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Critical review of eutrophication models for life cycle assessment

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Abstract

This paper evaluates the current state of life cycle impact assessment (LCIA) methods used to estimate potential eutrophication impacts in freshwater and marine ecosystems, and presents a critical review of the underlying surface water quality, watershed, marine, and air fate and transport (F&T) models. Using a criteria rubric, the authors assess the potential of each method and model to contribute to further refinements of life cycle assessment's (LCA's) eutrophication category. The F&T criteria assessed include sources of nutrient loading, transport and removal mechanisms, and nutrient transformation processes, as well as model structure, availability, geographic scope, and spatial and temporal resolution. The authors describe recent advances in LCIA modeling, and provide guidance on the best available sources of fate and exposure factors, with a focus on midpoint indicators. The critical review identifies gaps in LCIA characterization modeling regarding availability and spatial resolution of fate factors in the soil compartment, and identifies strategies to characterize emissions from soil. Additional opportunities are identified to leverage detailed F&T models that strengthen existing approaches to LCIA, or that have the potential to link LCIA modeling more closely with the spatial and temporal realities of effects from eutrophication.

Keywords

eutrophication; impact assessment; fate and transport; nitrogen; phosphorus; nutrient

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Introduction

Human contributions to increased cycling of nitrogen (N) and phosphorus (P) through the biosphere threatens the health of freshwater and marine ecosystems and the economic and life support functions they provide.¹ Harmful algal blooms (HABs) are caused by the rapid or exponential growth of algae and cyanobacteria, and can result from excess nutrient availability (i.e., eutrophication). HABs are responsible for billions of dollars in economic impacts associated with recreational activities, commercial fishing, property values, human health, and drinking water systems.² HABs are linked to eutrophication resulting from human activities (hereafter eutrophication), and usually result from elevated nutrient inputs to the system.³ The 2014 algal bloom in Lake Erie demonstrated the potential for impairment of the United States water supply as a result of anthropogenic nutrient loading and subsequent eutrophication impacts.⁴ Human inputs of N to the national landscapes and surface waters are dominated by fertilizer application, atmospheric deposition, and agricultural N-fixation.⁵ Scientists and managers alike need improved and reliable quantitative tools to address the challenges of eutrophication.

Life cycle assessment (LCA) supports sustainable decision-making by providing a comprehensive and structured accounting of the potential environmental and human health impacts associated with a product, service, or policy.⁶ To ensure LCA methods reflect the best science available, the methods and their underlying models must be updated. 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 (e.g., soil and water data layers in geographic information systems (GIS)) to better characterize and quantify nutrient fate and transport (F&T) through air, land, and water, as well as the associated ecosystem responses. In this paper, we review F&T models that can be used to improve estimates of nutrient-related impacts in LCA and thereby advance efforts to mitigate eutrophication of surface waters.

The process of eutrophication begins with increases in nutrient loading to ecosystems, typically limited by N or P. The availability of these formerly limiting nutrients stimulates primary production leading to adverse effects, including accumulation of algal toxins and taste and odor problems in drinking water.⁷ The death and microbial respiration of algae leads to decreases in dissolved oxygen (DO), resulting in hypoxia, mortality of benthic organisms, and habitat compression, all of which can have negative consequences for higher trophic species.⁸ Over time, as nutrients and organic matter accumulate, hypoxic events can become seasonal, leading to long-term changes in ecosystem structure and function.⁸ Each of these changes can have implications for human health, recreation, fisheries, property values, and other economic activities.

LCA and life cycle impact assessment (LCIA) aim to estimate this cause-effect chain and its midpoints (i.e., the fate and exposure (but not the effects) components of LCA/LCIA), for freshwater and marine ecosystems. However, without quantifying site-specific fate, transport, and loading of nutrients at appropriate spatial scales, LCA and LCIA's relevance for eutrophication may be limited. Furthermore, current LCA characterization models

combine marine and freshwater environments into a single impact category (e.g., Eutrophication Potential), or employ the simplifying assumption that P is limiting in freshwater ecosystems and N is limiting in marine ecosystems. However, these assumptions do not hold true in all situations, and current studies indicate that it is important to provide management for both N and P.^{9–11} It is also commonly assumed that atmospheric transport of P is negligible, and thus safe to exclude this pathway from characterization models. However, several recent studies demonstrate atmospheric P transport occurs,^{12–15} indicating that this assumption is worth revisiting.

