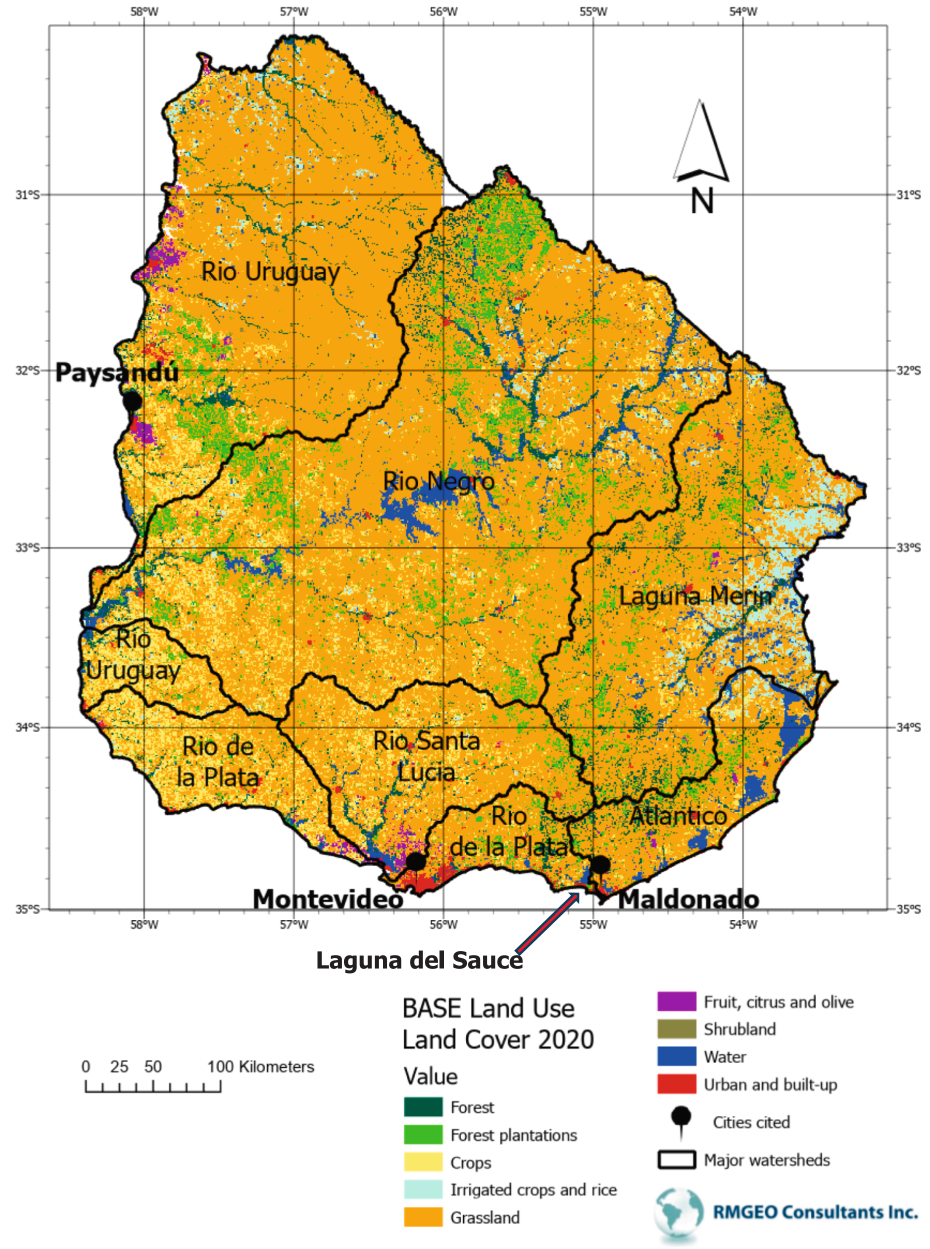


Fig. 2. Uruguay and its principal watersheds. Notes: Laguna del Sauce is identified by the red arrow at the base of the map and indicates a relatively large water body.). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: Reclassified Land Use Land Cover Map (2021, 30-meter resolution) identifying major watersheds (MGAP, 2021

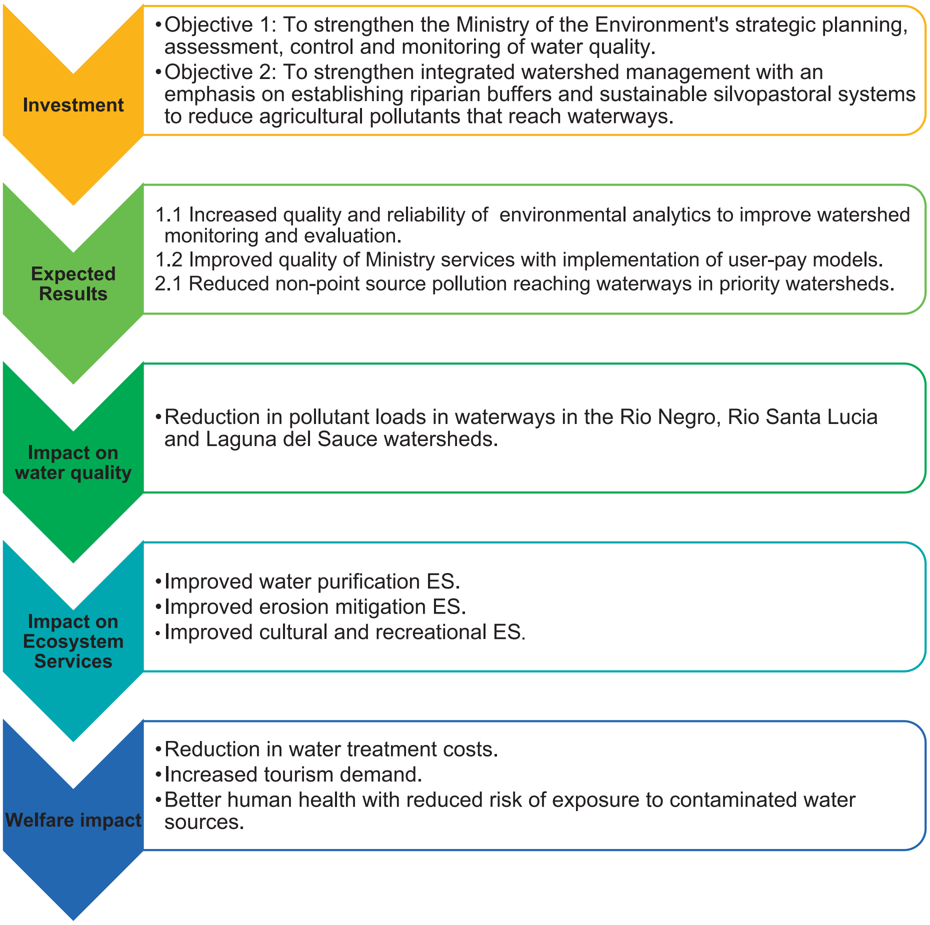
treatment to ensure water quality standards are upheld (Piaggio et al., 2018).

The Laguna del Sauce watershed (772 km^2) is located in the south-east of Uruguay, supplying potable water to the cities of Maldonado and Punta del Este. These cities are Uruguay's main tourism destinations, especially during the summer season, receiving 18% Uruguay's international visitation and 39% of total tourism expenditure in 2023 (Ministerio de Turismo, 2025). As with Santa Lucía, the watershed suffered intense upstream LULC change in the last two decades and episodes of water contamination have become more frequent (Piaggio et al., 2018; SARAS, 2010).

The Rio Negro watershed (69.7 thousand km^2), the largest of the three, is located in the center of Uruguay, spanning the width of the country from east to west. Some of Uruguay's largest hydroelectric facilities are located in the Rio Negro watershed, namely, Baygorria, Constitución (Palmar) and Rincón del Bonete. Over 2005 to 2020, these three hydroelectric plants produced an annual average of 69.01, 190.16 and 103.91 kilotons of petroleum equivalent (ktpe), respectively, accounting for approximately 44% of national hydroelectric output (Ministerio de Industria, Energía y Minería, 2025). Hydropower contributed 31% of Uruguay's total energy output in 2022. The Uruguayan Government designated the Rio Negro watershed as a priority watershed to fast track the preparation of environmental plans and baselines prior to the establishment of Uruguay's largest pulp and paper mill in Paso de Torres. This pulp mill has now been operational since 2023 and is the world's largest single line pulp and paper mill, producing an average of 2.1 million tons of pulp per year.[3]

---

[3] https://www.upmpulp.com/pulp-production/paso-de-los-toros/.



- Objective 1: To strengthen the Ministry of the Environment's strategic planning, assessment, control and monitoring of water quality.
- Objective 2: To strengthen integrated watershed management with an emphasis on establishing riparian buffers and sustainable silvopastoral systems to reduce agricultural pollutants that reach waterways.

1.1 Increased quality and reliability of environmental analytics to improve watershed monitoring and evaluation.
1.2 Improved quality of Ministry services with implementation of user-pay models.
2.1 Reduced non-point source pollution reaching waterways in priority watersheds.

- Reduction in pollutant loads in waterways in the Rio Negro, Rio Santa Lucia and Laguna del Sauce watersheds.

- Improved water purification ES.
- Improved erosion mitigation ES.
- Improved cultural and recreational ES.

- Reduction in water treatment costs.
- Increased tourism demand.
- Better human health with reduced risk of exposure to contaminated water sources.

Fig. 3. Theory of Change presenting the expected impact of The National Environmental Program for Sustainable Development on water quality and human well-being. .
Source: authors' own elaboration drawing on Keeler et al. (2015)

3.2. NEPSD potential impacts on ecosystem services

Riparian buffers generate a broad array of ES. Increasing forest cover in upstream watersheds, including buffers, stores carbon for climate change mitigation, reduces erosion, improves water quality (Piaggio and Siikamäki, 2021), enhances crop pollinator habitat (Riis et al., 2020) and in broader terms, contributes to water security. Increasing forested areas reduces the risk of vector-borne diseases, such as dengue (Piaggio et al., 2024). Riparian buffers provide benefits for fisheries by cooling waters and reducing thermal stress for fish which affects fish physiology, growth and behavior (Hall and Selker, 2021; Macedo et al., 2013). Cool water is also important for some industrial processes. Climate change will cause stream temperatures to rise in the absence of mitigating or adapting measures (van Vliet et al., 2013). A study by Langhans et al. (2022) found that increasing national forest cover by 1.9% in Costa Rica would increase water regulation, water quality and carbon storage ES.

