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Regional modeling of freshwater eutrophication in Argentina for Life Cycle Assessment

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Abstract

Aquatic eutrophication is a significant impact category in Life Cycle Assessment in countries with high environmental heterogeneity, such as Argentina. However, the usual practice in these studies is to use global characterization factors (given the lack of regional factors), which leads to results that generally do not reflect local conditions. To address this issue, phosphorus-based regional characterization factors are developed at the midpoint level to improve the spatial representativeness of this category. The methodology adapts and improves an existing model by differentiating the impact between ecological regions and incorporating observed concentrations of total phosphorus into the calculation of the effect factor. The model integrates nutrient transport processes in soil and water and the response of the receiving ecosystem within the cause-effect chain. As a result, three types of factors were developed to represent the Regionalized Aquatic Eutrophication Potential (kg P eq): factors for four regions of the country, an arithmetic national average, and a national average weighted by land area. The regional factors obtained range from 0.331 to 0.678 kg P eq in water and from 0.145 to 0.296 kg P eq for inputs to soil, demonstrating spatial variability in eutrophication potential. The use of global factors may underestimate or overestimate local impacts, whereas regionalization improves environmental consistency and identifies regions with greater eutrophic susceptibility. The proposed approach constitutes a methodological advance transferable to regions with limited data availability and provides a tool for environmental assessment and water management.

Highlights

o Regional characterization factors for aquatic eutrophication were developed for Argentina.

o The model is based on the fate and transport of phosphorus to aquatic ecosystems.

o The use of regional characterization factors improves environmental representativeness.

o Global characterization factors underestimated the regional impact when applied to Argentina.

o The methodology is transferable to other regions of the world.

1. Introduction

1.1. Concept and relevance of eutrophication

Aquatic ecosystems are closely related to their environment, and their dynamics are influenced by various factors at different spatial and temporal scales (Rechencq et al. 2024). Eutrophication is the process of changing from one trophic state to a higher one as a result of the incorporation of nutrients (Schindler 2006; Paerl and Huisman 2008), which causes deterioration in water quality and biodiversity, modifies the trophic network and increases the biomass of certain communities (Wurtsbaugh et al. 2019). The nutrients that most influence the process are phosphorus (P) and nitrogen (N). In some ecosystems, the limiting factor is the phosphate ion (PO_4^{3-}), as is the case in most continental lentic systems, while in marine ecosystems the limiting factor is N (Vásquez Zapata et al. 2012).

1.2. Current methods in Life Cycle Assessment (LCA)

LCA is a widely used approach for assessing environmental impacts associated with product systems (Muralikrishna and Manickam 2017). In Life Cycle Impact Assessment (LCIA), there are various methods for characterizing eutrophication, which differ in their inventory requirements, geographic coverage, spatial resolution, and modeled emission pathways. Despite these differences, these methods have in common the assessment of the potential impact of eutrophication based on: the inventory of nutrients emitted, their environmental fate through fate factors (FF), which represent transport and attenuation to the receiving compartment (freshwater or coastal seawater), and the subsequent exposure of the ecosystem to nutrient enrichment (exposure factor) and the effect (effect factor, EF) on aquatic species. This process allows the calculation of a midpoint impact indicator representing an increase in nutrients in the water (Payen and Ledgard 2017).

Initially, FFs for N and P were derived from European models, although in the absence of FFs for other continents, they have been used outside Europe (Struijs et al. 2009). The use of global CFs can lead to significant uncertainties when applied to specific environmental conditions in a region, hence the need for globally valid models, but with site-specific CFs (Payen and Ledgard 2017), especially in countries in the southern hemisphere where LCA studies are scarce, such as Argentina (Conci et al. 2022).

1.3. Geographical divide and the need for regionalization

Argentina has a wide variety of water bodies[1], although some of them suffer from severe eutrophication problems (Quirós 2000), which explains the variation in trophic status (Quirós 1991). Given that in countries such as Argentina, data on nutrient fate may be limited, the selection and regionalization of CFs poses a challenge. Although the development of methodologies has improved the description and assessment of aquatic eutrophication, there is still a need for improvements. Having damage indicators, as has been achieved for other categories such as human toxicity or ozone layer depletion, is a long-term goal, since certain constraints must first be overcome, such as the inability to calculate the bioavailability of nutrients. In the short term, a significant improvement could be the calculation of CFs with spatial differentiation for regions outside Europe or North America (Schmid 2008). In this context, the objective of this study is to develop regional indicators of aquatic eutrophication in freshwater ecosystems using the LCIA approach, following the environmental mechanism of the impact category and focusing on P emissions and the spatial differentiation of the impact. The research aims to provide methodological tools for the regional assessment of eutrophication in aquatic ecosystems in countries where site-dependent CFs are not available.