Our study aims to improve the characterization of eutrophication impacts in LCA with a focus on identifying opportunities to improve LCIA's representation of nutrient F&T through air, land, and water.

Our specific goals are to:

1. explore the current state of the science regarding the eutrophication impact category in LCA and LCIA methods;
2. review and compare select nutrient F&T models that can be used for assessing eutrophication in LCA and LCIA;
3. discuss potential linkages of these models to LCIA for eutrophication, and;
4. make recommendations for improving the eutrophication impact category in LCA and LCIA.

Our review of select nutrient F&T models focuses on sources of nutrient loading to each environmental compartment (e.g., water compartments, soil, and air), representation of nutrient speciation, and F&T mechanisms. We distinguish four model categories: (1) surface water quality models, (2) watershed models, (3) marine models, and (4) air quality models. Through structured model comparison and analysis, we identify candidate models for improving the representation of nutrient-related impacts in LCA, delineate which parameters are most important, and suggest ways to improve methods for characterizing eutrophication impacts in LCA while minimizing the practitioner's burden of data collection.

Model Selection Criteria and Review

A list of candidate F&T and LCIA models was created based on the results of Google Scholar and Google Web searches for peer-reviewed publications and model documentation published between 2007 and 2017. The searches combined the keywords “eutrophication” AND “(nitrogen OR phosphorus OR nutrient) AND (pollution OR fate OR impact OR hypoxia)”. Sources were added if they were referenced by multiple authors in the original search. Priority was given to models actively maintained and updated, regularly used, especially in the United States, applied by the U.S. Environmental Protection Agency (EPA), and considered to have potential to contribute to LCIA of eutrophication.

Each model was documented using a spreadsheet to assess its suitability for estimating eutrophication-related impacts in LCA. Refer to the Supporting Information (SI) for rubric details. General metadata documented included model type, institutional origin and ongoing

support, public availability, and aspects of scope, including geographic coverage, time step, and spatial resolution. Nutrient-related metadata included model representations of nutrient loading sources, nutrient species or groupings tracked, transport and removal mechanisms (i.e., processes that facilitate or minimize transport, respectively, through the biosphere), and nutrient transformation processes (which change the form or speciation of a nutrient). Figure 1 illustrates the relationship between nutrient input, transport, removal, and transformation as N and P cycle through the biosphere. Ideally, F&T models and LCIA methods would reflect accurately and precisely all relationships shown in Figure 1. Due to practical factors, however, such as lack of model sophistication, lack of site specificity, and technical challenges associated with determining spatial and temporal distribution of releases and emissions, simplifying assumptions must be made. The approach taken in this review is to include as much scientific detail as necessary and available and continually work toward methods and models that more realistically reflect observed environmental processes.

Assessment of Eutrophication in Life Cycle Assessment: State of the Practice

LCIA models are used to characterize environmental and human health impacts associated with the release of substances to the environment and the use of natural resources. For a given impact category (here, Eutrophication), LCIA estimates the relative severity of releases and emissions to various environmental compartments.

