CHAPTER 07

EXPLORING EUTROPHICATION IN LIFE CYCLE ASSESSMENT: THE NEED FOR A REGIONAL CHARACTERIZATION IN THE ARGENTINE PAMPAS AGROECOSYSTEM

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ABSTRACT: Increased awareness of environmental protection has spurred the development of methods to assess impacts, with life cycle approach tools gaining significant importance. These tools allow for the evaluation of the environmental profiles of analyzed systems, including risks such as eutrophication of water bodies and soils, which are incorporated into Life Cycle Impact Assessment models. However, in Argentina, both aquatic and terrestrial eutrophication are still underexplored within this framework. This study provides a comprehensive analysis of national and international literature on these impact categories, with a focus on terrestrial ecosystems due to the region's productive structure and agricultural expansion. The absence of prior research on the integrated analysis of aquatic and terrestrial ecosystems suggests that specific characterization factors for assessing potential impacts in environmentally significant areas have not yet been developed. Of the 106 articles reviewed from 1990 to August 2024, many focus on method development. Thus, methods and models suited to regional conditions will be chosen according to the Pellston Workshop 2018 guidelines. Given the limited studies in South America, developing characterization factors is essential. It is planned to select a model and continue with the characterization of ecosystems receiving eutrophying emissions. Argentina is recognized as one of the main agricultural regions in the world, with a core in the Pampas region. Developing indicators using the Life Cycle Impact Assessment approach is vital for quantifying potential environmental impacts from various activities, marking a significant step forward in understanding environmental risks in the region.

KEYWORDS: review, nitrogen, Accumulated Exceedance, midpoint, indicators, spatial regionalization.

RESUMO: O aumento da conscientização sobre a proteção ambiental estimulou o desenvolvimento de métodos para avaliar os impactos, com as ferramentas de abordagem do ciclo de vida ganhando importância significativa. Essas ferramentas permitem a avaliação dos perfis ambientais dos sistemas analisados, incluindo riscos como a eutrofização de corpos d'água e solos, que são incorporados aos modelos de Avaliação de Impacto do Ciclo de Vida. No entanto, na Argentina, tanto a eutrofização aquática quanto a terrestre ainda são pouco exploradas dentro dessa estrutura. Este estudo fornece uma análise abrangente da literatura nacional e internacional sobre essas categorias de impacto, com foco nos ecossistemas terrestres devido à estrutura produtiva e à expansão agrícola da região. A ausência de pesquisas anteriores sobre a análise integrada de ecossistemas aquáticos e terrestres sugere que ainda não foram desenvolvidos fatores de caracterização específicos para avaliar os possíveis impactos em áreas ambientalmente significativas. Dos 106 artigos revisados de 1990 a agosto de 2024, muitos se concentram no desenvolvimento de métodos. Assim, métodos e modelos adequados às condições regionais serão escolhidos de acordo com as diretrizes do Pellston Workshop 2018. Considerando os estudos limitados na América do Sul, o desenvolvimento de fatores de caracterização é essencial. Planeja-se selecionar um modelo e continuar com a caracterização dos ecossistemas que recebem emissões eutrofizantes. A Argentina é reconhecida como uma das principais regiões agrícolas do mundo, com um núcleo na região dos Pampas. O desenvolvimento de indicadores usando a abordagem de Avaliação de Impacto do Ciclo de Vida é vital para quantificar os possíveis impactos ambientais de várias atividades, marcando um avanço significativo na compreensão dos riscos ambientais na região.

PALAVRAS-CHAVE: revisão, nitrogênio, Excedência Acumulada, ponto médio, indicadores, regionalização espacial.

1. INTRODUCTION

The growing awareness of the importance of environmental protection and the potential impacts associated with products has increased interest in the development of methods to understand and address these impacts. One of the techniques developed in this sense is Life Cycle Analysis (ISO 2006a), which was born in the 1960s, and is defined as a tool to assess the potential environmental impacts and resources used throughout a product's life cycle, i.e. from raw material acquisition, via production and use stages, to waste management (ISO 2006b). However, it is in the 1990s when the consolidation of this methodology took place (Schmid 2008). This environmental assessment tool is widely used in the world's most industrialized countries. However, in developing countries it has spread with some delay due to methodological difficulties, high implementation costs, lack of motivation, etc. (Arena 1999). In this regard, the United Nations (2018) has established as a target of Sustainable Development Goal 12 to help developing countries to move towards more sustainable consumption and production patterns.

Remarkable methodological and application advances have been made at the international level and Argentina has not been alien to this development. However, globalization itself raises the need for common criteria and databases that allow specialists in each area to have reliable information to carry out their studies (Perez 2016). Potting et al. (2001) state that various authors call for further development in some impact categories so that they come closer and closer to measuring real damage to the environment and take into account temporal and spatial variability. To ensure that the results of a Life Cycle Assessment (LCA) are consistent, methods and their models must be continuously updated and the trend is to regionalize characterization factors (CFs) (Morelli et al. 2018; Civit 2009; Potting and Hauschild 2006).

By 2009, Civit stated that LCA studies had been carried out in the national context, although they had been limited by having to select among impact assessment methods that have been developed in contexts different from those of application, even in regional categories such as eutrophication, since site-dependent factors have not been developed for the region. This highlights the need for local or regional inventories and Life Cycle Impact Assessment (LCIA) models that include regional characteristics.

In Latin America, and specifically in Argentina, there are some precedents for the development of impact indicators for regional categories: water use in the wine chain (Civit et al. 2018), land acidification (Civit et al. 2014), desertification (Civit et al. 2013; Núñez et al. 2010), terrestrial eutrophication and land use (Civit 2009). However, there is still a lack of LCA studies on a national scale, in regions where this category may have environmental significance. Particularly, terrestrial eutrophication has not yet been explored in the field of LCA in Argentina, with only the regional precedent of the work of Civit (2009). Therefore, it is imperative to analyze the terrestrial fate and transport of land-applied nutrients, as the terrestrial eutrophication model is largely absent from the LCIA despite its importance for agriculture and other land-use sectors (Azevedo et al. 2013). The objective of this work is to analyze spatially the eutrophication category, in the context of LCA, in order to know the state of the art of the subject and to identify the research needs for the region, focusing particularly on terrestrial eutrophication.