2. Development of the regional midpoint model

The research is part of the LCIA within the LCA, in accordance with IRAM-ISO 14044 (2008). Since its inception, the LCA methodology has developed various LCIA methods aimed at both midpoint and end-point impacts (Civit 2009). Various forms of P can be included in eutrophication modeling, with the phosphate ion (PO_4^{3-}) being the most commonly used reference substance. Midpoint CFs are the product of a fate factor (FF) and an exposure factor (XF) (Morelli et al. 2018). Endpoint CFs typically consist of a fate factor (FF), an exposure factor (XF), and an effect factor (EF), and characterize the potential damage that exposure to eutrophicating substances could cause to human health, ecosystem quality, or natural resource availability. In this research, midpoint CFs are addressed and an approximation of the EF is made, without actually measuring the damage.

The methodological procedure followed these steps: definition of environmental variables, modeling of P fate and transport, calculation of CFs, and spatial aggregation at the regional scale. The proposed equation is based on the Schmid (2008) model. The potential contribution to eutrophication of system A, denoted $I_{Eu}\ (A)$, is calculated as the result of nutrient inputs that cause increased biomass production in water bodies. Following the usual terminology in LCIA, the impact caused by aquatic eutrophication in a system *(A)* within a geographical area can be expressed as follows (adapted from Seppälä et al. 2004[2]) (Eq. 1):

$$I_{Eu}\left(A\right) = \sum_{j=1}^{n} C_{j,i}\left(A\right) * E_j\left(A\right)$$

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where $I_{Eu}\ (A)$ represents the value of the aquatic eutrophication impact caused by system A, $C_{j,i}\ (A)$ represents the CF of substance j produced by system A that reaches a given aquatic zone i, and $E_j\ (A)$ represents the amount of substance j emitted by system A. The higher the score of the value $I_{Eu}\ (A)$, the more undesirable the system is. The impact category indicator in the method is algae growth (Seppälä et al. 2004).

If effect and transport factors are considered, the CF $C_{j,i}$ can be calculated as (Schmid 2008, adapted from Seppälä et al. 2004) (Eq. 2):

$$C_{j,i}\left(A\right) = n_{j,i}\left(A\right) * u_{j,i}\left(A\right) * Eqv_j$$

2

where $n_{j,i}\,(A)$ is the transport factor for substance j (0≤ $n_{j,i}$ ≤1) and indicates the portion of substance j that will reach a given aquatic zone i, and $u_{j,i}\,(A)$ is the effect factor for substance j (0≤ $u_{j,i}$ ≤1), indicating the amount of transported substance j that causes an increase in biomass production in zone i. Finally, Eqv_j is the equivalence factor for substance j. The equivalence factors for N and P can be expressed as PO_4- equivalents (Seppälä et al. 2004). Air emissions of P have not been taken into account as they have little significance in the generation of eutrophication (Potting et al. 2005).

This paper proposes an extension of the model developed by Schmid (2008), based on the methodology of Seppälä et al. (2004). The assessment of the EF is expanded by quantifying it based on the relationship between the regional TP concentration and a reference value corresponding to the average TP concentration in water bodies according to the classification of the Organization for Economic Cooperation and Development (OECD 1982), which indicates that the degree of trophic status is quantified as the average annual concentration of chlorophyll-a (Cl-a) in that environment (Table 1).