Environmental impacts in LCA are characterized at the endpoint or midpoint level. Endpoints are the ultimate impacts of interest, e.g. human health effects measured in disability-adjusted life years (DALYs) or ecological impacts measured as time-integrated species loss.¹⁶ Midpoints estimate the relative contribution of releases to an endpoint, at an earlier point (i.e., midpoint) on the cause-effect chain where an equivalency between substances can be established.¹⁶

Equation 1 illustrates the LCA framework used in LCA to calculate environmental and human health impacts using characterization factors (CFs).¹⁷ Midpoint CFs are the product of fate factors (FF) and an optional exposure factor (XF). Endpoint CFs are the product of midpoint CFs, effect factors (EFs), and an optional damage factor (DF). This paper focuses on models that quantify the FFs for N and P.

$$\text{Impact} = \left[\underbrace{\boxed{\text{FF}} \times \boxed{\text{XF}}}_{\text{Midpoint}} \times \underbrace{\boxed{\text{EF}} \times \boxed{\text{DF}}}_{\text{Endpoint}} \right] \times \underbrace{\text{Emission Quantity}}_{\text{LCI Phase}}$$

(1)

Development or selection of an appropriate eutrophication LCIA method should also consider the capacity to spatially differentiate impact potential based on location and the environmental compartment(s) involved. The feasibility and importance of spatial differentiation has been demonstrated for other impact categories^{18,19} and is partially employed within existing eutrophication LCIA methods.^{20,21} An ideal LCIA method will achieve practical simplicity while being scientifically robust and globally applicable. Flexibility and adaptability are also advantageous, given the spectrum of life cycle inventory (LCI) data quality, product system definitions, and scopes of study.

LCIA Methods

We consider four common LCIA methods as a basis for discussing the advancement of F&T models in midpoint assessment of eutrophication. The methods include:

TRACI 2.1, the *Tool for the Reduction and Assessment of Chemical and other Environmental Impacts* (TRACI), provides eutrophication midpoint CFs representative of average U.S. conditions,^{22–24} combining P-related freshwater and N-related marine impacts based on the Redfield ratio and stoichiometric equivalencies. Atmospheric FFs are developed from source receptor matrices based on the ASTRAP model.²¹ Estimated F&T of N in surface freshwaters and of atmospherically deposited N is based on the fraction of river basin precipitation reaching the ocean. All P releases to surface freshwater systems are assumed to reach a P-limited waterbody.

ReCiPe 2016 provides midpoint CFs for freshwater eutrophication for 157 countries using cumulative P FFs developed by Helmes et al.²⁰ Releases to soil are characterized by assuming 10% of the P reaches freshwater.^{25,26} Endpoint CFs are based on an emission-weighted global average effect factor.^{27,28} Marine eutrophication is not included. The previous version, ReCiPe 2008, provided CFs for freshwater and marine eutrophication at the midpoint and endpoint levels. The method represents average European conditions using the CARMEN model^{29,30} for soil, groundwater, and surface freshwater F&T of N and P and EUTREND for F&T of N releases to air. ReCiPe 2008 users are encouraged to report freshwater and marine eutrophication results separately,³¹ although combined CFs are provided based on the Redfield ratio. Endpoint CFs are presented in terms of species loss.

IMPACT World+ provides eutrophication midpoint CFs using cumulative fate factors for P in freshwater using Helmes et al.'s,²⁰ similar to ReCiPe 2016. Fate of N in surface freshwater is based on CARMEN's estimate of the European average, as was used in ReCiPe 2008 and EDIP 2003.³² No FFs are provided for the soil compartment, leaving these estimations to the LCI phase. Endpoint impacts are estimated in terms of partially disappeared fraction (PDF) of species per unit area over a given period.^{33,34} IMPACT World + will replace the IMPACT 2002 LCIA method³⁵ once it is released.

CML provides aquatic midpoint CFs for releases to soil, air, and water based on the Redfield ratio and the stoichiometric ratio of N and P in the releases.³⁶ The CFs for release of a given substance to soil and water are equivalent because F&T is not considered and terrestrial and aquatic eutrophication are combined. CFs for air emissions were last updated

in 2002 and incorporate atmospheric F&T using the RAINS model.³⁷ The CML method does not distinguish freshwater and marine eutrophication nor does it include endpoint metrics.

Nutrient Fate and Transport Models

The application of nutrient F&T models for multiple environmental compartments could improve the quantification of LCIA eutrophication midpoint assessment by providing site-specific and mechanistic estimates of N and P loadings. Based on our model selection criteria, we describe a select set of surface water quality models, watershed models, marine models, and air quality models with the potential for integration into LCIA (Table 1).