There are some trade-offs, however, between establishing riparian buffers and economic outcomes. While riparian buffers can enhance some ES, they can simultaneously reduce other ES such as food provisioning services from agricultural activities where buffers withdraw land from agricultural production. To compensate, different buffer widths can be designed to maximize multiple objectives and offset negative trade-offs (Semmens and Ancona, 2019). Multiple benefits are simultaneously enhanced where buffers are established in areas with steep topography that are generally less productive for agriculture and by withdrawing less productive areas that require intense fertilization (Langhans et al., 2022). In this way, buffers can be spatially targeted to balance environmental and socioeconomic outcomes (Cole et al., 2020).

Increased water purification ES in the priority watersheds will improve the quality of water entering water treatment plants and reduce water treatment costs and subsequent health risks related to human exposure to contaminated water. Additional benefits include reduction in eutrophication and algal blooms. Increased fish provisioning services could arise with enhanced fish stocks, fish species diversity and health. Cultural and recreational ES could be improved by creating higher quality experiences for water-based activities such as swimming, fishing, sailing and hiking, along with potential educational co-benefits. In economic terms, we expect the NEPSD investments will reduce water treatment and health costs associated with contaminated water sources and simultaneously boost recreational tourism demand.

3.3. NEPSD scenario Description

To simulate the key components of NEPSD, we implement a BASE or business-as-usual scenario and four intervention scenarios, each implemented at the Department level. A fifth scenario simultaneously implements all NEPSD interventions, representing the complete NEPSD policy package. The economic and statistical underpinnings of each scenario are described in detail in SI section 2.

The scenarios are as follows:

BASE: This scenario is the counterfactual reference scenario to which all other scenarios are compared. It presents the future trajectory of Uruguay's economy until 2050 in the absence of any new large public policies and investments. For each Department, due to the lack of Departmental data, we impose the same GDP growth rate across all Departments in the BASE. In the BASE, the exogenous part of Total

Factor Productivity growth is adjusted for consistency with the growth rates that are imposed. In non-BASE scenarios, GDP growth is invariably endogenous. We impose population projections by Department from INE (National Statistics Institute). In the BASE, we assume that exogenous variables such as government receipts and spending items grow at the same rate as GDP. The same assumption applies to non-government payments such as remittances and private foreign borrowing. For the non-BASE scenarios that follow, all these payments are assumed to be fixed at their BASE real values. In other words, we implicitly assume that they do not necessarily grow at the same rate of GDP.

INVEST: This scenario simulates the expenditure side of NEPSD by implementing an increase of $6 million in public investment. This investment is allocated to capital formation and services that contribute to achieving NEPSD goals.

GOVCAP: This scenario simulates NEPSD's first objective and the institutional strengthening and capacity building aspects of the Program. Twenty percent of the total investment is allocated to this component.

BUFFER: This scenario relates to NEPSD's second objective, aimed at reducing non-point source pollution that reaches waterways, specifically, through the planting of riparian buffers. To identify the areas requiring buffers, we consulted the Ministry of Environment's geospatial database, which documents the location and characteristics of legally compliant riparian buffers in the Santa Lucia and Laguna del Sauce watersheds; buffers in the Rio Negro were not included in the database at the time of writing.

We identified the areas in our BASE LULC map within the legislated riparian buffer zones that are uncompliant and/or not forested in all three watersheds and thus require tree planting under NEPSD. We established 30-meter buffers (15 m on each side of the waterway) for major waterways. Considering the three watersheds together, the total new buffer area is equal to 122,947 ha. This figure is slightly greater than the sum of areas withdrawn from cropland and grassland reported in Table 2 since it also includes withdrawals from LULC classes other than crops and grasslands. Fifty percent of the total investment is allocated to this component.

On the one hand, establishing riparian buffers reduces the total area available for crops and animal grazing. Accounting for the trees already present in the buffer zones, the planting of trees in buffers would remove 6,988 ha and 114,149 ha from total cropland (0.30%) and livestock pastureland (1.05%), respectively (Table 2). On the other hand, planting trees in buffers reduces overall rates of erosion in watersheds and provides pollinator habitat for adjacent farmland, which can positively impact agricultural productivity (Garibaldi et al., 2016; Klein et al., 2007; Panagos et al., 2018; Pimentel et al., 1995). In addition to these benefits, riparian buffers can improve water quality, with subsequent effects on tourism demand and water treatment costs.

SILVOPAST: This scenario simulates the implementation of sustainable productive silvopastoral systems in 5% of the Uruguayan area dedicated to livestock activities. This area amounts to 544,544 ha. Thirty percent of the total investment is allocated to this Program component. More sustainable and productive silvopastoral systems are able to maintain and enhance livestock output on a smaller land base with conservatively estimated productivity gains of up to 3% (Banerjee et al., 2023; Rodríguez, 2017). Additional measures in this intervention include limiting the access of cattle to watercourses, which reduces water contamination.

COMBI: This scenario is the simultaneous implementation of the INVEST, GOVCAP, BUFFER and SILVOPAST scenarios and represents the full impact of NEPSD Program.

4. Integrated Economic-Environmental modeling results

4.1. Land use land cover change and ecosystem service impacts

In the zoomed in view presented in Fig. 4, the riparian buffers planted in the COMBI scenario in 2050 on the right can be identified by comparing it with the BASE map on the left. The COMBI map reveals fill planting along the major waterways in the northeast of the Rio Negro watershed.

Fig. 5 (Panel A) presents erosion mitigation ecosystem services by major watershed. Erosion ES would improve the most in the Rio Negro, by 0.88% followed by the Santa Lucia watershed (0.12%). Continuing clockwise, climate regulation ES (Panel B) would be most enhanced in the Rio Negro (14.56%), Santa Lucia (3.65%) and Rio de La Plata (1.47%) watersheds. Water purification ES (Panel C) would improve the most in the Rio Negro, Santa Lucia and Rio de La Plata watersheds (3.45%, 0.44% and 0.27%, respectively). Water regulation ES (Panel D) would be most positively impacted in the Rio Negro, Santa Lucia and Rio de La Plata watersheds (1.41%, 0.26% and 0.15%, respectively).

Fig. 6 presents COMBI scenario impacts on climate regulation (Panel A), crop pollination (Panel B), water purification (Panel C), water

Table 2
Areas withdrawn from agricultural production by Department, in hectares and percent share as indicated.

	Cropland by Department	Grassland by Department	Buffer withdrawn from Cropland	Buffer withdrawn from grassland	Share withdrawn from cropland	Share withdrawn from grassland
Montevideo	7,041	1,262	1		0.0%	0.0%
Artigas	73,317	8,80,266	5	85	0.0%	0.0%
Canelones	46,607	1,66,944	−36	−1,307	−0.1%	−0.8%
Cerro Largo	1,06,866	9,67,413	−1,389	−8,161	−1.3%	−0.8%
Colonia	2,03,842	1,55,769	−13	−32	0.0%	0.0%
Durazno	1,05,754	8,66,129	−519	−19,157	−0.5%	−2.2%
Flores	1,31,330	3,38,651	−406	−9,090	−0.3%	−2.7%
Florida	57,169	6,35,046	−788	−15,662	−1.4%	−2.5%
Lavalleja	37,877	7,73,942		−2,354	0.0%	−0.3%
Maldonado	8,024	3,07,869	−41	−1,666	−0.5%	−0.5%
Paysandu	2,21,261	8,54,454	−2	−67	0.0%	0.0%
Rio Negro	2,92,730	3,95,566	−699	−10,207	−0.2%	−2.6%
Rivera	34,490	6,50,427	−833	−12,705	−2.4%	−2.0%
Rocha	1,33,238	7,00,067	−6	−4	0.0%	0.0%
Salto	81,732	9,14,115	−5	−38	0.0%	0.0%
San Jose	82,842	1,62,620	−2	−542	0.0%	−0.3%
Soriano	4,62,604	2,76,650	−1,124	−8,337	−0.2%	−3.0%
Tacuarembo	68,636	12,01,261	−1,137	−23,504	−1.7%	−2.0%
Treinta-y-Tres	1,44,999	6,42,429	6	−1,403	0.0%	−0.2%
Total	23,00,359	1,08,90,880	−6,988	−1,14,151		

Source: IEEM + ESM results.

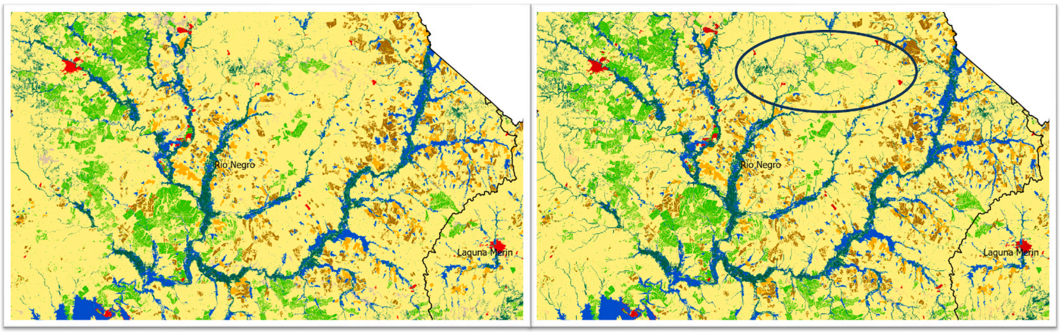


Fig. 4. Zoomed-in view of BASE (left) and COMBI (right) scenarios in 2050 indicating areas of planting riparian buffers. . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: IEEM+ESM results. Note: Oval shape on the map (right) indicates one area of riparian buffer planting where the green around waterways is more intense. Map legend follows that of Fig. 2