Table 1
OECD threshold values for the trophic classification (OECD 1982)

Trophic level	**Average TP (ug/L)**	**Average Cl-a (ug/L)**	**Max. Cl-a (ug/L)**	**Average DS (m)**	**Min. DS (m)**
Ultra-oligotrophic	< 4	< 1	< 2.5	> 12	> 6
Oligotrophic	< 10	< 2.5	< 8	> 6	> 3
Mesotrophic	10–35	2.5-8	8–25	6 – 3	3-1.5
Eutrophic	35–100	8–25	25–75	3-1.5	1.5–0.7
Hypereutrophic	> 100	> 25	> 75	< 1.5	< 0.7

Average PT: average PT concentration in a water body; Average Cl–a: average chlorophyll–a concentration; Max Cl–a: peak chlorophyll–a concentration; Average DS: average Secchi disk transparency; Min DS: minimum Secchi disk transparency

Finally, it is multiplied by the equivalence factor of the emitting substance. Thus, the proposed Eq. (3) is defined as:

$C_{j,i}\,(A)$ = *η j,i (A) · μj,i (A) · Equj*(3)

$C_{j,i}\,(A)$ = *η j,i (A) · (Ppi / Pu) · Equj*

where ηj,i (A) is the transport factor for substance j and indicates the portion of substance j that will reach a given aquatic zone i, μj,i (A) is the effect factor of substance j and designates how much of the transported substance j causes an increase in biomass production in zone i, Ppi is the total P concentration present in zone i, Pu is the concentration of P in an eutrophicated water body, and Equj is the equivalence factor for substance j based on Heijungs et al. (1992). To reduce the variability and asymmetry of TP data between different water bodies, a base-10 logarithmic transformation (log_{10}) is applied to obtain the Ppi value. This transformation allows the concentration scale to be homogenized and improves comparability between regions. The transformed values are normalized with respect to the logarithm of the maximum value (log_{10} (TPmax)), obtaining a dimensionless index between 0 and 1 that expresses the relative magnitude of the potential eutrophication effect, where 1 represents the condition of greatest impact and values close to 0 represent the best environmental reference situation. Eq. (4) for this calculation is defined as:

$$I\,norm = \frac{log_{10}\,(TPi)}{log_{10}\,(TPmax)}$$

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where I norm is the normalized TP index, TP_i is the P concentration at site i, and TPmax is the maximum recorded value. This dimensionless index varies between 0 and 1, with 1 representing the condition of greatest effect. The same calculation was performed to determine Pu.

The Regionalized Aquatic Eutrophication Potential of substance j, $C_{j,i}(A)$, is used as CF, combining transport and normalized effect in aquatic ecosystems, expressed in kg P eq. The resulting impact, or category indicator, is interpreted as regionalized potential algal growth, representing the equivalent eutrophicating load attributable to a unit of P emission.

2.1. Transport routes

Following Schmid (2008), Fig. 1 shows the main transport routes of P in continental waters and coastal seas considered in this research. Sources are grouped into direct nutrient inputs to soil (such as fertilizers and manure) and wastewater from urban or industrial sources.

Considering agricultural inputs, nutrients can be added directly to the soil and subsequently transported to aquatic ecosystems where they cause eutrophication. The most important sources of this input are fertilizers and manure used in agriculture. Considering the transport route, Eq. 5 calculates the CF of P added to the soil:

$$C_{j,\text{suelo},i} = (\tau_j \cdot \sigma_{j,i}) \cdot \mu_{j,i} \cdot Equ_j \quad (5)$$

where Cj, soil, i is the CF for substance j (P) contributed directly to the soil through different inputs (usually fertilizers or manure) that reaches a water body i (inland waters or coastal seas). In turn, τj describes the fraction of substance j present in the soil after consumption by plants and σj, i the fraction of substance j present in the soil that reaches water body i.

As for wastewater emissions from industries and households that, after being treated or not in treatment plants, are discharged into aquatic ecosystems, the CF of the P emissions contained therein is estimated (Eq. 6):

$$C_{j,\text{residuales},i} = \gamma_j \cdot \mu_{j,i} \cdot Equ_j \quad (6)$$

where Cj,residual,i is the CF for the eutrophying substance j (P) present in wastewater reaching an aquatic zone i (inland waters or coastal seas), and γj represents the fraction of the total substance j emitted that remains in the water after passing through treatment plants.

Unlike the model proposed by Schmid (2008), which assigns a generic effect factor (value 1) to the receiving ecosystem, this approach introduces regionalized values based on P concentration data in water bodies within the national territory. Eq. 7 breaks down the effect factor:

$$\mu_{j,i}(A) = (Ppi / Pu) \quad (7)$$

where μ j, i (A) is the effect factor of substance j and designates the amount of substance j transported that causes an increase in biomass production in zone i, Ppi is the total P concentration present in zone i, Pu is the P concentration of an eutrophicated water body, as detailed above.