AQUATOX^{38,39} and WASP⁴⁰ are surface water quality models, which differ from watershed models in that they only model surface freshwater systems at the reach or river network scale. Both models facilitate more detailed representation of F&T processes within surface freshwater bodies than typical watershed or LCIA models. WASP and AQUATOX track nutrient transformations within the water column including biological cycling, dual-nutrient growth limitation, light limitation, and temperature-dependent reaction kinetics. Both AQUATOX and WASP are US EPA models used to estimate water quality concentrations and fluxes in individual stream reaches and river networks for monitoring and regulatory purposes. Further details on F&T models are provided in the SI.

CARMEN,^{29,30} He et al. 2011,^{41,42} SPARROW,⁴³ NEWS 2,⁴⁴ SWAT,⁴⁵ and IMAGE-GNM^{46,47} are watershed models that simulate runoff, and F&T processes in soil, groundwater, and surface freshwater compartments within topography-delimited watersheds. Terrestrial biological processes are considered as they relate to the loading or retention of nutrients. SPARROW and NEWS 2 are hybrid models relying on mechanistic and empirical approaches to F&T modeling. SPARROW and IMAGE-GNM both facilitate uncertainty analysis of model results, whereas other models are primarily deterministic. IMAGE-GNM is a module within the IMAGE integrated assessment model. He et al. and SWAT are on the more mechanistic end of the spectrum, and the latter generally allows for incorporation of a wider suite of agricultural management practices than other models.

NCOM-CGEM,⁴⁸ FVCOM-GEM,⁴⁹ FVCOM-WQM,⁵⁰ and EFDC-WQM^{51–53} are examples of linked hydrodynamic water quality models. The hydrodynamic component of each model simulates fluid flow in estuarine and coastal regions, considering the influence of complex coastal geometry, tides, and forcing factors such as solar radiation and wind. Water quality modules simulate the response of biological communities to nutrient loading.

CMAQ,^{54–56} GEOS-Chem,⁵⁷ and CAMx⁵⁸ are all multi-scale air quality models that track the F&T of N compounds, ozone, particulate matter, toxics, and other airborne pollutants through the atmosphere. Multi-scale models utilize a nested grid structure to allow for higher grid resolution in select regions. Boundary conditions are established using a coarser regional or global grid resolution. All described models facilitate the simultaneous modeling of multiple pollutants in an integrated “one-atmosphere” model.⁵⁵ The one-atmosphere structure facilitates interactions between chemical species and mechanisms.

Fate and Transport Approaches to Assist LCIA for Eutrophication

The following sections describe pertinent model elements, as documented in the criteria rubric (see Table S4 in the SI). Current midpoint eutrophication methods generally lack site-specific F&T factors and precise modeling of nutrient loading at appropriate spatial scales (preferably with global coverage). Ideally, revisions to the eutrophication LCIA category would contribute to these needs.

Fate and transport in surface freshwaters

The surface water quality models and watershed models that best inform LCIA methods include diverse sources of nutrient loading and approaches to modeling in-stream transport. Three of these models—SWAT, WASP, and AQUATOX—also simulate nutrient transformation processes (Table 2). Most F&T models for surface freshwaters do not simulate nutrient transformation but are useful for other processes and compartments. Each of the following models is described in Table S2.

SPARROW does not model F&T mechanisms directly (except in-stream retention). However, it does include terrestrial non-point loading via F&T input data describing land use regimes, management practices, topography, climate, and soil type. These input data allow the model to empirically assess transport and removal mechanisms such as erosion and surface runoff.

These watershed models simulate nutrient loading from surface runoff and lateral subsurface flow. SWAT and IMAGE-GNM differentiate between lateral subsurface flow and groundwater percolation. CARMEN, NEWS 2, SWAT and IMAGE-GNM include nutrient loading associated with particulate nutrient erosion.