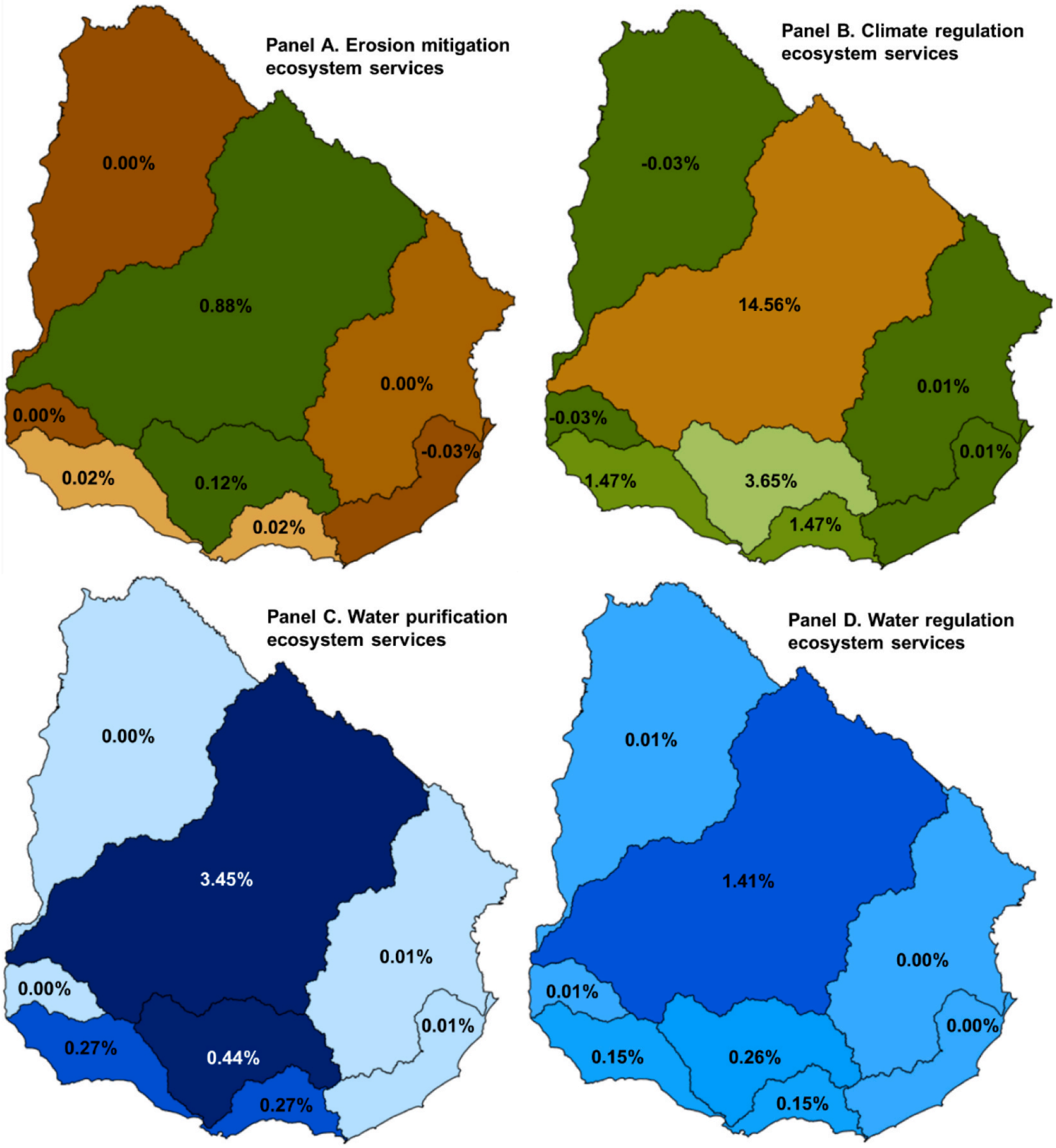


Fig. 5. Beginning at the top left moving clockwise, COMBI scenario impacts on erosion mitigation, climate regulation, water regulation and water purification ecosystem services as a percent difference from BASE in 2050. .
Source: IEEM+ESM results

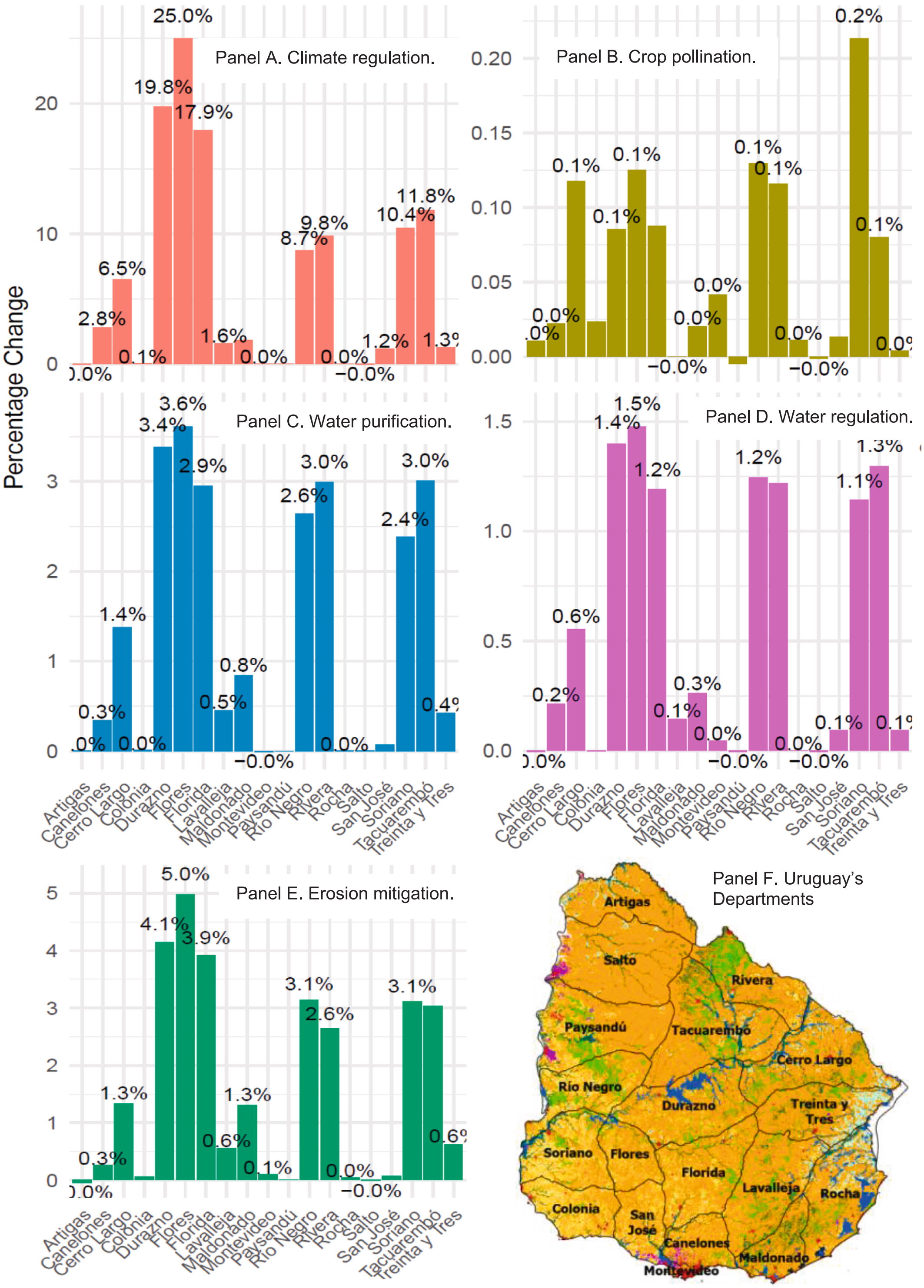


Fig. 6. COMBI scenario impacts on climate regulation, crop pollination, water purification, water regulation and erosion mitigation (Panels A, B, C, D and E, respectively) as a percent difference from BASE in 2050, for 19 departments of Uruguay (Panel F). .
Source: IEEM+ESM results

regulation (Panel D) and erosion mitigation (Panel E) ES by department in 2050. In general, impacts would be positive across Departments and in numerous cases, those Departments experiencing the greatest positive impacts for one ES would also experience relatively large positive impacts in other ES. Climate regulating ES would be especially enhanced in Florida, Durazno and Flores. Crop pollination services would increase the most in Soriano and Flores. Water purification ES would increase the most in Flores, Tacuarembó and Rivera. Water regulation ES would be most positively affected in Flores, Durazno and Tacuarembó. Erosion mitigation ES would be enhanced the most in Flores, Durazno and Florida.

Table 3 presents COMBI scenario impacts on ES expressed in monetary terms. The Table provides a somewhat different picture than Fig. 6 since large percentage change impacts in Fig. 6 could be more symptomatic of changes arising from relatively small BASE values rather than outsized impacts. In Table 3, food provisioning services would decline

Table 3
Cumulative ecosystem service flows in 2050 in millions of (2023) US Dollars.

Department	Food provisioning	Forestry provisioning	Water purification, Tourism	Water purification, Treatment Cost	Erosion mitigation	Crop pollination
Artigas	11.3	0.0	0.3	0.1	0.0	0.5
Canelones	28.9	0.0	2.4	2.4	0.2	4.7
Cerro Largo	−50.3	0.7	0.3	0.5	0.2	3.5
Colonia	142.8	0.0	0.9	0.2	0.1	2.1
Durazno	−103.3	1.3	0.2	0.3	0.4	2.5
Flores	−48.4	0.1	0.1	0.1	0.5	3.7
Florida	−48.5	0.6	0.3	0.3	0.3	1.6
Lavalleja	−1.2	0.7	0.3	0.5	0.1	0.3
Maldonado	−2.2	0.0	1.8	1.5	0.1	1.7
Montevideo	2.4	0.0	19.2	5.5	1.0	14.5
Paysandu	33.8	0.7	0.5	0.2	0.0	−0.5
Rio Negro	−52.0	0.9	0.4	0.7	0.9	8.7
Rivera	−75.2	1.8	0.4	0.6	0.3	1.9
Rocha	16.3	0.2	0.4	0.1	0.0	0.7
Salto	23.2	0.0	0.5	0.2	0.0	0.2
San Jose	133.8	0.0	0.2	0.8	−0.2	1.0
Soriano	−32.3	0.2	0.4	0.5	0.9	23.0
Tacuarembo	−135.9	2.0	0.3	0.5	0.3	1.6
Treinta-y-Tres	0.5	0.2	0.2	0.1	0.2	0.2
National	−156.3	9.3	29.1	14.8	5.4	71.8

Source: IEEM + ESM results. Note that climate and water regulation ecosystem services are not reported in this table since they are not valued in monetary terms.

the most in Tacuarembó (US$135.9 million) and Durazno (US$103.3 million) and would increase the most in Colonia and San Jose (US$142.8 million and US$133.8 million, respectively). Tacuarembó, Rivera and Durazno would experience the greatest increase in forestry provisioning ES (US$2.0 million, US$1.8 million and US$1.3 million, respectively). Water purification ES proxied for by changes in tourism demand would increase the most in Montevideo, Canelones and Maldonado (US$19.2 million, US$2.4 million and US$1.8 million, respectively). Water purification ES proxied for by changes in water treatment costs would increase the most in Montevideo, followed by Canelones and Maldonado (US$5.5 million, US$2.4 million and US$1.5 million, respectively).

Erosion mitigation ES would improve the most in Montevideo, Rio Negro and Soriano (US$1.0 million, US$0.9 million and US$0.9 million, respectively). Crop pollination ES would be most improved in Soriano (US$23.0 million), followed by Montevideo (US$14.5 million) and Rio Negro (US$8.7 million). Overall, the NEPSD investment would positively affect forestry provisioning, water purification, erosion mitigation and crop pollination ES by US$9.3 million, US$43.9 million, US$14.8 million, US$5.4 million and US$71.8 million, respectively. Food provisioning ES would be the only ES negatively affected with a net reduction of US$156.3 million.