2.2. Model validation

Eutrophication represents a regional environmental impact, and it may be necessary to develop models based on location (Henryson et al. 2017). To validate the proposed model, the geographical regionalization of Argentina based on the proposal by Quirós (2004) was selected (Table 2).

Table 2
Main average limnological characteristics of the water bodies studied (Quirós 2004)

Water body districts	N° of environments in each district	Georegion	Area (km^2)	TP	TN*	TN:TP	Cl-a (mg/m^3)
Chaco-pampa	25	2	98	290	8583	56	63.8
(2)		Max	1984	1288	28750	145	405.3
		Min	1.4	23	2660	6	1.6
West and Northwest	27	3	30.6	68	2008	60	20.3
(3)		Max	330	477	11200	147	218.1
		Min	0.1	5	653	6	0.9
Andrean Patagonia (4)	33	4	103.7	7	697	146	2.3
		Max	1466	33	2242	335	54.1
		Min	0.6	1	186	31	0.2
Patagonian Plain (5)	13	5	252.3	111	2515	48	9
		Max	816	608	7900	75	41.8
		Min	0.6	4	223	4	0.4

*TN: Total N.

Regional CFs for aquatic eutrophication in Argentina were estimated based on transport values and normalized TP values. A representative CF was obtained for each of the regions considered, reflecting local conditions and relative susceptibility to impact. In addition, two integrative values were calculated for the country: a national arithmetic mean and a surface-weighted mean.

1.1.1. Fertilizers and impact on water

Argentine soils have a robust level of nutrients, where the low national demand for fertilizers is not consistent with Argentina's global relevance in the world grain markets. 2021 closed as the year with the highest fertilizer consumption, with a total of around 5.6 million tons (Rebora et al. 2023). Agriculture has altered the flow of phosphorus into the oceans (Andrade et al. 2017), promoting eutrophication, an increase in biomass, changes in the composition of algal species, and fluctuations in pH and dissolved oxygen, thereby affecting water quality (Smith et al. 1999).

1.1.2. Wastewater data in Argentina

Seventy-five percent of Argentina's territory is arid or semi-arid (Abraham and Salomón 2011). Most of the water is used for agricultural and industrial production, while only 10% is used for human consumption. Katopodis et al. (2023) indicates that 63.1% of urban areas have sewerage coverage, meaning that around 15.7 million people lack access to sewerage networks and regional inequalities are evident. Many treatment plants have maintenance deficiencies, affecting effluent quality. Of 600 treatment plants, 376 (serving more than 10,000 inhabitants) serve some 22 million inhabitants. Seventy-one percent of the plants are in fair or poor condition, and lagoon systems show the greatest deterioration (81%). Only 27.6% of the wastewater collected is treated properly. Of the total effluent generated (3.2 billion m^3/year), only 17.3% reaches plants in good condition, while 38.9% are partially treated and 6.9% are discharged untreated into receiving water bodies.

3. Results obtained for Argentina

2.1. Direct agricultural inputs to the soil

According to Eq. 5, the variables for the CF of P contributed to the soil are calculated. To determine the fraction of substance j present in the soil after consumption by plants, the value given by Bonadeo et al. (2017) is taken, which indicates that of the total P in the plant, 50% or more is found as inorganic phosphates, which predominate in the conducting or reserve organs, while in the reproductive organs (e.g., seeds), they are mainly found in organic forms. Due to low requirements, generally within the soil-plant-animal system, less than 10% of total P enters the plant-animal life cycle, and more than 90% remains in the soil. That is, 90% of P will be available, establishing $\tau j = 0.9$.

To calculate $\sigma j, i$, the fraction of substance j present in the soil that reaches water body i, values available in SimaPro for three different crops are considered, using the ReCiPe 2016 Midpoint method, as no other more regional values are available. Thus, PO_4^{3-} emissions transported by water to the river for tomatoes (Spain) were 0.00001 kg, for soybeans (Argentina) 0.0002 kg, and for corn (Argentina) 0.00010 kg, obtaining an average and defining $\sigma j = 0.33$.

2.2. Wastewater discharges into aquatic ecosystems

Following Eq. 6, the fraction of total P emitted that remains in the water after passing through treatment plants is calculated based on data provided by INDEC (2025) and Katopodis et al. (2023). According to the latest national census, the Argentine population is estimated at 45,892,285 inhabitants for the year 2022 (INDEC 2025), with a production of 0.975 kg P/capita/year, an average value derived from different authors (Rodríguez et al. 2022), and an annual production of 44,744.98 t P is obtained.