WASP, AQUATOX, TRACI 2.1, and IMPACT World+ model F&T processes in the surface freshwater compartment. They accept point and non-point sources of nutrient loading, but do not calculate releases to surface freshwater from soil applications. ReCiPe 2016 assumes that 10% of P released to soil reaches freshwater.

Models vary widely in how they track N and P species in surface freshwaters. For example, He et al. aggregates N species tracked in the soil compartment into total N and dissolved inorganic nitrogen (DIN) within surface freshwater. Diffuse terrestrial sources are modeled as total N, while DIN flows are based on data from wastewater treatment plants. He et al. does not model P compounds. CARMEN, ReCiPe 2016, TRACI 2.1, IMPACT World+, and IMAGE-GNM track total N and total P in the surface freshwater compartment.

Representation of nutrient transport and retention within waterbodies also varies. TRACI calculates N transport to coastal ecosystems based on the fraction of watershed area that drains to the ocean, assuming that N transport is proportional to hydrologic transport.²¹ In TRACI, 100 percent of P input to freshwater is assumed to reach a waterbody where it is the limiting nutrient. By contrast (for N), CARMEN assumes that 30 percent of N released or transported to surface freshwater is lost via denitrification, while the remainder is transported to coastal ecosystems.³¹ Rather than assuming a percentage, IMAGE-GNM

considers in-stream transport as a function of advection, settling, sediment exchange, and denitrification. Finally, the model documentation for He et al. notes that nutrient transmission losses are considered, but no rates of detention are given.

In addition to retention mechanisms, SWAT, WASP, and AQUATOX track transformation of nutrients through several organic and inorganic forms. All three models account for advective transport. AQUATOX additionally accounts for diffusion, which can occur both between surface freshwater grid cells and stratified layers of a lake or reservoir.

Each model represents different biological processes that affect activities such as sedimentation. SWAT uses generic algal growth, whereas WASP distinguishes between suspended and attached growth. AQUATOX models a multi-level food web. Biological categories in AQUATOX include algae, macrophytes, invertebrates, fish, and final bioaccumulative species, such as bald eagles or mink.

As organisms die and decompose, they become available for mineralization or dissolution into dissolved inorganic forms. SWAT, WASP, and AQUATOX include representation of mineralization, nitrification, and track levels of DO. Atmospheric diffusion (i.e. reaeration, and the photosynthetic production of oxygen by algae and aquatic macrophytes) increases the concentration of DO. Respiration, sediment oxygen demand, CBOD, and nitrification all decrease concentrations of DO, which can ultimately lead to hypoxia.

Fate and transport in soil and groundwater

Representation of nutrient species within the soil varies considerably between models (Table 3).

ReCiPe 2008 uses the CARMEN model, which is currently the only model to provide spatially differentiated soil FFs for P. These FFs are specific to Europe. The N soil FFs from Cosme et al.^{62–64} are based on the NEWS 2 model, and provide the only example of global soil FFs. No global, spatially differentiated FFs are available for P, and none of the current LCIA methods provide soil FFs based on detailed F&T modeling. The watershed models may yield insights into filling these gaps.

In contrast to CARMEN, SPARROW employs a probabilistic, statistical approach to F&T. The model accepts GIS inputs for precipitation, evapotranspiration, land use, topography, soil permeability, and management practices. It then uses these inputs to fit a nonlinear regression equation to estimate the non-conservative transport of N and P from diffuse and point sources on the land surface to rivers and streams, and through river and stream systems.

CARMEN and IMAGE-GNM represent nutrient species in the soil ecosystem as total N and total P. NEWS 2 uses aggregated nutrient categories that distinguish between dissolved organic, dissolved inorganic, and particulate forms. Both SWAT and He et al. model specific nutrient species, which facilitates representation of nutrient transformation within soil and groundwater grid cells. SWAT and He et al. track vegetative, detrital, and humic N and P.