1.1 CHARACTERIZATION OF ENVIRONMENTAL IMPACTS

To characterize the potential impacts of substances released throughout the life cycle of a product, process or activity, impact models make use of CFs. This CFs represent the consequences of an environmental intervention on a receptor in a "cause-effect" chain, defining midpoint and endpoint factors. The impact of the emission of a pollutant or toxic substance has three dimensions which are fate, exposure and effect and therefore various LCIA methods have been proposed (Civit 2009).

Morelli et al. (2018), express that without quantifying the fate, transport and loading of site-specific nutrients at appropriate spatial scales, the relevance of the for eutrophication may be limited. On the other hand, current characterization models combine marine and freshwater environments into a single impact category, or employ the simplifying assumption that phosphorus (P) is limiting in freshwater ecosystems and nitrogen (N) is limiting in marine ecosystems. However, and current studies indicate that it is important to provide management for both N and P (Conley et al. 2009; Paerl and Scott 2010; Davis et al. 2015). More sophisticated LCIA methodologies have begun to be disseminated that take into account not only the quantity of emissions produced, but also the place where they are released, their fate

and the damage they produce, whether on the natural or artificial ecosystem or on human health (Civit et al. 2006).

1.2 EUTROPHICATION

Eutrophication is defined as the abnormally high nutrient enrichment of an ecosystem (Olivera et al. 2016). It occurs when N and P compounds that have been emitted by natural or anthropogenic sources are deposited, then reach the soil or water bodies causing a harmful effect such that it modifies the living conditions of the different species that inhabit and develop in them (Morelli et al. 2018; Civit 2009; Finnveden and Potting 1999). In freshwater ecosystems, eutrophication manifests itself with decreased dissolved oxygen and algal blooms that give a characteristic greenish color and is a consequence of increased P concentration, while in marine ecosystems it results from increased concentration of N compounds (Civit 2009). If inputs of eutrophying substances exceed the capacity of ecosystems to assimilate these inputs there may be changes in habitat (Hassan et al. 2005). In the last century, increased emissions of nitrogenous compounds from agriculture and industry have increased atmospheric N deposition in semi-natural ecosystems (Erisman et al. 2013; Galloway et al. 2008) with consequences for biodiversity (Dise et al. 2011; Bobbink et al. 2010). In this regard, excess N can change the structure and function of N-limited terrestrial ecosystems, favoring a (typically) restricted number of adapted species (Henderson 2015).

In Payen et al. (2019) indicate that although eutrophication occurs naturally, the LCIA focuses on connecting emissions from anthropogenic sources, with the impacts of eutrophication. Inorganic P and N compounds are the major contributors to eutrophication: phosphate (PO_4^{3-}), NH_3 or NH_4^+ (ammonia and ammonium), NO_3- (nitrate) and gaseous nitrogen oxides (NOx) (Henderson 2015). Aquatic (freshwater and marine) and terrestrial eutrophication are among the impact categories assessed in LCA studies to determine the environmental profile of products, processes and activities, and are included in all models used in the LCA phase. They represent a regional environmental impact, which means that site-based modeling may be necessary for an accurate representation of impacts (Henryson et al. 2017). Until a few years ago, eutrophication was considered as a single impact category. In 1992 that the

difference between terrestrial and aquatic eutrophication was made explicit, because terrestrial ecosystems are affected by the contribution of emissions of N compounds (N oxides and ammonia) emitted into the air throughout the life cycle of products, processes or activities, by atmospheric deposition or nitrification (Civit 2009). The time scales over which eutrophying emissions reach and impact a receiving site vary by compound and emission compartment (Galloway 2003).

Given that Argentina has an extensive bioclimatic variability and that it is a producer of raw materials and intermediate products that are incorporated into various production systems in different parts of the world, when assessing impacts it is necessary to have factors that characterize the potential effect that the environmental intervention has in one place and not in another. Therefore, due to the high variability of eutrophication impacts (Helmes et al. 2012), approaches that provide spatial differentiation are preferable (Payen et al. 2019).

2. METHODS

This study updates the article by Conci et al. (2022) and extends the review of papers in the 1990-2020 series up to and including August 2024. The bibliographic review was carried out through the search of different academic papers, using the following search engines: Google Scholar, Science Direct, Springer Link, Scielo, REDIB, OAJI, DOAJ, JSTOR, Latindex, Publindex, Dialnet and Redalyc. We also reviewed the proceedings of scientific events, such as the International Conference of Life Cycle Assessment in Latin America (CILCA), Argentine Life Cycle Meeting (ENARCIV), Argentine Association of Renewable Energies and Environment (ASADES), Meeting of the International Center for Earth Sciences (E-ICES), Meeting of Engineering Researchers and Teachers (ENIDI) and pages of the Food and Agriculture Organization (FAO), Society of Environmental Toxicology and Chemistry (SETAC), National Institute of Agricultural Technology (INTA), Life Cycle Initiative, among others related to the subject. Previously, key words were determined as a search strategy (in Spanish and English). These were combined in the fields "title", "abstract" and "keywords" considering papers published between 1990 (consolidation of the LCA) and its update to August 2024. In the field "without the words" "heavy metals, construction and electrical energy" were filled in, since the search engines