From this, the nutrients consumed in treatment plants are subtracted, taking into account that 17.3% of the population is connected to adequate treatment and 38.9% to inadequate treatment, leaving 6.9% without treatment (Katopodis et al. 2023). As the outfalls are primary treatment facilities, 30% (0.3) correspond to this type and the remaining 70% (0.7) to secondary treatment facilities. Considering that primary and secondary treatment facilities produce a removal rate of 10% (0.1) and 42% (0.42) of P, respectively (in the absence of specific data for Argentina, values published in Schmid 2008 are used), the amount of P treated in treatment plants for Argentina is calculated to be 14,497.37 t P/year (32.4% of the total amount produced). Based on this, 30,247.61 t P/year are discharged into the environment. Finally, it is obtained that in Argentina the fraction of the total P emitted that remains in the water after passing through the treatment plants is $\gamma j = 0.68$.

2.3. Calculation of the regional effect factor

To calculate Ppi, the maximum TP values in Table 1 of Quirós (2004) are used, and to calculate Pu, the maximum limit values defined by the OECD (1982) as the worst environmental situation (Eq. 7) are used. Table 3 shows the results of the $\log_{10}$ applied and its normalization to obtain the effect factor in each region, where each unit in $\log_{10}$ represents an order of magnitude in the concentration of P.

Table 3
TP values to define the effect factor.

Regions	Chaco-pampa	West and Northwest	Andrean Patagonia	Patagonian Plain
Range for Argentina (Quirós 2004)				
TP present mean*	290	68	7	111
log_{10}(TP mean)**	2.462	1.833	0.845	2.045
log_{10}(TP mean) norm**	0.792	0.589	0.272	0.658
TP present max*	1288	477	33	608
log_{10}(TP max)**	3.110	2.679	1.519	2.784
log_{10}(TP max) norm**	1	0.861	0.488	0.895
TP present min*	23	5	1	4
log_{10}(TP min)**	1.362	0.699	0	0.602
log_{10}(TP min) norm**	0.438	0.225	0	0.194
OECD range (1982)				
TP threshold max*	100	100	100	100
log_{10}(TP max)**	2	2	2	2
log_{10}(TP max) norm**	1	1	1	1
TP threshold min*	35	35	35	35
log_{10}(TP min)**	1.544	1.544	1.544	1.544
log_{10}(TP min) norm**	0.772	0.772	0.772	0.772
μ Argentina				
FC final effect max**	1	0.861	0.488	0.895

* Min= minimum; max= maximum. TP expressed in mg/m3; **Dimensionless unit. Norm= normalized.

2.4. Transport routes of P to Argentine freshwater ecosystems

Following equations 5 and 6, Table 4 shows the results of the regional CFs obtained for each of the transport routes considered.

Table 4
P concentrations in wastewater and P concentrations from direct agricultural inputs to soil

CFs	Regions			
	Chaco-pampa	West and Northwest	Andrean Patagonia	Patagonian Plain
γ*	0.68	0.68	0.68	0.68
μ max*	1	0.861	0.488	0.895
Equ**	3.06	3.06	3.06	3.06
Cj,residuals,i**	2.081	1.792	1.016	1.863
τ*	0.9	0.9	0.9	0.9
σ*	0.33	0.33	0.33	0.33
μ max*	1	0.861	0.488	0.895
Equ**	3.06	3.06	3.06	3.06
Cj,soil,i**	0.909	0.783	0.444	0.814

* Dimensionless unit; **Expressed in kg PO_4^{3-} eq/kg substance j emitted.

2.5. Regional midpoint CFs

The CFs obtained for the study region in kg P eq are presented below. Table 5 shows the calculation for estimating the weighted average CF per area (data from Tables 2 and 4).

Table 5
Calculation of the weighted average CF per area

Regions	Weighted average CF per area	Substance j = P (water)	Substance j = P (soil)
Chaco-pampa	Regional CFs (kg P eq) * regional area (km^2)	66.477	29.035
West and Northwest		17.878	7.808
Andrean Patagonia		34.348	15.002
Patagonian Plain		153.204	66.914
	Weighted total sum (kg P eq * km^2)	271.907	118.759
	Sum of areas (km^2)	484.6	484.6
	Weighted average (kg P eq)	0.561	0.245

Table 6 shows the values from Table 5 and presents the final CFs for P emitted to water and soil: by region and national arithmetic mean.