In CARMEN, the ratio of N transported by surface water runoff and via groundwater flow is determined by landscape factors including aquifer type, soil texture, topography, land cover, and seasonal temperature. CARMEN assumes that the exclusive transport route for agricultural P to surface freshwaters is via P that is attached to eroding sediments. P losses are calculated based on loading and sediment yield. Sediment yield is a function of an empirical constant that fits factors for rainfall intensity, slope, soil texture, and land use to observed values of sediment transport.³⁰

NEWS 2 aggregates soil and groundwater F&T mechanisms for DIN and DIP into a single coefficient. DON, DOP, and an additional DIP export (for soil weathering) are calculated using a global export coefficient in combination with a runoff modulation function. The DON and DOP exports represent a combination of leaching losses associated with soil organic matter as well as a generic export from terrestrial nutrient loading. Erosion of PN and PP are addressed in a separate submodel using regression techniques that incorporate soil, groundwater, and surface water inputs to estimate total suspended solids transport. Empirical relationships to total suspended solids are used to calculate particulate nutrient transport. Removal of N and P via crop harvest and livestock consumption is also included empirically.

SWAT and He et al. track species-specific soil nutrient pools. Both models include losses due to volatilization and denitrification. In addition, He et al. estimates gaseous N losses via nitrification. Both models include nutrient flows related to vegetation, e.g. plant uptake of inorganic nutrients, litter fall, conversion to detrital forms, and harvesting of crop biomass and removal from the watershed. He et al. does not include erosion as a transport mechanism, whereas SWAT links erosion rates to the movement of particulate inorganic P (PIP) and particulate organic N (PON). SWAT and He et al. differ in their treatment of surface runoff and leaching. He et al. uses an aggregated transport factor as a function of runoff and soil water storage whereas SWAT includes separate representation of surface runoff, lateral subsurface flow, and percolation to groundwater. Groundwater percolation in SWAT represents movement to deep groundwater, which prohibits lateral flow into surface waters. SWAT assumes that only nitrate reaches waterbodies via movement through the soil. Both DIP and nitrate are transported in surface runoff. Use of groundwater from both deep and shallow aquifers returns some nitrate to the soil surface. SWAT also considers upward movement of water, and nitrate in solution, from shallow aquifers into unsaturated soil layers to replace water lost via evapotranspiration, termed revaporization.

Additional cycling between nutrient species and forms is represented in both SWAT and He et al. Both models include mineralization, nitrification, and stabilization/humification. SWAT divides humic N/P and PIP into active and stable pools. Stable forms must first move into the active pool before they can be mineralized. Detrital and humic N/P are mineralized to dissolved inorganic nutrient forms. SWAT assumes that mineralization increases the nitrate pool whereas He et al. assumes the increase affects the ammonia pool. (Ammonia is transformed into nitrate via nitrification.) Fresh, detrital forms of N/P are stabilized as humus in both models. SWAT differentiates the direct transformation of detritus to active humic forms, which it terms decay. The active form of PIP rapidly reaches equilibrium with DIP. Stable PIP is immobilized, but can rejoin the active system via transfer to active forms.

SWAT includes a nitrate decay term for N entering a deep aquifer, which represents removal of nitrate via general chemical and biological processes.⁴⁵

Fate and transport in the marine ecosystem

LCA research has traditionally ignored marine-specific impact categories due to the inherent complexity of the science.⁵⁹ Many of the common LCIA methods, including TRACI, EDIP 2003, LUCAS, and CML 2002, present eutrophication results as a single impact based on the Redfield ratio. IMPACT World+ and ReCiPe 2008 treat marine and surface freshwater eutrophication separately, relying on the assumption that marine ecosystems tend to be limited by N. Both models use a simplified N F&T assumption that 70 percent of N inputs into surface freshwater ecosystems make their way to coastal waters.