In terms of carbon emissions, COMBI, with its greater pace of economic growth, would result in an additional 8.61 kilotons (kt) of CO_2e emitted from the increased consumption of fossil fuels. This would be offset through the increase in climate regulation services delivered by NEPSD with an additional 15,170 kt of carbon stored, equivalent to 55,674 kt of CO_2e. Net emissions with NEPSD Program implementation would thus be a 55,665 kt reduction in CO_2e. If a monetary value were to be assigned to the carbon emissions avoided, following Lange et al. (2018) and The World Bank (2021) using a value of US$20 tons of CO_2e emissions, the NEPSD Program would generate an additional US$1.1 billion in climate regulation ES which is notably more than all other ES combined.

4.2. Economic impacts

Table 4 shows the individual contribution of each of the NEPSD Program components on key macroeconomic indicators in cumulative terms in 2050. Focusing on GDP, the INVEST scenario would have a negative impact as would the BUFFER scenario, on the order of US$46.6 million and US$1,983.9 million, respectively. All other scenarios would make net positive contributions to GDP. The SILVOPAST scenario would make the greatest contribution to GDP followed by the GOVCAP scenario (US$2,412.1 million and US$362.4 million, respectively). The overall impact of the NEPSD Program on GDP would be US$748.2 million. Impacts on wealth would be positive though less than impacts on GDP. Cumulative wealth would increase with NEPSD implementation, by US$166 million. A sensitivity analysis confirms the robustness of the parameter assumptions used in the water quality interventions (SI section 4). In this sensitivity analysis, positive GDP and wealth impacts persist even under highly conservative assumptions where the tourism visitation elasticity and water treatment cost shocks are reduced by 50%.

Table 4
Cumulative impacts on macroeconomic indicators in millions of (2023) US Dollars.

	INVEST	GOVCAP	BUFFER	SILVOPAST	COMBI
GDP	−47	362	−1,984	2,412	748
Wealth	−7	163	−568	580	166
Private consumption	−45	951	−1,681	2,061	1,311
Private fixed investment	−17	165	−596	608	164
Exports	−20	259	−1,075	1,047	148
Imports	−8	183	−948	894	178

Source: IEEM + ESM results.

Table 5 provides a Departmental-level break-down of impacts on key macroeconomic indicators for the COMBI scenario. Focusing on GDP, the most important impacts would be found in Montevideo, followed by Colonia and San Jose. The wealth impacts also follow this trend. More negative impacts would be found in Tacuarembó, Durazno and Rivera.

Fig. 7 presents the individual contributions of the NEPSD scenarios to net present value, considering a 12% opportunity cost of capital, which is the standard discount rate used by some multilateral development banks including the Inter-American Development Bank (Banerjee et al., 2019; IDB, 2019). The full NEPSD investment would result in a US$290 million return on the investment. The SILVOPAST scenario would make the greatest contribution to net present value followed by GOVCAP (US $430 million and US$199 million, respectively). The BUFFER scenario presents a negative US$329 million net present value though the combination of all other scenarios would offset this negative impact.

Table 5
COMBI scenario impacts on macroeconomic indicators by Department as a difference from BASE in millions of (2023) US Dollars.

Department	Private consumption	Investment	Exports	Imports	GDP	Wealth
Artigas	54.8	2.4	7.9	9.9	44.9	2.5
Canelones	116.3	15.7	−1.2	11.4	53.6	4.9
Cerro Largo	33.3	3.0	−6.4	−2.9	4.2	−14.5
Colonia	127.2	7.8	−17.8	50.1	142.4	43.1
Durazno	−2.5	2.3	−0.3	−8.9	−35.6	−24.2
Flores	5.6	1.3	−0.3	−4.5	−16.1	−16.9
Florida	67.0	3.1	−8.2	6.5	18.7	−35.0
Lavalleja	44.6	2.6	10.0	10.4	34.6	3.1
Maldonado	58.3	9.2	12.9	6.6	32.0	18.5
Montevideo	381.9	83.3	97.2	24.3	213.7	205.6
Paysandu	82.0	4.7	8.4	16.1	66.5	6.7
Rio Negro	23.9	3.8	11.5	2.8	−8.1	−16.8
Rivera	0.4	3.5	−2.3	−10.6	−24.0	−8.5
Rocha	54.0	3.0	7.5	11.2	45.5	5.8
Salto	67.8	4.5	13.7	9.7	56.5	10.7
San Jose	121.4	4.8	0.7	48.3	131.5	29.9
Soriano	37.7	3.9	14.2	2.5	5.7	−14.9
Tacuarembo	4.7	3.1	−5.5	−11.3	−44.2	−35.9
Treinta-y-Tres	32.9	2.0	6.0	6.4	26.2	2.3
National	1,311.3	164.1	148.0	177.9	748.2	166.4

Source: IEEM + ESM results.

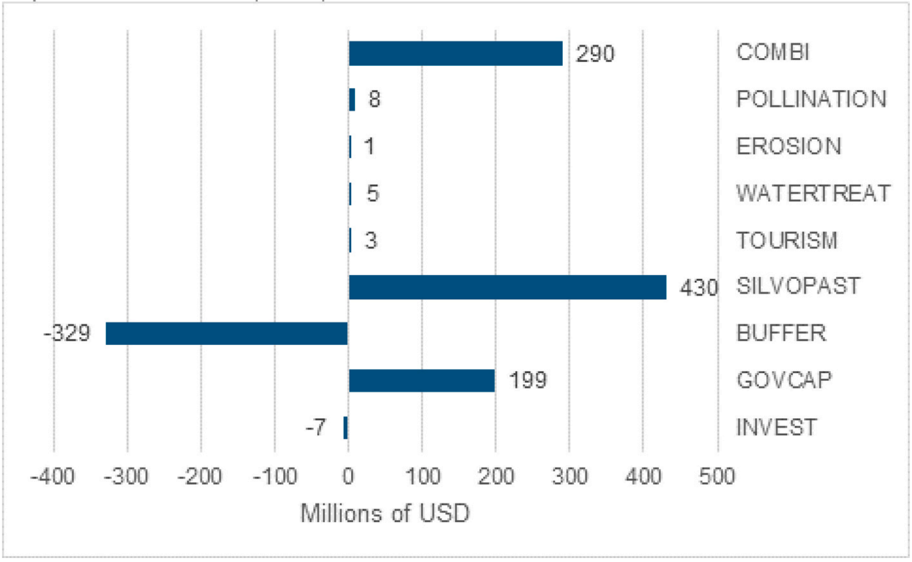


Fig. 7. Net Present Value contribution of each scenario with a 12% opportunity cost of capital in millions of (2023) US Dollars. .
Source: IEEM+ESM results

5. Discussion and Conclusions

5.1. Interpretation of key results

Results of this study show that overall, the NEPSD Program would have a positive effect on the economy, the environment and Uruguayan society. Cumulative GDP and wealth would be enhanced by US$748.2 million and US$166.4 million, respectively. The Program would generate a US$290 million return, against US$6 million upfront investment cost. Regulating ES would be positively impacted by US$130.4 million though this would not quite offset the entirety of the food provisioning ES decline (US$156.3 million). NEPSD would increase the combustion of fossil fuel by 8.61 KT of CO_2e, though this would be more than offset by the NEPSD-driven increase in climate regulation services, with an additional 15,170 KT of carbon stored. This net 55,665-KT reduction in CO_2e would make an important contribution to Uruguay's Nationally Determined Contributions (Republica Oriental del Uruguay, 2024). If a conservative value of carbon is assigned to these emissions reductions, the NEPSD Program would generate an additional US$1.1 billion in climate regulation ES, outweighing the value of all other ES combined.

Considering the impact of the individual components of the NEPSD Program on economic indicators, the investment (INVEST) scenario alone would result in a decline in GDP and wealth, due to a crowding out effect of private investment (US$46.6 million and US$7.5 million, respectively). This crowding out is a short-run phenomenon that is somewhat common where only the effects of the public investment are considered (Afonso and Aubyn, 2008; Argimon et al., 1997; Banerjee et al., 2015). The establishment of riparian buffers (BUFFER) would have a relatively large and negative impact on GDP, but the wealth impacts would be just 29% of the GDP impacts. The smaller negative impact on wealth occurs because wealth accounts for changes in natural capital stocks and environmental quality, both of which would be enhanced with the implementation of riparian buffers.

Improving the management of livestock production through more productive and efficient silvopastoral systems (SILVOPAST) would strongly enhance GDP and wealth. At the national level, the contribution of this component of NEPSD was sufficient to compensate for the land withdrawn from agricultural production necessary for the establishment of riparian buffers. This is an indication to policy makers that if agricultural output is to be maintained or increased, enhancing silvopastoral systems would be an effective approach to offsetting the output effects of riparian buffers as these silvopastoral systems increase the efficiency of resource use on a finite land base.

With regard to the ES impacts of the NEPSD Program, climate regulation, crop pollination, water purification, water regulation and erosion mitigation ES would increase across almost all Departments. Of the regulating ES, and excluding the expost valuation of climate regulation ES, crop pollination would make the greatest economic contribution (US$71.8 million) by increasing habitat availability for crop pollinators, which increases the productivity of pollination-dependent crops. Notably, 33% of the crops grown in Uruguay exhibit some level of dependence on insects for their pollination, including soybean, oranges and other citrus, tomatoes, apples and pears. While we consider only the agricultural productivity effects of changes in pollinator abundance, there is an emerging body of literature highlighting the nutritional importance of adequately pollinated crops for human diets and health (Chaplin-Kramer et al., 2014; Garibaldi et al., 2022; Katumo et al., 2022; Smith et al., 2022, 2015).

By implementing the NEPSD Program, water purification ES would generate an additional US$43.9 million in value followed by US$5.4 million from erosion mitigation ES. The relatively small impact on erosion mitigation ES compared with some previous IEEM + ESM applications (Banerjee et al., 2023; Banerjee et al., 2025b) is related to the size of the policy interventions as well as Uruguay's mostly flat topography, especially in riparian areas where riparian buffers would be targeted. Changes in land cover and land management practices on more steeply sloped topographies have a more pronounced effect on erosion mitigation ES.

Reductions in eutrophic conditions and algal blooms would be an important contribution from establishing riparian buffers, especially in the Uruguayan context. While these ES values are non-trivial ($43.9 million), the implementation of NEPSD would entail a relatively small amount of land cover change in buffer areas in the priority watersheds, equivalent to 0.71% of Uruguay's total land area. Applications of our methods to larger policy and investment programs with more widespread impacts have yielded greater impacts on ES, for example, large-scale initiatives for afforestation and forest restoration, among others (Banerjee et al., 2025a; Banerjee and Cicowiez, 2022).