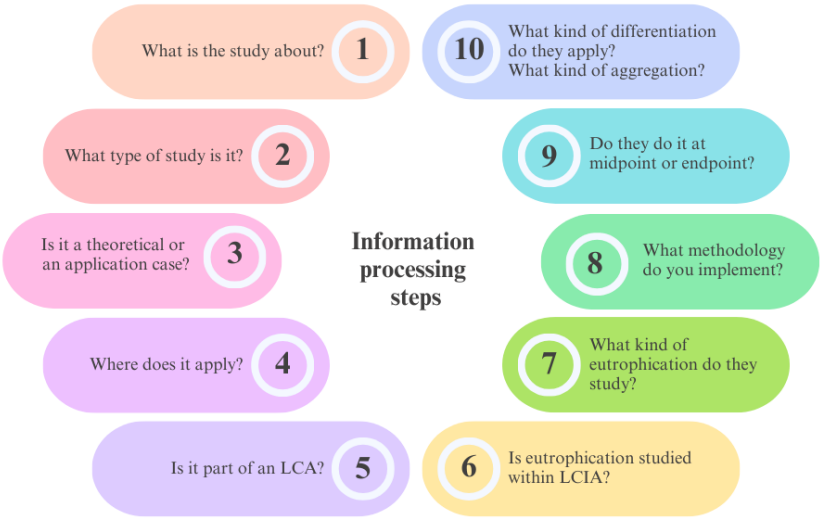
produced results that were not directly related to the objective of the research. The words selected were: eutrophication and Life Cycle (or Life Cycle Analysis); eutrophication and Life Cycle Assessment (or Life Cycle Impact Assessment); eutrophication and indicators; aquatic eutrophication and Life Cycle; marine eutrophication and Life Cycle; terrestrial eutrophication and Life Cycle; eutrophication and regional impact indicators; and regionalization of impacts and Life Cycle.

To select the appropriate bibliography, we first reviewed the titles, abstracts and keywords to identify the type of information contained in each one. Next, different essential aspects were considered to process the information, such as: whether it was a theoretical or application case, where it was applied, whether it was framed within the LCA and LCIA methodology, and if so, what methods and models were used, what kind of eutrophication, whether it was studied at the midpoint or endpoint level, and finally, differentiation[1] and aggregation[2] (Figure 1). These data, by means of the statistical tool offered by the Excel program (2013), allowed the consecutive analysis of the bibliography found.

1 According to Klopffer (1996), the main problem with lifecycle assessment consists in the absence of true relationships between interventions and environmental effects. The interventions established in the inventory analysis are expressed in amounts per functional unit, and in principle nothing is known about the source-strength and variation over time of the examined processes. Due to this lack of differentiation, which is inherent to LCA, no environmental concentrations can be predicted and, as a consequence, it does not seem possible to evaluate whether a no-effect level is surpassed. However, Potting and Hauschild (1997) argue that it is possible to say something sensible about the surpassing of no-effect-levels and the expected occurrence of actual impact without precise information about the resuiting environmental concentration.

2 Verones et al. (2019) recommend that method developers explore approaches for assessing uncertainty associated with different levels of spatial, temporal, or archetypal aggregation to identify optimal assessment scales. The uncertainty might arise from either upscaling (increasing spatial, temporal, or any other scale by aggregation) or downscaling (decreasing spatial, temporal, or any other scale by increasing resolution).

Figure 1 Information processing steps.



Source: Authors

3. RESULTS AND DISCUSSION

3.1 MAIN FEATURES OF EUTROPHICATION STUDIES

From the initial search, out of 4662 studies found, 106 (additional data are given in Online Resource 1) were selected that responded to the interests sought, developed in the field of LCA, as set out in ISO 14040 (2006a) and 14044 (2006b). These include research articles, review articles, discussions, case studies, state of the art, commentaries, analyses, reports, critical reviews, meeting reports, doctoral theses, letters to the editor, global guides, books and chapters, scientific-technical support, abstracts at scientific events and methodology reports. Table 1 shows that there are few research papers that analyze aquatic and terrestrial eutrophication categories in the same study. There is an analysis of aquatic eutrophication, whether freshwater or marine, on the one hand, and terrestrial eutrophication on the other.

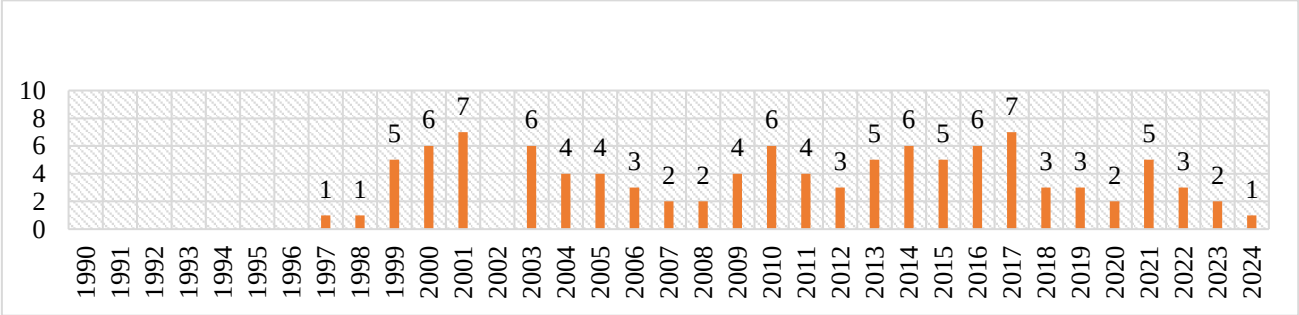
Table 1. Number of papers published by topic. 1990-August 2024 series.