The IMPACT World+ LCIA method features global, spatially-explicit FFs for atmospheric N emissions that deposit to coastal waters.⁶⁰ Cosme et al. have developed a new set of global, spatially-differentiated N FFs based on the NEWS 2-DIN model that integrate with XFs and EFs for 66 large marine ecosystems (LMEs).^{44,61}

The new Cosme et al.⁶² model represents N F&T in the marine compartment as the sum of advective and denitrification losses (Table 4). Advective losses are determined based on an inverse function of residence time in the coastal region, with longer residence times leading to lower removal rates and increased quantities of N available to contribute to eutrophication.

Surface freshwater FFs for Cosme et al. stem from DIN removal coefficients from the NEWS 2-DIN submodel.^{63,64} The XFs translate N loading into primary production and then track the fate of the resulting biological N (BN). A fraction of BN sinks to the bottom of the euphotic zone, where it contributes to oxygen demand as it is broken down by microorganisms. EFs translate oxygen depletion into the potentially affected fraction (PAF) of species.

AQUATOX includes an estuarine submodel that handles stratification, tidal amplitude, water balance, and mixing. The submodel also represents the effects of salinity on mortality and gamete loss, sinking rates of suspended particulates, and volatilization.

The remaining four models, NCOM-CGEM, FVCOM-WQS, FVCOM-GEM, and EFDC-WQM have capabilities specific to both estuarine ecosystems and coastal ocean regions (i.e. those on the continental shelf). All four models rely on complex hydrodynamic models to estimate the circulation of water within the specified modeling region, utilizing regionally specific datasets that include information on tides, temperature, bathymetry, heat flux, wind, and precipitation. The models track speciated N and P through various organic and inorganic forms, modeling specific chemical reactions such as nitrification, denitrification, and mineralization. The rate of reaction in each of these cases is formulated as a function of temperature, salinity, and oxygen availability, as applicable. The models diverge notably in their representation of organic material, sediment layer dynamics, and biological state variables. FVCOM-GEM is the only model to not explicitly track DO concentration as a state variable.

Fate and transport in the atmosphere

Atmospheric transport of nutrients for use in eutrophication LCIA modeling has evolved considerably in the last three decades. Early models, such as CML,⁶⁵ provided no spatially differentiated CFs for nutrient emissions. Potting et al. (1998) was the first to develop a set of spatially-differentiated CFs.⁶⁶ TRACI estimated N-deposition from NO_x releases in North America using source-receptor matrices (SRMs) that were created based on the ASTRAP model.²¹ The ASTRAP model provides estimates at the geographic scale of U.S. states and Canadian provinces. ReCiPe 2008 derives atmospheric FFs by iterating between CARMEN and EUTREND to derive deposition estimates for watersheds and coastal seas in Europe.

IMPACT World+ uses annual average atmospheric FFs developed in Roy et al. (2012).⁶⁰ Roy et al. created a new approach to calculating SRMs at a global scale based on the output of the GEOS-Chem air quality model at a 2° × 2.5° grid level. GEOS-Chem simulates NO_x, HNO₃, and NH₃ transport and deposition using meteorological data and emissions for the year 2005. The approach of Roy et al. builds on earlier work demonstrating the use of SRMs for LCA.^{24,66–68}

The air quality models GEOS-Chem, CMAQ, and CAMx feature similar coverage of pollutants and F&T mechanisms. Each model uses emissions data as input, which in all three cases includes industrial and mobile sources, biomass burning, agricultural emissions, and dust, with the flexibility to include additional sources. Emissions data are mapped to a geographic grid using a tool such as the Sparse Matrix Operator Kernel Emissions Modeling System (SMOKE).⁶⁹ All three models include advection, diffusion, and wet and dry deposition processes to simulate transport between grid cells in the atmosphere.