Table 6
Regional CFs, national arithmetic mean, and weighted by area.

CFs (kg P eq)	Substance j = P (water)	Substance j = P (soil)
For region	0.678	0.296
Chaco-pampa	0.584	0.255
West and	0.331	0.145
Northwest	0.607	0.265
Andrean Patagonia		
Patagonian Plain		
National arithmetic mean	0.550	0.240
Area-weighted mean	0.561	0.245

An analysis of each region shows that the Chaco-pampa is the region with the greatest potential impact, due to a high average concentration of nutrients in water bodies, making it a critical area in terms of eutrophication. This is followed by the Patagonian Plain, the western and northwestern regions of the country, and finally the Andean Patagonia, which is the region with the lowest impact, possibly due to a low concentration of TP, lower ecological sensitivity, or lower connectivity of nutrients with vulnerable water bodies.

2.5.1. Application of CFs obtained in a specific LCA

Following Eq. 1, data from the Life Cycle Inventory and freshwater aquatic eutrophication CFs calculated in an LCA of tomatoes produced in the Uco Valley region, located in the central-western part of the province of Mendoza, Argentina (Piastrellini et al. 2024), were used. The LCA was carried out using SimaPro software, using the CML Baseline model (World 2000). The global CF for aquatic eutrophication is set at 0.000163 kg PO_4^{3-} eq. If the amount of fertilizer emitted during all stages of the production process of 1 kg of tomatoes is 0.000381 kg P and the outflow to surface water is 0.00000516 PO_4^{3-} eq, the impact is 0.0000000202 kg P eq for the input and 0.000000000274 kg P eq for the outflow. When applying the CF for the West and Northwest region, the results are as follows (Table 7):

Table 7
Results of the application case.

Substance	Emissions (kg P)	CFs (kg P eq)	I_{Eu} (A) (kg P eq)	Global impact (kg P eq)	Percentage variation between impacts
P (water)	0.000381	0.584	0.000225	0.0000000202	0.00897%
P (soil)	0.000381	0.255	0.0000971	0.0000000202	0.02080%

If the national arithmetic mean CF is applied, the result is 0.000209 kg P eq for P in water and 0.0000914 kg P eq for P in soil. Finally, using the weighted average CF per surface area, we obtain 0.000213 kg P eq for P in water and 0.0000933 kg P eq for P in soil.

4. Discussions

4.1. Transport routes and regional characteristics for defining CFs

The Chaco-Pampas regions exhibit higher values associated with eutrophic, hyper-eutrophic, or saline aquatic ecosystems, whereas the Patagonian Andes and Tierra del Fuego exhibit ultra-oligotrophic to oligotrophic conditions (Drago and Quirós 1995; Quirós et al. 2002). The trophic states of waters on the Patagonian plateau range from mesotrophic to eutrophic, as do most in

the central-west and northwest (Quirós 2004). At higher nutrient concentrations and shallower depths, these ecosystems exhibit greater algal biomass (Quirós 2000). This supports the ability of the proposed approach to capture regional environmental heterogeneity, an aspect particularly relevant in countries with high hydrological variability such as Argentina. The differences observed between regions are consistent with their characteristic trophic states, and the calculated CFs represent the maximum potential contribution of P to biomass growth (Schmid 2008). Thus, the calculation of the regional EF highlights that, in the Patagonian Plain, the average TP (log10 = 2.045) is more than an order of magnitude higher than that of Andean Patagonia (0.845), which is reflected in the final CFs. This allows for a comparison of the regions and the expression of differences in impact without extreme values dominating the scale due to regions with very large differences in TP concentration.

Tomato cultivation was selected as the case study due to its regional significance, intensive use of fertilizers, and availability of primary data. It follows that the use of global factors underestimates and fails to capture the potential impact of aquatic eutrophication in the study area.

4.2. Comparison with existing models

Table 8 presents a comparison between the CFs obtained in this study (using national arithmetic mean CFs) and those available in the literature for Argentina, which are scarce and global in scope. Three different approaches are presented for calculating CFs for freshwater eutrophication caused by phosphorus in Argentina, derived from global, national, and regionally scaled national models.