The NEPSD Program reduced sediment loads substantively, by almost 120 million tons. Depending on the location of these reductions, hydropower generation and the costs of generating electricity could be affected. Sedimentation can affect hydropower generation and costs by reducing reservoir storage capacity and physically damaging hydropower turbines (Annandale et al., 2016; Kumar and Saini, 2022; Mussi et al., 2023; Perera et al., 2023; Schellenberg et al., 2017). Interactions between sediment loads and hydropower generation present additional benefits of the NEPSD Program beyond the economic contribution of ES that were quantified in this study.

Finally, with regard to trade-offs, in the absence of complementary policies, the withdrawal of land for the creation of riparian buffers would have a negative impact on food provisioning ES while enhancing the supply of other ES. In many countries where food insecurity prevails, this trade-off may not be politically acceptable. The case of Uruguay may be different, however, since it is a large exporter of food and is currently capable of feeding up 28 million people, or over three times its current population. The quality of these calories in terms of the composition of a healthy diet would require deeper examination, however (Juri et al., 2022; Perazzoli, 2019).

5.2. Regulating ecosystem services and water purification in integrated frameworks

A frontier area for integrated economic-environmental modeling is the inclusion of regulating ES, which are critical for underpinning the supply of other ES, human health and safety, and environmental quality (Bennett et al., 2009; Power, 2010). The challenge of integrating regulating ES in IEEM + ESM and other integrated frameworks lies in: (i) establishing a quantitative linkage or transmission pathway between a modeled change in the biophysical supply of the service and a change in human well-being which is captured by a change in one or more variables in the economic model (IEEM + ESM), and; (ii) developing heuristics that enable the calculation and implementation of an economic shock to account for the modeled changes in ES supply for applicability across countries and contexts in a rapidly deployable manner.

If the integration of the ES is not generalizable across countries with small adjustments, case-by-case integration is possible but requires more time and expense. The focus of IEEM since its conceptualization (Banerjee et al., 2016) has been on developing tools that can be rapidly deployed to inform the policy cycle and meet the demands from policymakers and multilaterals in real-time. In this paper, we have advanced integrated analytical frameworks by demonstrating proof of concept of the integration of water purification services in a macroeconomic model and developed the heuristics for rapid IEEM deployment in other countries. Future work on integration of water purification ES with macroeconomic models could seek to incorporate the sustainability of this ES relative to eutrophication thresholds (for example, La Notte et al. (2017) and La Notte and Dalmazzone (2018)). However, doing so requires the use of more sophisticated and calibrated models capable of quantifying in-stream nutrient concentrations, which are less likely to have the needed data available and to be rapidly deployable in decision contexts for which IEEM + ESM was developed.

Clean water interacts with human well-being in numerous ways. Our approach for integrating water purification services in IEEM focused on two such aspects: demand for water-based recreational activities and water quality effects on water treatment costs. The global significance of water-based tourism contributes to the generalizability of the approach to integrate water quality within other integrated economic-environmental analytical frameworks. Most countries across the world offer water-based tourism opportunities. Notably, coastal tourism is responsible for approximately 50% of global tourism demand and accounts for US$4.6 trillion (5.2%) of global GDP (Northrop, 2022). Lake and riverine-based tourism also deliver important benefits to local economies. For example, in the United States, these activities generated US$12.7 billion in spending and directly supported 210,000 jobs (United States Army Corps of Engineers, 2023).

Improvements to the econometrically estimated relationship between water quality and tourism demand stand to be made. As noted earlier, we were able to identify only one study which estimated this relationship and used variables commonly available in different country contexts while compatible with the relevant variables in IEEM and the outputs of the InVEST Nutrient Delivery Ratio model. The Breen et al. (2018) study was based on survey data from waterways for just one country, Ireland, which is an obvious limitation. The implementation of new studies in countries with varying biophysical and socioeconomic contexts would enable *meta*-analysis and could improve the current formulation. In this study, we have demonstrated proof of concept and left the door open for further refinement as the science advances.

The integration of water quality's effects on water treatment cost is also generalizable across countries that abstract surface water for consumptive purposes. Water supply systems are affected by LULC management practices in raw water source watersheds (Cazcarro et al., 2016; McDonald et al., 2016; Price and Heberling, 2018). Where information on source watersheds and treatment costs is readily available as in the Uruguayan case, this integration can be based entirely on local data on the source watersheds and domestic water treatment costs. In the absence of country-specific data, global estimates are emerging which relate population density and agricultural land use in source watersheds with sediment and nutrient loads. McDonald et al. (2016), for example, found that for a 10% increase in cropland utilization, there would be a 1.6%, 1.3% and 0.1% increase in sediment, nitrogen and phosphorous loading, respectively. In the absence of local data, such global estimates could be readily integrated into frameworks such as IEEM + ESM.

In terms of water quality impacts on water treatment costs, one key consideration is the lag time between the on-the-ground intervention, the establishment of riparian buffers in this case, and water quality improvements in Uruguayan waterways. We based our estimates of lag times on the available evidence (Meals et al., 2010), though additional research in this area would be valuable to improve the knowledge base on the effectiveness of green infrastructure, including riparian buffers, in contributing to regulating ES.

In addition to water quality interactions with tourism demand and water treatment costs, other interactions between clean water and human well-being could be considered. For example, cleaner water abstracted from surface water bodies in rural areas can have important health implications with economic value, from improved labor productivity to reduced sickness and related health care costs (Carr and Neary, 2008; Lin et al., 2022; Russ et al., 2022). These relationships can be captured in integrated frameworks such as IEEM + ESM where the marginal effect of a water quality improvement can be linked to labor productivity and expenditures on healthcare. In the case of Uruguay, however, since the country has achieved near universal access to safe drinking water, this linkage would be less relevant though certainly important for low-income, developing countries with limited access to safe drinking water.

Notably, our approach to integrating ES into IEEM generates as a byproduct an estimate of the economic value of that ES. In the case of erosion mitigation and crop pollination ES, we use a production function approach to valuation. In the case of water purification ES, observed prices are used in the valuation. Both approaches are considered to provide the highest level of accuracy and spatial resolution of all the methods compatible with the principles of the System of National Accounts and the System of Environmental-Economic Accounting, Ecosystem Accounting (i.e., Tier 3 valuation methods; NCAVES and MAIA, 2022; UN et al., 2024). This compatibility with national accounting frameworks carries enhanced credibility with government decision makers including Ministries of Finance responsible for national budget allocations, since results generated with IEEM + ESM are consistent with the government's own national accounting framework.

What is the scope for integrating additional ES into integrated economic-environmental frameworks such as IEEM + ESM? First, it is useful to review the ES that are currently captured in IEEM + ESM and to what degree they are represented. IEEM on its own generates results on most provisioning ES including food, timber, fisheries, fuel and mining assets. Cultural and recreational ES are represented through changes in tourism and recreational demand related to scenario-driven impacts on natural capital assets. Thus far, IEEM has been linked to erosion mitigation, climate regulation (carbon storage), water regulation (both seasonal and annual), water purification, crop pollination and coastal protection spatial ES modeling with results generated in biophysical units. The dynamic IEEM + ESM workflow has integrated erosion mitigation, crop pollination and water purification ES where periodic changes in ES flows resulting from policy or investment interventions affect the decisions of economic agents in the model. In this workflow, marginal economic values for those ES considered are generated. The integration of these ES and feedbacks between economic variables in IEEM and ES are sensible because impacts on the flows of these ES are generally achievable by the actions of a single country.

There are some ES, however, where the actions of a single country are generally insufficient to affect the flow of that ES and associated environmental and economic outcomes. Various aspects of climate regulation ES fall under this category. For example, for a country the size of Uruguay, while investments to reduce emissions will contribute to reducing global emissions, its own actions are likely to have a limited impact on sea level rise, extreme events and global precipitation and temperature patterns. While potentially small on a global scale, these impacts are still important. To account for these climate impacts, we integrate climate damage functions (Banerjee et al., 2025a, 2024a; Roson and Sartori, 2016) in IEEM + ESM. Policy scenario analysis in this context then considers global cooperation to reduce emissions which is indeed expected to have an impact mitigating climate change. This has been our approach to capturing climate regulation impacts in various IEEM+ESM contributions to the World Bank's Country Climate and Development Reports and other climate relevant analyses (Banerjee et al., 2025a, 2024a; Banerjee and Cicowiez, 2025).

While climate-driven hazards like landslides and flooding can be modeled spatially, their high degree of local specificity limits the generalizability of such integration across different countries. This trade-off between local precision and global applicability is the primary reason these services have not yet been standardized within IEEM + ESM. Nevertheless, we are currently advancing the framework's frontier by linking flood mitigation and air quality regulation via the INCA models (Vallecillo et al., 2019, 2020) in a forthcoming IEEM + ESM application for Malaysia.

It is our view that we are approaching a practical limit to the integration of ES into macroeconomic frameworks like IEEM while maintaining generalizability and rapid deployment capabilities. With the inclusion of (i) most provisioning, cultural, and recreational services, alongside erosion mitigation, water purification and pollination; (ii) the biophysical treatment of water regulation and coastal protection; and (iii) damage functions for climate regulation, IEEM + ESM now captures the most critical economic feedbacks. Integrating services beyond this core set becomes increasingly context-specific. For example, modeling impacts on local microclimates requires highly localized data and unique transmission pathways that are difficult to generalize across countries.

Generalizability and standardized heuristics are critical for enabling the rapid deployment of IEEM + ESM, allowing for policy feedback within a timeframe of days to a few weeks. While bespoke, more complex integrations are possible, they invariably extend development timelines beyond the practical needs demanded for agile decision making. Future advancements in model interoperability and reusability (Bagstad et al., 2025), i.e., to more effectively represent context-specific transmission pathways, may eventually mitigate this trade-off. For now, however, the tension between the additional integration of more context-specific ES and rapid deployment capabilities remains a defining constraint for integrated modeling.

5.3. *The multiregional approach*

In addition to advancing the integration of water purification ES in a macroeconomic model, this work develops the first multi-regional, dynamic IEEM + ESM framework. This spatial disaggregation shifts the analysis from national averages to Department-level specificity, enabling the precise targeting of investments and the reporting of localized results. Furthermore, a multiregional approach illuminates critical inter-regional tradeoffs by quantifying asymmetric impacts across jurisdictions. Providing such detailed distributional analysis is vital for informing equity considerations and crafting policy mechanisms that mitigate potential disparities between regions.

In this study, this regional dimension revealed interesting consequences of NEPSD Program implementation. When we consider the land that is withdrawn from production for riparian buffers (Table 2), we find that seven Departments – Cerro Largo, Durazno, Florida, Río Negro, Rivera, Soriano and Tacuarembó – would face some of the largest withdrawals. This is especially true in the case of grassland, where withdrawals range from around 8,000 ha to over 23,000 ha. Based on this finding, we may expect that these same Departments would face the largest negative impacts on GDP on a relative basis.