Number of papers published by topic 1990-August 2024 series			
	Topics	**Abbreviations**	**Number of papers**
	Life Cycle Analysis	LCA	17
	Life Cycle Impact Assessment	LCIA	19
In the context of LCA	Eutrophication	E	5
	Freshwater eutrophication	FE	16
	Marine eutrophication	ME	7
	Freshwater and marine eutrophication	FE+ME	2
	Terrestrial eutrophication	TE	6
	Aquatic and terrestrial eutrophication	AE+TE	1
	Methods	M	28
	Indicators	I	5
	Total number of papers		**106**

The selected "LCA" papers provide a framework for analyzing the study of eutrophication and putting it into context as the state of the art. For this reason, those that were not directly related to the impact category under study were excluded.
Source: Authors

Temporally, there were years in which scientific production on the subject increased (Figure 2). Thus, we can observe the appearance of works from 1997 onwards, no scientific production on the subject in the period 1990-1996. Klöpffer (2014), in relation to SETAC, expresses that although its structure was modified during standardization by ISO, the basic discussions took place in a relatively short period between 1990 and 1993. Nevertheless, SETAC has continued to provide a forum for discussion of LCIA and related life cycle methods. Together with the United Nations Environment Programme (UNEP) a joint project, the "UNEP/SETAC Life Cycle Initiative" (Töpfer 2002) was founded in 2002 leading to a globalization of life cycle methods.

Figure 2. Number of papers published per year. 1990-August 2024 series.

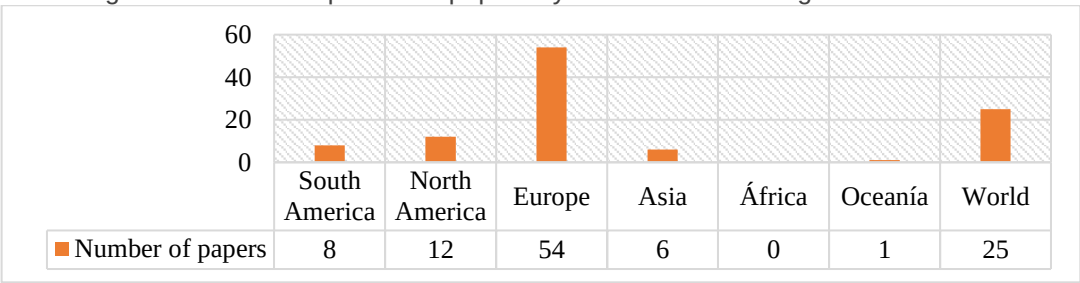


Source: Authors

Spatially, the geographical distribution of eutrophication studies has been mostly concentrated in European countries, with a deficiency in South American

countries (Figure 3). This distribution considers both application and theoretical sites, taking into account the place of origin of the authors. Of 106 studies, 51% are concentrated on the European continent, followed by 23.58% with worldwide application, North America (11.32%), South America (7.56%), Asia (5.6%), Oceania (0.94%) and finally Africa (0%). These data show the need to carry out LCA work on the impact of eutrophication on aquatic and terrestrial ecosystems in the countries of the South.

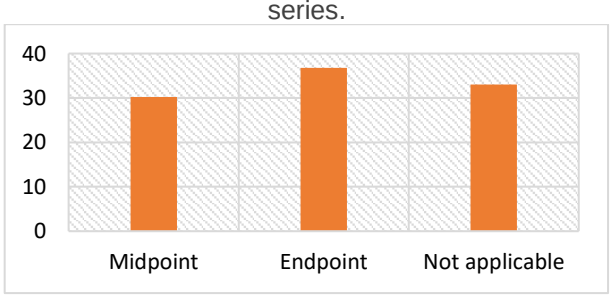
Figure 3. Number of published papers by continent. 1990-August 2024 series.



Source: Authors

ISO 14040 (ISO 2006a) establishes three general environmental categories to be addressed in LCIA, which are human health, resource use and ecological consequences. Indeed, of the 106 papers selected, 30% (32) study up to the midpoint, 37% (39) reach the endpoint and 33% (35) not applicable CFs (Figure 4). At this point, it is suggested to provide CFs for both the midpoint and the endpoint in relation to eutrophication (Payen et al. 2019), since both types of indicators are useful depending on the decision context (Rosenbaum et al. 2018).

Figure 4. Number of papers published according to the study or application of CFs. 1990-August 2024 series.



Source: Authors

In view of the above, it is possible to differentiate which studies have considered a geographic application and which have been limited to theoretical cases, based on

the continent. Thus, 57.5% (61) of the selected papers were application cases, while the remaining 42.5% (45) were theoretical cases (Table 2). Of the application case articles, 41% of which were located in Europe, 31% worldwide and the rest in the other continents. Theoretical cases are represented by 64.4% in Europe, 13.3% worldwide, another 13.3% in North America and 9% in South America. Of the 106 papers, only 4 were developed in Argentina (particularly in the province of Mendoza), where 2 of them are application cases focused on terrestrial eutrophication and none on aquatic eutrophication.

Table 2. Number of papers by theoretical or application case and continent. 1990-August 2024 series

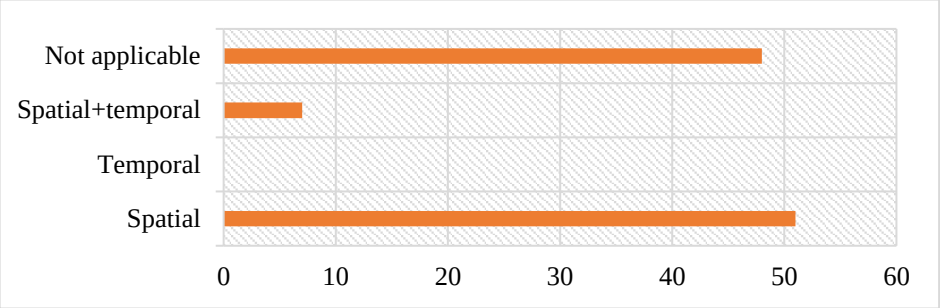
Number of papers by theoretical or application case and continent
1990-August 2024 series

Continent	Application case	Theoretical case
South America	4	4
North America	6	6
Europe	25	29
Asia	6	0
África	0	0
Oceanía	1	0
World	19	6
Total number of papers	**61**	**45**

Source: Authors

For many categories, the impact of a given element depends on where that flow occurs and has site-dependent CFs (Potting and Hauschild, 2006), where not taking them into account can give misleading results (Azevedo et al. 2013; Potting and Hauschild 2006). Therefore, spatial differentiation is considered an important step to improve the LCA methodology (Hellweg and Milà i Canales, 2014). However, several authors call for further development in some impact categories so that they also take into account temporal variability (Schmid 2008; Seppälä et al. 2001). Specifically, it is observed that of the selected papers, 49% (46) do not apply/correspond to a type of differentiation in their analyses, 45% (43) work with spatial differentiation, 6% (6) combine spatial and temporal and 0% with temporal differentiation only (Figure 5).