Table 8
Comparison of CFs

CFs (kg P eq / kg substance emitted)				
Substance	**World***	**Argentina****	**Argentina regionalized*****	**Percentage variation between the model by** Payen et al. (2021) **and the CFs obtained**
P (water)	0.008	1.004	0.550	54.78%
P (soil)	0.008	0.894	0.240	26.84%

*IMPACT World+ Midpoint V1.05 (Bulle et al. 2019. Calculation of aquatic eutrophication based on the model by Helmes et al. 2012); **Global calculation (model by Payen et al. 2021); ***National arithmetic mean with regional CFs.

The values obtained reveal a substantial difference between the calculated CFs (Table 8). The impact of eutrophication in the study by Bulle et al. (2019) is spatially assessed using the global model with a resolution of 0.5° × 0.5° developed by Helmes et al. (2012), based on global hydrological data. The IMPACT World+ global model (Bulle et al. 2019) assigns a value of 0.008 kg P eq/kg P, representing a global average. This value tends to underestimate the potential impact of eutrophication when applied to local contexts. Meanwhile, the model by Payen et al. (2021) incorporates explicit spatial differentiation and estimates a CF for Argentina of 1.004 kg P eq/kg P (water) and 0.894 kg P eq/kg P (soil). These values represent an improvement over global factors by including regional P export and fate parameters. The authors developed the fate factors for application to both diffuse soil emissions and point source nutrient emissions to freshwater, at the watershed scale with global coverage and at the national and global scales through weighted aggregation of emissions and the distinction between agricultural and non-agricultural emissions. The modeled fate processes include nutrient attenuation from land to water bodies and within them. However, their direct application in local studies requires a level of resolution for hydrological and emission data that is not always available. Finally, the regional CFs obtained in this study (0.550 kg P eq/kg P for water and 0.240 kg P eq/kg P for soil) show a reduction compared to the national values obtained by Payen et al. (2021). This suggests that incorporating local information, such as limnological quality, the effective surface area of water bodies, and regional variability in nutrient retention and transport processes, allows for a more accurate representation of the actual potential magnitude of the impact. The use of regional CFs improves environmental representativeness and avoids over- or underestimation of the impact that can occur when applying generic or global-scale factors in local LCA studies. The developed regional model, by using observed TP concentrations and normalizing the values relative to the maximum (critical case), more accurately reflects the eutrophic response of aquatic ecosystems, reducing the uncertainty associated with the use of generic factors.

4.3. Advantages and methodological innovation

The methodological innovation lies in replacing the generic value with regionalized EFs derived from empirical data on TP concentrations in Argentine water bodies. The model retains the structure based on the environmental mechanisms of P (emission-transport-impact) but introduces an explicit representation of the sensitivity of the regional aquatic ecosystem without compromising compatibility with the LCA methodological framework. Due to the great diversity of its aquatic ecosystems, this approach is not implemented at the watershed scale because it would generate such a high number of CFs that the tool would become impractical (Schmid 2008); therefore, the regional scale is appropriate for Argentina.

LCA end users are provided with CFs for specific regions, a national average, and a value weighted by land area. The methodology developed is replicable in other regions of the world provided that regional water quality data are available, addressing the growing need for spatial regionalization in LCA. For the end user, the approach provides CFs directly applicable in LCA studies, allowing the eutrophic impact of a given production system to be differentiated based on the geographic location of its emissions. The selection of the CF will be based on the type of study and the spatial aggregation level of the LCA. Thus, regional CFs are more suitable for assessments with a spatially differentiated approach. The national arithmetic average represents the country's average performance without considering the size of the regions. In contrast, the area-weighted average shows that each CF contributes in proportion to the area it occupies within the national territory.

4.4. Limitations and opportunities for improvement

The lack of data on diffuse sources of phosphorus is acknowledged, although it is more difficult to model discharges than emissions, and models are generally unable to calculate aquatic eutrophication with precision and accuracy (Resano Goizueta 2019). Furthermore, the study could be expanded to other regions of the country, and the TP values could be updated. However, when specific water bodies are analyzed, it is observed that TP values fall within the range for each region (e.g., Andén and Pizzolon 2025). In the future, land-use data could be included to improve the model's regionalization.