Our multi-regional IEEM + ESM approach, however, presented a more nuanced picture (Table 5). Instead, we found that Cerro Largo, for example, would experience a positive impact on GDP with the full implementation of NEPSD, as would Florida and Soriano – three of the same Departments experiencing large withdrawals of land for buffers. The reason for the positive impacts on these Departments, despite experiencing larger land withdrawals, is explained by the fact that they receive a relatively larger increase in investment in sustainable silvopastoral systems. Indeed, they are Departments that have relatively larger pasture areas.

Departmental-level changes in ES are also notable (Table 3). While at the national level, ES gains would nearly offset losses in food provisioning ES, some departments would experience large gains in food provisioning services (e.g., Colonia, San Jose) and others would face large declines (Durazno, Rivera, Tacuarembó). Montevideo would experience notable gains primarily from pollination and tourism ES, while several departments (e.g., Lavalleja, Maldonado, Soriano) would experience declines in food provisioning services while being offset by increases in other ES. By identifying the beneficiaries of these ES gains and losses, policies to address inequities could be better designed to account for this spatial heterogeneity in ES impacts.

Thus, the multiregional approach is powerful in its ability to identify Departments that would experience disproportionately larger impacts with policy implementation. As we see from the example above, simply identifying the Departments that would suffer larger land withdrawals would not provide an accurate view of which Departments would be most affected from an economic perspective. The correct identification of the most affected Departments enables the formulation of complementary policies that can offset negative impacts, for example, increasing their share of sustainable silvopastoral systems. In general, the results generated could inform the refinement of the NEPSD investment strategy to reallocate more investment to those Departments that stand to lose from NEPSD implementation, thereby distributing benefits more equitably from a regional perspective.

It is worth noting that development of a multi-regional framework involves a significant increase in effort above that required for a single region or single country IEEM application. Analysts will need to weigh the advantages of the multiregional approach versus the costs. Requirements to build a basic multiregional database include: (i) an indicator such as sectoral output by region or sectoral employment by region that enables allocation of sectoral production across regions; (ii) an indicator that enables allocating household consumption across regions such as regional population and household consumption per capita per region; (iii) factor endowments by region, and; (iv) estimates of interregional trade and the regional exports and imports to and from the rest of the world.

Where policy and investment interventions do not involve a spatial component, the advantages of applying a multi-regional framework likely do not outweigh the costs. Where a national-level policy is the subject of analysis, for example, a change in household income tax, the multi-regional approach may provide limited additional insights. In the case of a change in indirect taxes on firms, however, the multi-regional approach could shed light on which sectors in each region would be more affected by the change, providing actionable data to target complementary policies. Certainly, as shown in this study, where policies and investments are oriented toward natural capital and ES, there is often a strong spatial component, which the multi-regional framework can shed light on.

5.4. Concluding Remarks

The analysis of NEPSD underscores its multifaceted benefits for Uruguay's economy, environment and society. Despite some short-term trade-offs, the overall results point to substantial long-term gains including significant increases in GDP, wealth and the value of future ES flows. The multiregional approach captures spatial heterogeneity in both environmental outcomes and economic dynamics, providing the granularity needed for targeted equitable and efficient policy design. Moreover, the integration of water purification ES into a macroeconomic model such as IEEM marks an important advancement in the quantification of non-market ecological benefits alongside traditional economic metrics. Spatially explicit economic and ES analytics generated with IEEM + ESM enable a more nuanced understanding of trade-offs and synergies across sectors and regions, offering a replicable model for other nations with varying biophysical and socio-economic contexts.

CRediT authorship contribution statement

Onil Banerjee: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Martin Cicowiez:** Writing – review & editing, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Kenneth J. Bagstad:** Writing – review & editing, Visualization, Validation, Software, Methodology, Data curation. **Matías Piaggio:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Renato Vargas:** Writing – review & editing, Visualization, Software, Methodology. **Pablo Kok:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was developed with funding from RMGEO Consultants Inc. (Project: Globalizing IEEM + ESM Infrastructure and Analytics; Grant Agreement JS-2026) and the generous contributions of co-authors' time. Special thanks are given to Nirendra Nath Banerjee and Julieta Do Carmo Banerjee. The views expressed here are those of the authors and do not necessarily represent the official position of the Data Foundation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2026.101853.

Data availability

Data will be made available on request.

References

Afonso, A., Aubyn, M., 2008. Macroeconomic rates of return of Public and Private Investment: Crowding-In and Crowding-out Effects. European Commission, Frankfurt.

Aguilera, A., Haakonsson, S., Martin, M.V., Salerno, G.L., Echenique, R.O., 2018. Bloom-forming cyanobacteria and cyanotoxins in Argentina: a growing health and environmental concern. Limnologica 69, 103–114. https://doi.org/10.1016/J.LIMNO.2017.10.006.

Aminu, M., Matori, A.-N., Yusof, K.W., Malakahmad, A., Zainol, R.B., 2015. A GIS-based water quality model for sustainable tourism planning of Bertam River in Cameron Highlands, Malaysia. Environ. Earth Sci. 73, 6525–6537. https://doi.org/10.1007/s12665-014-3873-6.

Anido, C., 2021. Las cianobacterias presentes en las playas de Montevideo, Uruguay en 2018-2019 revelan un conflicto ambiental creciente. Carlos Anido congreso AUGM 2019.

Annandale, G.W., Morris, G.L., Karki, P., 2016. Extending the Life of Reservoirs. World Bank Publications - Books.

Argimon, I., Gonzalez-Paramo, J.M., Roldan, J.M., 1997. Evidence of public spending crowding-out from a panel of OECD countries.

Arrow, K.J., 2005. Personal Reflections on Applied General Equilibrium Models. Cambridge University Press, Cambridge.

Aubriot, L., Zabaleta, B., Bordet, F., Sienra, D., Risso, J., Achkar, M., Somma, A., 2020. Assessing the origin of a massive cyanobacterial bloom in the Río de la Plata (2019): Towards an early warning system.

Bagstad, K.J., Balbi, S., Adamo, G., Athanasiadis, I.N., Affinito, F., Willcock, S., Magrach, A., Hayashi, K., Harmáčková, Z.V., Niamir, A., Smets, B., Buchhorn, M., Drakou, E.G., Alfieri, A., Edens, B., Morales, L.G., Vári, Á., Sanz, M.-J., Villa, F., 2025. Interoperability for ecosystem service assessments: why, how, who, and for whom? Ecosyst. Serv. 72, 101705. https://doi.org/10.1016/j.ecoser.2025.101705.

Banerjee, O., Bagstad, K.J., Cicowiez, M., Dudek, S., Horridge, M., Alavalapati, J.R.R., Masozera, M., Rukundo, E., Rutebuka, E., 2020. Economic, land use, and ecosystem services impacts of Rwanda's Green Growth strategy: an application of the IEEM+ESM platform. Sci. Total Environ. 729.

Banerjee, O., Cicowiez, M., 2025. Integrated Economic-Environmental Modeling (IEEM) Analytics to support Malaysia's Country climate and Development Report of the World Bank. RMGEO Consultants Inc., Bangkok.

Banerjee, O., Cicowiez, M., 2022. Integrated Economic-Environmental Modeling (IEEM): India's Nationally Determined Contribution. RMGEO Consultants Inc., Jakarta.

Banerjee, O., Cicowiez, M., Gachot, S., 2015. A Framework for Ex-Ante Economic Impact Assessment of Tourism Investments. Inter-American Development Bank, Washington DC.

Banerjee, O., Cicowiez, M., Honeck, E.C., Dechjejaruwat, R., Markandya, A., Pollitt, H., Muthukumara, M.S., 2024a. Arresting environmental degradation to build wealth in Thailand. Sci. Total Environ. 956, 177386. https://doi.org/10.1016/j.scitotenv.2024.177386.

Banerjee, O., Cicowiez, M., Horridge, M., Vargas, R., 2016. A Conceptual Framework for Integrated Economic–Environmental Modeling 25.

Banerjee, O., Cicowiez, M., Macedo, M.N., Malek, Ž., Verburg, P.H., Goodwin, S., Vargas, R., Rattis, L., Bagstad, K.J., Brando, P., Coe, M.T., Neill, C., Marti, O.D., Murillo, J.Á., 2022. Can we avert an Amazon tipping point? The economic and environmental costs, Environmental Research Letters, p. 17.

Banerjee, O., Cicowiez, M., Malek, Ž., Verburg, P.H., Vargas, R., Goodwin, S., Bagstad, K. J., Murillo, J.Á., 2023. Banking on strong rural livelihoods and the sustainable use of natural capital in post-conflict Colombia. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-023-03740-w.

Banerjee, O., Cicowiez, M., Moreda, A., 2019. Evaluating the Economic Viability of Public Investments in Tourism. Journal of Benefit Cost Analysis 11, 101–130.

Banerjee, O., Cicowiez, M., Honeck, E.C., Muthukumara, M.S., Stapleton, K.A., 2025a. Investing in forests Enhances ecosystem services and economic growth in Cambodia: evidence from the Integrated Economic-Environmental Modelling (IEEM) approach. Ecosyst. Serv. 71, 101695. https://doi.org/10.1016/j.ecoser.2024.101695.

Banerjee, O., Cicowiez, M., Garcia-Trujillo, G., Bagstad, K.J., Dudek, S., Johnson, J.A., Albagli, E., Gonzalez, M., Yung, M.A., 2025b. Land Use Strategies for Achieving Chile's Nationally Determined Contributions. Environ. Res. Ecol. 4, 3. https://doi.org/10.1088/2752-664X/adf22f.

Banerjee, O., Cicowiez, M., Vargas, R., Molina-Pérez, E., Bagstad, K.J., Malek, Z., 2024b. The Economics of Decarbonizing Costa Rica's Agriculture. Forestry and Other Land Uses Sectors, Ecological Economics, p. 208.

Beltran, C., 2019. Las cianobacterias no aflojan y sitian la capital. El Pais.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404. https://doi.org/10.1111/j.1461-0248.2009.01387.x.

Breen, B., Curtis, J., Hynes, S., 2018. Water quality and recreational use of public waterways. J. Environ. Econ. Policy 7, 1–15. https://doi.org/10.1080/21606544.2017.1335241.

Carr, G.M., Neary, J.P., 2008. Water quality for ecosystem and human health. Unep/earthprint.

Cazcarro, I., López-Morales, C.A., Duchin, F., 2016. The global economic costs of the need to treat polluted water. Econ. Syst. Res. 28, 295–314. https://doi.org/10.1080/09535314.2016.1161600.

Chaplin-Kramer, R., Dombeck, E., Gerber, J., Knuth, K.A., Mueller, N.D., Mueller, M., Ziv, G., Klein, A.-M., 2014. Global malnutrition overlaps with pollinator-dependent micronutrient production. Proc. R. Soc. B Biol. Sci. 281, 20141799. https://doi.org/10.1098/rspb.2014.1799.