Figure 5. Number of published papers by type of differentiation. 1990-August 2024 series



Source: Authors

The spatial aggregation is dependent on the object of research, so it differs according to the study and place of application, standing out among the selected works: global, continental, by country, different regional scales; climatic zones; terrestrial ecozones; agricultural soils, crops, agricultural systems; oceans, marine and coastal zones and ecosystems, watersheds, river basins, estuaries, hydrographical units; natural areas; urban areas; and economic sectors.

Despite recent efforts to capture the effects of eutrophication on LCIA, there is no clear consensus on the use of a specific impact indicator and methods that do not take fate into account and lack modeling of effects are still being used. There is a need to identify and achieve consensus on scientific matters (Frischknecht et al. 2019). The Life Cycle Initiative recommends employing spatially explicit models with global coverage, aggregating CFs using agricultural, non-agricultural, or global emissions weights, and using existing environmental concentrations for effects models. Guidance is needed on which quantitative life cycle-based indicators are best suited to measure and monitor impacts on human health, ecosystems and natural resources (Jolliet et al. 2018; Frischknecht and Jolliet 2016).

Since the beginning of the LCA methodology, several LCIA methods have been proposed (Civit 2009). Consequently, it is necessary to provide guidance to practitioners (Payen et al. 2019). The following methods (and models) are considered in this work: Accumulated Exceedance (AE) (Seppälä et al. 2006); CML 2002 (Guinée et al. 2002); EDIP 2003 (Potting and Hauschild 2005); IMPACT 2002+ (Jolliet et al. 2003); IMPACT World+ (Bulle et al. 2019); LC-Impact (Verones et al. 2016); ReCiPe 2008 (Goedkoop et al. 2013, 2009); ReCiPe 2016 (Huijbregts et al. 2017, 2016) and TRACI (Norris 2008; Bare et al. 2003). In relation to the analysis of the selected papers, it is possible to identify several LCIA methods that have been applied or recommended

by the authors according to the study context (Table 3). Thus, according to the scope of the research, there are:

Table 3. Methods according to scope of research. 1990-August 2024 series

Methods according to scope of research 1990-August 2024 series		
Midpoint	***Endpoint***	
AE	AE	IMPACT 2002+
CML, CML 2001, CML 2002	CARMEN	IMPACT World+
CML-IA	CML 2001, CML 2002	LC-impact
DAIA (Decision Analysis Impact Assessment)	ECO-INDICATOR 98, 99	LIME
ECO-INDICATOR 99	Ecological Scarcity Method (Ecopoints 2006)	RAINS-LCA
ECO-SPEED	EDIP, EDIP 97, EDIP 2003	ReCiPe, ReCiPe 2008, ReCiPe 2016
EDIP 2003	EPS 2000	TRACI
IMPACT 2002+	ILCD 2009	
LIME		
ReCiPe, ReCiPe 2008		
TRACI		

Source: Authors

Product certification schemes such as EPD (Environmental Product Declarations) or PEF (Product Environmental Footprint) recommend, for example, CML 2002 and ReCiPe 2016. Various authors discuss the best practice for eutrophication and it is necessary to select that method that suits the conditions at the study site. Bach & Finkbeiner (2017) and Hauschild et al. (2013) indicate that the recommended method for characterization at the midpoint level is the AE model, as documented in Seppälä et al. (2006) and Posch et al. (2008), which models the AE of critical N loads in sensitive terrestrial ecosystems. Now, for aquatic eutrophication, Bach & Finkbeiner (2016) recommend ReCiPe from Goedkoop et al. (2009), where the model considers the change in substance concentration, to name a few authors. As for the models, ECOSENSE, EMEP, EMEP/MSC-W, EUTREND, fate and transport (F&T) models, Mechanistic biological model, NEWS 2, NEWS 2-DIN, RAINS, RUSLE, have been identified for the midpoint, while for the endpoint, the following have been highlighted: ANOVA, ECOSENSE, EUTREND, Tropospheric GEOS-Chem model, WMI (Windrose Model Interpreter), LUCAS, MEEuP, NEWS 2-DIN, OVERSEER nutrient budget model, USES-LCA 2. 0, USLE-Swiss Agricultural Life Cycle Analysis (SALCA).

Morelli et al. (2018) perform a critical review of eutrophication models for LCA. They indicate that historically, LCA studies have estimated eutrophication impacts based on global or continental average models. However, the science is advancing toward methods that utilize location-specific characteristics to better characterize and quantify nutrient fate and transport through air, land, and water, as well as the associated ecosystem responses.

Currently, Payen et al. (2019) suggest that for freshwater eutrophication the mid-level indicator measures potential freshwater eutrophication in P equivalents (Peq) based on the fate model of Helmes et al. (2012). While, the CFs at the endpoint level calculate damages (PDF .m3.yr) to freshwater ecosystems based on the above fate plus the inclusion of the effect of total P changes in autotrophs, aquatic invertebrates and fish from Azevedo et al. (2013). For marine eutrophication, the midpoint indicator measures marine eutrophication potential in N-equivalents (Neq) based on Cosme et al. (2017b). At the endpoint level, CFs calculate damage (PDF.m^3.yr) to benthic ecosystems for six heterotrophic taxonomic groups across five climate zones based on Cosme et al. (2017a). For terrestrial eutrophication, no consensus has yet been reached. It is recommended to use regional inventory data when possible or to perform an uncertainty analysis. This denotes the importance of matching inventory databases with available impact models (Payen et al. 2019). Regionalization has the potential to identify any regional occurrences of environmental unsustainability that would be overlooked through global assessment, given the spatially uneven distribution of carrying capacity as well as environmental impacts of many elementary flows (Bjørn et al. 2020).