In a given body of water, eutrophication may be limited by P or N, or co-limited by both nutrients, depending on the ratio of P to N and their concentrations (Francoeur et al. 1999). Zhou et al. (2024) developed globally regionalized CFs for the impacts of P and N and indicate that eastern South America (Argentina) belongs to regions with P limitation and undesirable periphyton growth. Therefore, in this study, P is considered the limiting nutrient for freshwater eutrophication, and no CFs have been derived for N in water in Argentina; this could be a point to consider in future research, incorporating atmospheric deposition as well as transport pathways in soil and water. Likewise, other aspects not addressed in this study could be examined, such as the analysis of environmental conditions involving non-homogeneous or non-steady-state mixtures in aquatic ecosystems, since the regional parameters here represent average environmental behaviors and temporal variability is not modeled.

5. Conclusions

This study proposes a methodological extension for assessing aquatic eutrophication within the framework of the LCIA using site-dependent CFs, which incorporate spatial differentiation based on regional empirical data and maintain the consistency of the LCA's cause-effect chain. The developed CFs represent the Regionalized Aquatic Eutrophication Potential for P, integrating transport processes and the normalized effect of the receiving ecosystem. Their application in Argentina allowed for the definition of three levels of spatial aggregation (regional, national arithmetic mean, and area-weighted average) that facilitate the adaptation of the indicator to different study objectives. The results show that global factors may overestimate or underestimate impacts in specific contexts, highlighting the need for regionalization to improve environmental representativeness. The methodology is transferable to other regions of the world through the incorporation of local data and transforms the LCA-based eutrophication assessment into a tool sensitive to the environmental context, useful for supporting sustainability decisions and water resource management. The impact model identifies regions most susceptible to eutrophication processes and promotes responsible production and consumption strategies aligned with the Sustainable Development Goals related to water and the protection of aquatic ecosystems.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

EC: conceptualization, methodology, research, formal organization and analysis, and original writing; ARB: writing-review and editing; APA: writing-review and editing; BMC: writing-review and editing and analysis.

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Footnotes

1. Freshwater bodies include rivers and streams, lakes and ponds, reservoirs, and wetlands, and they support aquatic ecosystems that, in this study, are the recipients of environmental impacts.
2. Seppälä et al. (2004) estimated CFs that took into account nutrient bioavailability for 11 sectors in Finland, based on three different scenarios, noting that this was an approach subject to considerable uncertainty and that further research was needed on the roles of different nutrient forms in aquatic eutrophication (Schmid 2008).
3. The conversion from kg PO_4^{3-} eq (results from Table 3) to kg P eq was performed using a stoichiometric factor of 0.326, corresponding to the mass fraction of P present in the phosphate ion, calculated from the ratio between their molar masses. This calculation is shown in Table 5.

Figures

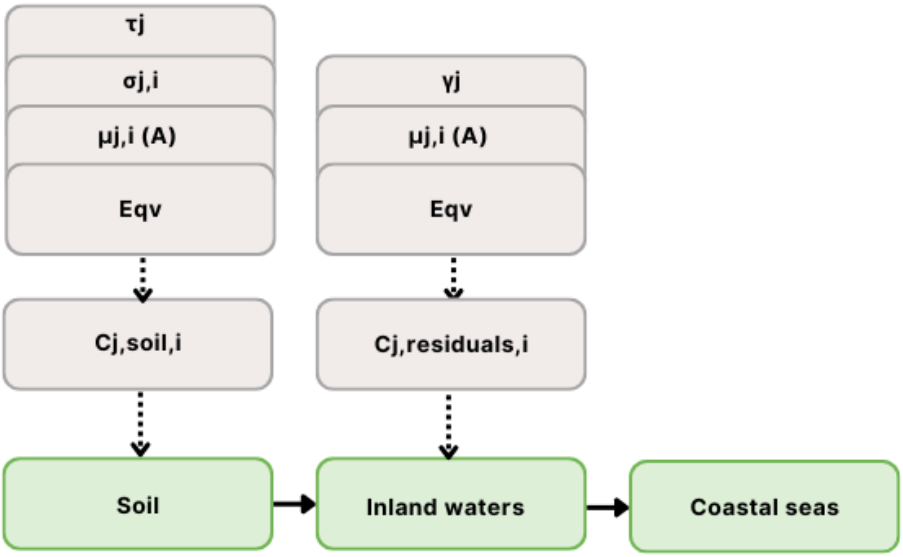


Figure 1

Main transport routes for P considered in the model.

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