Chaplin-Kramer, R., Hamel, P., Sharp, R., Kowal, V., Wolny, S., Sim, S., Mueller, C., 2016. Landscape configuration is the primary driver of impacts on water quality associated with agricultural expansion. Environ. Res. Lett. 11, 074012. https://doi.org/10.1088/1748-9326/11/7/074012.

Cole, L.J., Stockan, J., Helliwell, R., 2020. Managing riparian buffer strips to optimise ecosystem services: a review. Agr Ecosyst Environ 296, 106891. https://doi.org/10.1016/j.agee.2020.106891.

Danelon, A.F., Augusto, F.G., Spolador, H.F.S., 2021. Water resource quality effects on water treatment costs: an analysis for the Brazilian case. Ecol. Econ. 188, 107134. https://doi.org/10.1016/j.ecolecon.2021.107134.

Dearmont, D., McCarl, B.A., Tolman, D.A., 1998. Costs of water treatment due to diminished water quality: a case study in Texas. Water Resour. Res. 34, 849–853. https://doi.org/10.1029/98WR00213.

DIEA, 2018. Anuario Estadístico Agropecuario, Anuario Estadístico Agropecuario. Montevideo. https://doi.org/10.1016/S0367-326X(02)00066-7.

Dorevitch, S., DeFlorio-Barker, S., Jones, R.M., Liu, L., 2015. Water quality as a predictor of gastrointestinal illness following incidental contact water recreation. Water Res. 83, 94–103. https://doi.org/10.1016/j.watres.2015.06.028.

Dorevitch, S., Panthi, S., Huang, Y., Li, H., Michalek, A.M., Pratap, P., Wroblewski, M., Liu, L., Scheff, P.A., Li, A., 2011. Water ingestion during water recreation. Water Res. 45, 2020–2028. https://doi.org/10.1016/j.watres.2010.12.006.

Egan, K.J., Herriges, J.A., Kling, C.L., Downing, J.A., 2009. Valuing Water Quality as a Function of Water Quality measures. Am. J. Agric. Econ. 91, 106–123. https://doi.org/10.1111/j.1467-8276.2008.01182.x.

El Pais, 2019. Cianobacterias invadieron las playas de Montevideo. El Pais.

Elsin, Y.K., Kramer, R.A., Jenkins, W.A., 2010. Valuing Drinking Water Provision as an Ecosystem Service in the Neuse River Basin. J. Water Resour. Plan. Manag. 136, 474–482. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000058.

EPA, 1999. Guidance manual for compliance with the interim enhanced surface water treatment rule: Turbidity provisions (No. EPA-815-R-99-010). Environmental Protection Agency, Washington D.C.

European Commission, International Monetary Fund, Organisation for Economic Cooperation and Development, United Nations, Bank, W., 2009. System of National Accounts 2008. EC, IMF, OECD, UN, WB.

European Environment Agency, 2018. The Common International Classification of Ecosystem Services (CICES: Towards A Common Classification of Ecosystem Services [WWW Document]. URL https://cices.eu/ (accessed 1.1.18).

Ferrari, G., del Carmen Perez, M., Dabezies, M., Miguez, D., Saizar, C., 2011. Planktic Cyanobacteria in the lower Uruguay River, South America. Fottea 11, 225–234. https://doi.org/10.5507/fot.2011.021.

Forster, D.L., Bardos, C.I., Southgate, D.D., 1987. Soil erosion and water costs 349–352.

Freeman, M.A., 1995. The Benefits of Water Quality Improvements for Marine Recreation: a Review of the Empirical evidence. Marine Resource Economics 10, 385–406. https://doi.org/10.1086/mre.10.4.42629129.

Garibaldi, L.A., Carvalheiro, L.G., Vaissière, B.E., Gemmill-Herren, B., Hipólito, J., Freitas, B.M., Ngo, H.T., Azzu, N., Sáez, A., Åström, J., An, J., Blochtein, B., Buchori, D., García, F.J.C., Oliveira da Silva, F., Devkota, K., Ribeiro, M. de F., Freitas, L., Gaglianone, M.C., Goss, M., Irshad, M., Kasina, M., Filho, A.J.S.P., Kiill, L.H.P., Kwapong, P., Parra, G.N., Pires, C., Pires, V., Rawal, R.S., Rizali, A., Saraiva, A.M., Veldtman, R., Viana, B.F., Witter, S., Zhang, H., 2016. Mutually beneficial pollinator diversity and crop yield outcomes in small and large farms. Science 351, 388–391. https://doi.org/10.1126/science.aac7287.

Garibaldi, L.A., Gomez Carella, D.S., Nabaes Jodar, D.N., Smith, M.R., Timberlake, T.P., Myers, S.S., 2022. Exploring connections between pollinator health and human health. Philosophical Transactions of the Royal Society b: Biological Sciences 377, 20210158. https://doi.org/10.1098/rstb.2021.0158.

Gianessi, L.P., Peskin, H.M., Young, G.K., 1981. Analysis of national water pollution control policies: 1. a national network model. Water Resources Research 17, 796–802. https://doi.org/10.1029/WR017i004p00796.

Hall, A., Selker, J.S., 2021. High-resolution temperature modeling of stream reconstruction alternatives. River Research and Applications 37, 931–942. https://doi.org/10.1002/rra.3824.

Hamilton, K., 1999. Sustaining Economic Welfare: estimating changes in Per Capita Wealth, Policy Research Working Papers. The World Bank. https://doi.org/10.1596/1813-9450-2498.

Hamilton, K., Clemens, M., 1999. Genuine Savings rates in developing Countries. The World Bank Economic Review 13, 333–356.

Holmes, T.P., 1988. The Offsite Impact of Soil erosion on the Water Treatment Industry. Land Economics 64, 356. https://doi.org/10.2307/3146308.

Idb, 2019. Ex-Ante Economic Analysis of the Environmental Management Strengthening Program for the MVOTMA: UR-L1157. Inter-American Development Bank, Washington DC.

Johnson, J.A., Baldos, U.L., Hertel, T., Liu, J., Nootenboom, C., Polasky, S., Roxburgh, T., 2020. Global futures: Modelling the Global Economic Impacts of Environmental Change to support Policy making. Technical Report, World Wide Fund for Nature WWF-UK, Surrey.

Jones, R.W., 1965. The Structure of Simple General Equilibrium Models.

Juri, S., Baraibar, M., Clark, L.B., Cheguhem, M., Jobbagy, E., Marcone, J., Mazzeo, N., Meerhoff, M., Trimble, M., Zurbriggen, C., Deutsch, L., 2022. Food systems transformations in South America: Insights from a transdisciplinary process rooted in Uruguay. Front. Sustain. Food Syst. 6. https://doi.org/10.3389/fsufs.2022.887034.

Katumo, D.M., Liang, H., Ochola, A.C., Lv, M., Wang, Q.-F., Yang, C.-F., 2022. Pollinator diversity benefits natural and agricultural ecosystems, environmental health, and human welfare. Plant Diversity 44, 429–435. https://doi.org/10.1016/j.pld.2022.01.005.

Keeler, B.L., Wood, S.A., Polasky, S., Kling, C., Filstrup, C.T., Downing, J.A., 2015. Recreational demand for clean water: evidence from geotagged photographs by visitors to lakes. Frontiers in Ecology and the Environment 13, 76–81. https://doi.org/10.1890/140124.

Klein, A.-M., Vaissière, B.E., Cane, J.H., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Tscharntke, T., 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society b: Biological Sciences 274, 303–313. https://doi.org/10.1098/rspb.2006.3721.

Kruk, C., Martínez, A., de la Escalera, G.M., Trinchin, R., Manta, G., Segura, Á.M., Piccini, C., Brena, B., Fabiano, G., Pírez, M., Gabito, L., Alcántara, I., Yannicelli, B., 2019. Floración excepcional de cianobacterias tóxicas en la costa de Uruguay, verano 2019. INNOTEC 36–68. https://doi.org/10.26461/18.06.

Kumar, K., Saini, R.P., 2022. Economic analysis of operation and maintenance costs of hydropower plants. Sustainable Energy Technologies and Assessments 53, 102704. https://doi.org/10.1016/j.seta.2022.102704.

La Notte, A., Dalmazzone, S., 2018. Sustainability assessment and causality nexus through ecosystem service accounting: the case of water purification in Europe. Journal of Environmental Management 223, 964–974. https://doi.org/10.1016/j.jenvman.2018.06.072.

La Notte, A., Maes, J., Dalmazzone, S., Crossman, N.D., Grizzetti, B., Bidoglio, G., 2017. Physical and monetary ecosystem service accounts for Europe: a case study for in-stream nitrogen retention. Ecosystem Services 23, 18–29. https://doi.org/10.1016/j.ecoser.2016.11.002.

Lange, G.-M., Wodon, Q., Carey, K. (Eds.), 2018. The Changing Wealth of Nations 2018: Building a Sustainable Future. World Bank, Washington DC.

Langhans, K.E., Schmitt, R.J.P., Chaplin-Kramer, R., Anderson, C.B., Vargas Bolaños, C., Vargas Cabezas, F., Dirzo, R., Goldstein, J.A., Horangic, T., Miller Granados, C., Powell, T.M., Smith, J.R., Alvarado Quesada, I., Umaña Quesada, A., Monge Vargas, R., Wolny, S., Daily, G.C., 2022. Modeling multiple ecosystem services and beneficiaries of riparian reforestation in Costa Rica. Ecosystem Services 57, 101470. https://doi.org/10.1016/j.ecoser.2022.101470.

Lee, L.-H., Lee, Y.-D., 2015. The impact of water quality on the visual and olfactory satisfaction of tourists. Ocean & Coastal Management 105, 92–99. https://doi.org/10.1016/j.ocecoaman.2014.12.020.

Lin, L., Yang, H., Xu, X., 2022. Effects of water pollution on human health and disease heterogeneity: a review. Frontiers in Environmental Science 10, 880246.

Macedo, M.N., Coe, M.T., DeFries, R., Uriarte, M., Brando, P.M., Neill, C., Walker, W.S., 2013. Land-use-driven stream warming in southeastern Amazonia. Philosophical Transactions of the Royal Society b: Biological Sciences 368, 20120153. https://doi.org/10.1098/rstb.2012.0153.

McDonald, R.I., Weber, K.F., Padowski, J., Boucher, T., Shemie, D., 2016. Estimating watershed degradation over the last century and its impact on water-treatment costs for the world's large cities. Proceedings of the National Academy of Sciences 113, 9117–9122. https://doi.org/10.1073/pnas.1605354113.

Meals, D.W., Dressing, S.A., Davenport, T.E., 2010. Lag Time in Water Quality Response to best Management Practices. A Review.

Mengist, W., Soromessa, T., Feyisa, G.L., 2020. A global view of regulatory ecosystem services: existed knowledge, trends, and research gaps. Ecological Processes 9, 40. https://doi.org/10.1186/s13717-020-00241-w.