3.2 UNDERSTANDING THE PRIMARY ASPECTS OF EUTROPHICATION STUDIES IN TERRESTRIAL ECOSYSTEMS

The inclusion of terrestrial eutrophication in LCIA methodologies was later than in the case of aquatic. Thus, Lindfors et al. (1995) were the first to consider it, proposing the use of CFs for aerial nitrogen compounds deposited on the soil. According to the analysis carried out, of the 95 papers selected, only 6 are focused on terrestrial eutrophication, and Table 4 shows the most relevant characteristics of each one.

Among the works cited, it is observed that they correspond between 2000 and 2011, with greater development and application in Europe (66.6%), followed by South America, particularly in the province of Mendoza (33.3%). Considering the scope, 4 (66.6%) works reached the midpoint and 2 (33.3%) the endpoint. In turn, all have considered site-dependent spatial differentiation, with different levels of aggregation and, in some cases, temporal differentiation. Site-dependent spatial differentiation is made by distinguishing between source types and the environment that will then receive the deposition, knowing a priori their sensitivity to exposure. The geographical scale is defined at the level of regions or countries and varies between 50-500 km (Potting and Hauschild 2006).

Table 4. Main characteristics of terrestrial eutrophication studies

Reference	Place	Is it a case of application?	Dimensions	Differentiation	Aggregation	LCIA methods and models
Huijbregts et al. (2000)	Europe	Yes	Fate, exposure and effect (endpoint)	Temporal and spatial	Europe and a number of European regions	Spatially explicit regional air pollution information and simulation model (RAINS-LCA)
Seppälä et al. (2006)	Europe	Yes	Emissions (midpoint)	Spatial: site-dependent; temporal	35 European countries and 5 sea areas for 2002 emissions and emissions predicted for 2010	EMEP Lagrangian model. EcoSense. RAINS. The are chosen category indicator, AE and unprotected ecosystem area (UA).
Civit et al. (2006)	Mendoza, Argentina (South America)	Yes	Emissions and depositions (midpoint)	Spatial	Regional level: Mendoza	EDIP 2003 (Program ISC 31)
Schmid (2008)	Galicia, Spain (Europe)	Yes	Emission, deposition and regional critical load (midpoint)	Spatial	Regional level: Galicia	AE was used as the category indicator
Civit (2009)	Mendoza, Argentina (South America)	Yes	Emissions, depositions and dispersion (midpoint)	Spatial: site-dependent	Regional level: Mendoza	The impact model proposed here is based on the proposal of Potting et al (2004) and was adapted and modified according to the needs identified and the characteristics of the ecosystems present in the region studied
Gallego et al. (2011)	Galicia, Spain (Europe)	Yes	Deposition, emissions and critical loads (midpoint)	Spatial	Regional level: Galicia	AE was used as the category indicator

Source: Authors

Methodologically, Huijbregts et al. (2000) describe the spatially explicit regional air pollution information and simulation model (RAINS-LCA), which was developed for the calculation of acidification and terrestrial eutrophication potentials for Europe and a number of European regions, taking fate, background depositions and effects into account. The results indicate that it is important to use region-specific and time-specific terrestrial acidification and eutrophication potentials.

For their part, Seppälä et al. (2006) chose as category indicator the AE, was computed according to the calculation methods developed in the work under the United Nations Economic Commission for Europe (UNECE) Convention on Longrange Transboundary Air Pollution (LRTAP). Sulphur and N depositions to 150x150 km^2 grid cells over Europe were calculated by source-receptor matrices derived from the EMEP Lagrangian model of long-range transport of air pollution in Europe. For the comparison, the results based on the use of UA indicator were calculated by 10% and 50% reductions of emissions that corresponded to the common practice used in the previous studies. Thus, the comparison between country-dependent CFs calculated by the AE and UA indicators showed that these two approaches produce differences between characterisation factors for many countries/areas in Europe.

Schmid (2008) developed regional factors for aquatic and terrestrial eutrophication in Galicia, Spain. He established AE values, reflecting the amount of N accumulated above the critical load, as a category indicator, based on nitrogenous compound deposition levels and the sensitivity of their terrestrial ecosystems, taking as a starting point the method developed by Seppälä et al. (2006). In fact, the factors obtained were lower than those available for Spain, which demonstrates the importance of calculating factors at the regional level. Similarly, Gallego et al. (2011) used the AE and required actual values of deposition, emissions and critical loads. The results obtained confirm that it is a suitable category indicator for terrestrial eutrophication estimation.

As a regional antecedent, Civit et al. (2006) presented the results obtained from the modeling of N deposition in soils and its comparison with the threshold values for a representative crop of the region (garlic), a step prior to the determination of equivalence factors for the terrestrial eutrophication impact category for the arid central-western region of Argentina. The results show that under the conditions analyzed, eutrophication would not occur in these crops, since in no case is the

threshold value exceeded. Later, Civit (2009) developed an impact model based on the proposal of Potting & Hauschild (2006), was adapted and modified according to the needs and characteristics of the arid region of central-western Argentina. The model calculated the CFs in terms of the effect on the decline in production that could be caused by the deposition of N compounds, comparing the deposition of these substances with the threshold values of the species that exist in these ecosystems: grapevine and garlic. As results, he obtained that the impact model developed has allowed to verify the applicability of the model in definite cases of impact assessment and to demonstrate that the use of generic factors or worse, foreign site-dependent factors, can effectively lead to obtain erroneous results overestimating the impact considered. The procedure followed to determine the CFs of terrestrial eutrophication could be applied to other regions of the national territory, taking as a basis the most representative crops and their respective N thresholds in each one of them.

It is observed that the AE indicator is widely used to determine the impacts of terrestrial eutrophication in different regions of the world, considering the spatial differentiation and the particular characteristics of the sites under study.

3.2.1 Incorporating Accumulated Exceedance in studies of terrestrial eutrophication

As explained in Table 4, the use of the AE indicator (number of N equivalents that are above the critical load) stands out among the LCIA methods.

In the last century, enhanced emissions of nitrogenous compounds caused by agricultural and industrial activities have increased atmospheric N deposition in natural and semi‐natural ecosystems across the world (Erisman et al., 2013; Galloway et al., 2008). As N deposition increases, it is normal for N availability in the soil to increase significantly, often resulting in a crossing of an N saturation threshold (Dise & Wright 1995; Brenner et al. 2005; Nilsson et al. 2006; Stevens et al. 2006), which in turn often leads to increased N losses through flushing (Dise & Wright 1995). Crossing this threshold is often considered as an indicator of negative N effects, as N availability would be higher than the ecosystem is able to process (Pilkington et al. 2005; Fowler et al. 2013). The responses of plant communities to N deposition vary depending on the environmental context (Perring et al. 2018; Simkin et al., 2016; Vellend et al., 2017).

In the work of Huijbregts et al. (2000), the hazard index above and below the critical loads is used as CFs, where the latter can be defined as a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur, according to present knowledge". Among several results, they obtained that a larger dispersion is found among the region-specific terrestrial eutrophication potentials of NH_3 compared to the terrestrial eutrophication potentials of NOx, because the transport potential of NOx is higher than that of NH_3. The maximum regional differences between the terrestrial eutrophication potentials are up to 1.5 orders of magnitude, depending on the substance and the scenario chosen: "above and below critical load" or "below critical load only". Something to consider is that, in general, critical ecosystem loads for N are high and are due to immobilization and denitrification of N in the soil and net uptake by plants (UBA 1996).

Seppälä et al. (2006), using emitter-receptor matrices based on the Lagrangian long-range air pollutant transport model developed by EMEP and the most updated critical load moment data (Hettelingh et al. 2004), developed CFs for 35 European countries. In this case they took into account as a category indicator the variation that occurs in AE with a marginal variation in emissions in a given country and year (Schmid 2008). The authors considered calculating corresponding CFs for European countries and five maritime areas. They indicate that the prerequisite for calculating the AE indicator type for a region is the definition and calculation of the exceedance of the critical load of a single ecosystem. As reference emissions, we used the national emissions for the year 2002 as well as the predicted emissions for the year 2010, as reported by EMEP (Vestreng et al. 2004). Among their results, they show that the indicator produces reliable CFs for applications requiring small changes in national emissions, which are typical of LCIA applications.

On the other hand, Schmid (2008) indicates that AE is one of the most widely used impact category indicators. The author has established the values based on the deposition levels of nitrogen compounds and the sensitivity of their terrestrial ecosystems to eutrophication, using the regional emission, deposition and critical load values for the calculation of CFs. In his work, he has shown that AE is a good indicator, since it allows obtaining stable CFs and negligible characterization errors when evaluating minor variations in emissions (< 100 t), which are those that usually occur

in LCA. The most important advantage is that it allows evaluating how the impact varies when the amount of deposition exceeding the critical load changes (Seppälä et al. 2006) and thus corrects one of the disadvantages of approximation-based methodologies. In the specific case of this study, the excess is defined as the amount of N deposited above the critical load, for Galicia in 2001, using NOx and NHx CFs. In Gallego et al. (2011), the results obtained confirm that AE is a suitable category indicator for the estimation of terrestrial eutrophication.

As recommendations and perspectives, Gallego et al. (2011) express that a comprehensive comparison of AE and risk index (HI) methodologies for terrestrial eutrophication would be interesting, as both apply the above-threshold-only approach (Huijbregts et al. 2000; Seppälä et al. 2006). Civit (2009) indicates that while HI uses a scaling coefficient to quantify the exceedance and evaluates the marginal changes that occur in that coefficient, AE is based on the absolute difference between deposition and the critical load or tolerable threshold and evaluates the marginal changes in cation exchange capacity that occur. Another indicator that appears in Seppälä et al. (2006) is the UA. The authors note that it is commonly used as a category indicator in the determination of CFs, although it is only suitable for large changes in emissions and does not lead to environmental benefits in terms of CFs if deposition after emission reductions is still higher than the critical load.

3.2.2 Significance of Accumulated Exceedance Application in Argentine Pampean Agroecosystems

While the European Union strategy on air pollution aims to achieve a 35% reduction in the ecosystem area exceeding critical loads of eutrophication by 2030, relative to 2005 (EC, 2013a), this would only be achieved if the maximum number of technically feasible reduction measures were implemented (EC, 2013b). On the other hand, in the eastern United States, N deposition is declining from historical peaks in the 1970s and 1980s as a result of stricter air quality standards associated with the Clean Air Act of 1990 and subsequent policy (Burns et al. 2011). However, deposition is increasing or unchanged in the western United States, and there is a shift in the composition of deposition toward more reduced forms of N nationally (Li et al. 2016). Furthermore, even though deposition may be declining in some regions such as the

east, these rates still far exceed pre-industrial rates and the estimated sensitivities of many ecological endpoints in the region (Baron et al. 2011, Pardo et al. 2011).