Mgap, 2021. Cobertura y Uso del Suelo 2020/21. Ministerio de Ganaderia, Agricultura y Pesca, Montevideo.

MGAP, 2015. Regiones agropecuarias del Uruguay. Montevideo.

Ministerio de Industria, Energía y Minería, 2025. Fuentes de energía primaria.

Ministerio de Turismo, 2025. Observatorio de Turismo Inteligente.

Murray, C., Forster, L., 2001. study of pesticide use, farming practices, and community drinking water treatment costs in the Maumee and Great Lakes Basins. (No. Rep. Series AEDE-RP-0013-01), Agricultural, Environmental and Development Economics. Ohio State University, Columbia.

Mussi, F.B., Mendes, A.B., Catapan, A., Tortato, U., 2023. Ecosystem Services and Environmental Investments: a case study of the Itaipu Hydroelectric Plant. Produto & Produção 24, 97–116.

Natural Capital Project, 2025. InVEST 3.16.0a1. Stanford University, University of Minnesota, Chinese Academy of Sciences, The Nature Conservancy, World Wildlife Fund, Stockholm Resilience Centre and the Royal Swedish Academy of Sciences., Stanford.

NCAVES, MAIA, 2022. Monetary valuation of ecosystem services and ecosystem assets for ecosystem accounting: Interim Version 1st edition, No. 1st edition. United Nations Department of Economic and Social Affairs, Statistics Division, New York.

Northrop, E., 2022. Opportunities for Transforming Coastal and Marine Tourism: Towards Sustainability. Regeneration and Resilience, High Level Panel for a Sustainable Ocean Economy.

O'Neil, J.M., Davis, T.W., Burford, M.A., Gobler, C.J., 2012. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. Harmful Algae 14, 313–334. https://doi.org/10.1016/J.HAL.2011.10.027.

Paerl, H.W., Huisman, J., 2008. Blooms like it Hot. Science 320, 57–58.

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., Bosello, F., 2018. Cost of agricultural productivity loss due to soil erosion in the European Union: from direct cost evaluation approaches to the use of macroeconomic models. Land Degradation & Development 29, 471–484. https://doi.org/10.1002/ldr.2879.

Perazzoli, A.G., 2019. Uruguay: País productor de alimentos para un sistema alimentario disfuncional. Agrociencia Uruguay 23, e70–e. https://doi.org/10.31285/AGRO.23.1.8.

Perera, D., Williams, S., Smakhtin, V., 2023. Present and Future losses of Storage in Large Reservoirs due to Sedimentation: a Country-Wise Global Assessment. Sustainability 15. https://doi.org/10.3390/su15010219.

Piaggio, M., Guzman, M., Pacay, E., Robalino, J., Ricketts, T., 2024. Forest Cover and Dengue in Costa Rica: Panel Data Analysis of the Effects of Forest Cover Change on Hospital Admissions and Outbreaks. Environmental and Resource Economics. https://doi.org/10.1007/s10640-024-00853-2.

Piaggio, M., Siikamäki, J., 2021. The value of forest water purification ecosystem services in Costa Rica. Science of the Total Environment 789, 147952. https://doi.org/10.1016/j.scitotenv.2021.147952.

Piaggio, M.J., Alpizar, F., Guzman, M., Ruta, G., 2018. Instrumentos de Política para Control de la Contaminación del Agua y la Emisión de GEI por Fuentes Difusas Provenientes de la Actividad Agropecuaria. Banco Internacional de Reconstrucción y Desarrollo / Banco Mundial, Washington DC.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and Economic costs of Soil erosion and Conservation Benefits. Science 267, 1117–1123. https://doi.org/10.1126/science.267.5201.1117.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies.

Price, J.I., Heberling, M.T., 2018. The Effects of Source Water Quality on Drinking Water Treatment costs: a Review and Synthesis of Empirical Literature. Ecological Economics 151, 195–209.

Republica Oriental del Uruguay, 2024. Tercera Contribucion Determinada a nivel Nacional al Acuerdo de Paris. Republica Oriental del Uruguay, Montevideo.

Riis, T., Kelly-Quinn, M., Aguiar, F.C., Manolaki, P., Bruno, D., Bejarano, M.D., Clerici, N., Fernandes, M.R., Franco, J.C., Pettit, N., Portela, A.P., Tammeorg, O., Tammeorg, P., Rodríguez-González, P.M., Dufour, S., 2020. Global Overview of Ecosystem Services provided by Riparian Vegetation. BioScience 70, 501–514. https://doi.org/10.1093/biosci/biaa041.

Rodríguez, R.C., 2017. Reducción de Emisiones Rancho Ganadero: Una Alternativa Ambientalmente Responsable y Sostenible para el Desarrollo Rural en Colombia. Inter-American Development Bank, Bogota.

Roson, R., Sartori, M., 2016. Estimation of Climate Change Damage Functions for 140 Regions in the GTAP 9 Data Base (No. 2), Policy Research Working Paper No. 7728. World Bank, Washington D.C.

Russ, J., Zaveri, E., Desbureaux, S., Damania, R., Rodella, A.-S., 2022. The impact of water quality on GDP growth: evidence from around the world. Water Security 17, 100130. https://doi.org/10.1016/j.wasec.2022.100130.

SARAS, 2010. Bases técnicas para el manejo integrado de Laguna del Sauce y cuenca asociada. Universidad de la República y South American Institute for Resilience and Sustainability Studies, Maldonado.

Schellenberg, G., Donnelly, C.R., Holder, C., Ahsan, R., 2017. Dealing with Sediment: Effects on Dams and Hydropower Generation. Hydro. accessed 10.30.24 Review. https://www.hydroreview.com/world-regions/north-america/dealing-with-sediment-effects-on-dams-and-hydropower-generation/.

Semmens, D., Ancona, Z., 2019. Monarch Habitat as a Component of Multifunctional Landscape Restoration using Continuous Riparian Buffers. Frontiers in Environmental Science 7. https://doi.org/10.3389/fenvs.2019.00126.

Small, N., Munday, M., Durance, I., 2017. The challenge of valuing ecosystem services that have no material benefits. Global Environmental Change 44, 57–67. https://doi.org/10.1016/j.gloenvcha.2017.03.005.

Smith, M.R., Mueller, N.D., Springmann, M., Sulser, T.B., Garibaldi, L.A., Gerber, J., Wiebe, K., Myers, S.S., 2022. The lost opportunity from insufficient pollinators for global food supplies and human health. The Lancet Planetary Health 6, S3. https://doi.org/10.1016/S2542-5196(22)00265-0.

Smith, M.R., Singh, G.M., Mozaffarian, D., Myers, S.S., 2015. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. The Lancet 386, 1964–1972. https://doi.org/10.1016/S0140-6736(15)61085-6.

Sutherland, I.J., Villamagna, A.M., Dallaire, C.O., Bennett, E.M., Chin, A.T.M., Yeung, A.C.Y., Lamothe, K.A., Tomscha, S.A., Cormier, R., 2018. Undervalued and under pressure: a plea for greater attention toward regulating ecosystem services. Ecological Indicators 94, 23–32. https://doi.org/10.1016/j.ecolind.2017.06.047.

The White House, 2023. Biden-Harris Administration Releases Final Guidance to Improve Regulatory Analysis. Briefing Room Press Release.

Torremorell, A., Hegoburu, C., Brandimarte, A.L., Rodrigues, E.H.C., Pompêo, M., da Silva, S.C., Moschini-Carlos, V., Caputo, L., Fierro, P., Mojica, J.I., Matta, Á.L.P., Donato, J.C., Jiménez-Pardo, P., Molinero, J., Ríos-Touma, B., Goyenola, G., Iglesias, C., López-Rodríguez, A., Meerhoff, M., Pacheco, J.P., de Mello, F.T., Rodríguez-Olarte, D., Gómez, M.B., Montoya, J.V., López-Doval, J.C., Navarro, E., 2021. Current and future threats for ecological quality management of south American freshwater ecosystems. Inland Waters 11, 125–140. https://doi.org/10.1080/20442041.2019.1608115.

UN, EC, FAO, IMF, OECD, UNEP, World Bank, 2024. System of EnvironmentalEconomic Accounting – Ecosystem Accounting (Statistical Papers), Series F No. 124. Department of Economic and Social Affairs.

United Nations, European Commission, Food and Agriculture Organization, International Monetary Fund, Organisation for Economic Cooperation and Development, The World Bank, 2014. System of Environmental Economic Accounting 2012- Central Framework. UN, New York.

United States Army Corps of Engineers, 2023. Recreation: Economic Impact. Institute for Water Resources, Washington D.C.

United States Environmental Protection Agency, 2024. Guidelines for Preparing Economic analyses. U.S, Environmental Protection Agency, Washington, DC, United States.

Valin, H., Havlík, P., Forsell, N., Frank, S., 2013. Description of the GLOBIOM (IIASA) model and comparison with the MIRAGE-BioF (IFPRI) model.

Vallecillo, R.S., La, N.A., Kakoulaki, G., Kamberaj, J., Robert, N., Dottori, F., Feyen, L., Rega, C., Maes, J., 2019. Ecosystem services accounting - Part II pilot accounts for crop and timber provision, global climate regulation and flood control [WWW Document]. JRC Publications Repository. https://doi.org/10.2760/631588.

Vallecillo, S., Kakoulaki, G., La Notte, A., Feyen, L., Dottori, F., Maes, J., 2020. Accounting for changes in flood control delivered by ecosystems at the EU level. Ecosystem Services 44, 101142. https://doi.org/10.1016/j.ecoser.2020.101142.

van Vliet, M.T.H., Vögele, S., Rübbelke, D., 2013. Water constraints on European power supply under climate change: impacts on electricity prices. Environmental Research Letters 8, 035010. https://doi.org/10.1088/1748-9326/8/3/035010.

Vesterinen, J., Pouta, E., Huhtala, A., Neuvonen, M., 2010. Impacts of changes in water quality on recreation behavior and benefits in Finland. Journal of Environmental Management 91, 984–994. https://doi.org/10.1016/J.JENVMAN.2009.12.005.

Wade, T.J., Sams, E., Brenner, K.P., Haugland, R., Chern, E., Beach, M., Wymer, L., Rankin, C.C., Love, D., Li, Q., Noble, R., Dufour, A.P., 2010. Rapidly measured indicators of recreational water quality and swimming-associated illness at marine beaches: a prospective cohort study. Environmental Health 9, 66. https://doi.org/10.1186/1476-069X-9-66.

World Bank, 2025. Mainstreaming Nature into World Bank Macroeconomic Models. Overview Report, World Bank Group, Washington, DC.

World Bank, 2021. The changing Wealth of Nations 2021: managing assets for the Future. World Bank, Washington D.C.