In the case of Latin America, current and future agricultural practices are and will be critical in determining the human impact on the N cycle, due to the importance of the agricultural sector in the economies of most of the region (Martinelli et al. 2006). At the same time, differences both in climatic and edaphic properties as well as socioeconomic policies make generalization difficult in terms of predicting the consequences of human activity in this region (Austin et al. 2006). Argentina is currently considered one of the major agricultural regions of the world, with most activity centered in the Pampa region (Hall et al. 1992). This points to the need to apply regional factors in southern countries, where there is insufficient data on eutrophication in the aquatic and terrestrial ecosystems of these regions.

Pereyra (2012) states that the great eco-environmental variability of Argentina is materialized in a complex mosaic of landscapes and soils, being able to differentiate 12 regions, each characterized by a particular association of soils resulting from a specific arrangement of formation factors and pedogenetic processes. That the incidence or degree of determination of a given factor varies from one region to another and even within the same region.

Dominguez & Rubio (2019) provide an overview of the main agricultural characteristics of the different regions of the country. In the northwestern region, the climate favors the development of subtropical agriculture. In the Cuyo Region, intensive agriculture under irrigation predominates. In the Patagonian Region, the production of edible crops is strongly limited by extreme climatic conditions. The central zone comprises the Pampean Region, characterized by highly favorable conditions for agriculture. Argentina has some of the most fertile soils in the world, especially those located in the Pampean Region. In this sense, soils constitute one of the greatest assets of Argentina and give the country the capacity to produce food for more than ten times its current population (Rubio et al. 2019).

The expansion and intensification of agriculture has probably been the most remarkable fact of Argentine agriculture in recent decades. This has been mainly associated with the reconversion of new areas with no agricultural background; the reconversion to full cropping of land previously rotated with livestock; the dramatic increase in the area planted with soybean; the expansion of double cropping; and the

increase in the area cultivated under no-tillage systems (Magrin et al. 2005; Paruelo et al. 2005; Boletta et al. 2006), eliminating hundreds to millions of hectares of natural forests (Montenegro et al. 2007). Lavado (2016) indicates that degradation processes have different degrees of anthropogenic causality, varying levels of extension and a diverse scale of severity.

Local extensive agricultural systems continue to show a deficit in nutrient replenishment and some local aquifers have a high concentration of nitrates (Rubio et al. 2019). Thus, it is possible to apply regional CFs for Argentina, where its productive matrix, soil use and management, and international trade, highlight the need to assess the environmental impacts of products, processes or activities on terrestrial ecosystems. Given the environmental variability and diversity of its productive systems, it is considered important to select a minimum set of species representative of each region to apply and evaluate the EA as a category indicator of N deposition in the region. The work of Civit (2009) in the province of Mendoza, taken as a regional background reference, shows that it is feasible and valid for Argentina to apply regional CFs such as the AE and that extrapolation to other regions of the country is possible, considering the environmental and productive characteristics of land use in each of them.

Although this article has not focused particularly on aquatic eutrophication, regional antecedents of eutrophication in lakes and lagoons in Argentina are the basis for its next analysis within the context of Life Cycle Analysis, since no studies have been reported within this methodology. Several authors have recognized that Argentina presents serious Eutrophication problems in some of its lakes and reservoirs (Quirós 2000) (e.g., Mengo et al. 2019; Espósito et al. 2016; Ledesma et al. 2013; Mariñelarena & Gómez 2008).

4. CONCLUSION

The growing concern for environmental sustainability has driven more detailed research into potential impacts in various regions. After an extensive literature review, where 4662 studies related to eutrophication and LCA were analyzed, 106 emphasized the importance of spatial analysis. It is evident that further development and updating of studies in this impact category are necessary. Only 6 studies focus on Latin America,

and of these, 4 were conducted in Argentina. Although aquatic eutrophication is more commonly studied due to the large number of watersheds in the region, terrestrial ecosystems should not be overlooked. The expansion of the agricultural frontier, changes in soil use and management, and the disappearance of natural plant species are urgent issues in the southern region of the American continent.

The focus on terrestrial eutrophication aims to establish a foundation for developing research in Argentina, contributing to regional environmental sustainability. It is surprising that the progress in terrestrial eutrophication has not kept pace with aquatic eutrophication. This is concerning because changes in the functions and composition of N-poor species are significant environmental problems that require further investigation.

The spatial regionalization of eutrophication impact mechanisms, adapted to the specific characteristics of Argentine ecosystems where economic activities occur, is essential for LCIA. Without regional values, using CFs developed for other locations could result in unrepresentative outcomes, given the bioclimatic diversity across the region.

The study of terrestrial eutrophication in Argentina, using the accumulated surplus indicator, is feasible. This involves selecting a minimum set of cultivated or natural species to determine whether N depositions exceed critical thresholds and cause potential impacts. If this impact category proves irrelevant, it would be a positive finding. This research can continue with further characterization of the ecosystems receiving emissions. The data collected will help select the most appropriate midpoint impact model adapted to regional conditions. This will follow the guidelines established at the Pellston Workshop held in May 2018 in Valencia, Spain (Payen et al. 2019).

The importance of this research and the availability of suitable methods have been clearly demonstrated. However, the task is complex. It is not simply about applying an existing method to a new case but involves addressing several challenges. These include regional diversity in life cycle inventory data, consideration of impact mechanisms in aquatic and terrestrial ecosystems, study of the fate, transport, and deposition of limiting substances in receiving areas, and the generation of site-dependent CFs due to the regional nature of eutrophication. In addition, spatial and temporal differentiation must be applied.

Therefore, this first step suggests that developing regional indicators within the LCIA stage is justified for research in Argentina. Eutrophication has not yet been fully explored in the field of LCIA at the regional level. This contribution would provide essential data to quantify the potential impacts resulting from various economic activities.

For our research, defining the Accumulated Surplus and regional characterization factors is crucial. These will help evaluate the effects of eutrophication in the ecosystems of southern Latin America, particularly in the Pampean agroecosystems of Argentina. This would set a precedent for studying environmental risks in the region concerning productive systems.

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CONFLICTS OF INTERESTS

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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