Chemistry modules specify chemical mechanisms and reaction rates which facilitate the models' key function of projecting the concentration of chemical species resulting from specified global emissions scenarios and meteorological input data. Multiple chemistry modules are available to achieve better regional performance or chemistry representation for a species or chemical class of interest. All modules include chemistry mechanisms that cover gas-phase reactions, aqueous chemistry, organic and inorganic aerosol formation and partitioning, photolysis, and adsorption to dust. Each of the air quality models includes nitrogenous chemicals that contribute to eutrophication. None of the models include atmospheric F&T of P, which is a shortcoming given the emerging opinion that windblown P can contribute to nutrient loading in surface water.^{12–15}

CAMx and CMAQ are regional models that can be applied globally when linked with GEOS-Chem or other global models to provide initial boundary conditions. All models provide nested grid capability, which allows local areas of interest to be treated at a finer level of spatial and temporal resolution than surrounding regions. CAMx and CMAQ are commonly operated on 36, 12, or 4 km grids over large regions, with finer grid resolutions of 1–2 km used in more limited local areas. GEOS-Chem operates on a coarser grid that varies between approximately 28 and 140 km (0.25° and 1.25°) on each side. Grid size influences air pollutant concentration, particularly for species with short atmospheric lifespans and compact dispersal ranges, which are often underestimated at coarse model resolutions.^{70,71} Secondary particulates, some of which are nitrogenous, are thought to be

less affected by coarse grid resolutions.⁷² NO_x has a relatively short atmospheric lifespan, on the order of 4 hours to 1 day, indicating that accurate modeling of its atmospheric transport may require fine grid resolutions.^{73,74}

Built-in source apportionment methods may be an alternative to SRMs for the development of atmospheric FFs. Source apportionment relates emission sources to their impact on ambient air quality. CAMx, CMAQ, and GEOS-Chem can each perform source apportionment during a model run (as a function of a source attribution algorithm), after a model run via additional processing, or as part of a sensitivity analysis. Both CAMx and CMAQ store mass throughput data for individual chemical mechanisms and time steps, which requires significant computing resources over large model extents.⁷⁵ Sensitivity analyses, in which all or part of an individual source of interest are removed from a model run, provides an opportunity to quantify the effect of the source on dependent air quality results. These are often called zero-out simulations and constitute a “brute force” sensitivity analysis that can be applied to all air quality models.⁵⁸

Evaluation of model approach and utility for assessing midpoint impacts

The five LCIA models reviewed (including Cosme et al.) vary considerably in approach and level of detail by which they quantify eutrophication midpoint impacts. Midpoint eutrophication impacts are expressed in three ways depending on the method selected:

1. **The Redfield ratio** describes a generic elemental composition of algae. The ratio is used to develop an equivalency between elements and nutrient forms based on stoichiometric relationships, calculating biomass growth as a function of nutrient loading.
2. **Residence time** of nutrients in freshwater or marine environments is calculated as a function of nutrient loading, retention and removal, and approximates the availability of nutrients to contribute to eutrophication. Given an emission rate, these residence times also indicate steady-state mass in each compartment.
3. **Oxygen depletion** expresses midpoint impacts as kg O₂ depleted per kg of N influent to the marine ecosystem. The XF calculation is based on a simple ecological response model.⁶⁴

Early eutrophication LCIA models, such as CML, did not model nutrient F&T, and instead assumed that increased nutrient emissions would yield increased impacts regardless of environmental compartment or location. More recent modeling efforts identify the importance of capturing F&T spatial variability in eutrophication impacts and recommend the use of F&T models when information is available to LCA practitioners on the location of a nutrient release.

TRACI 2.1 uses advection as a proxy indicator of N F&T, providing a novel, simplified approach that was well suited to historical data availability and LCA tools. More sophisticated approaches to nutrient F&T estimation are now available that simulate nutrient retention, water use, and denitrification.^{20,44,61} While ReCiPe 2008 is limited to the European geographic scope, it remains the only freshwater LCIA method that incorporates P

soil and groundwater F&T modeling when calculating midpoint CFs, a feature which is lost in the ReCiPe 2016 update and in the proposed IMPACT World+ method. ReCiPe 2016 and IMPACT World+ do, however, improve upon the simplified approach to nutrient F&T in surface freshwaters used by ReCiPe 2008 via the cumulative FFs of Helmes et al.²⁰ while expanding to a global geographic scope. No significant advancements are made to the marine eutrophication impact category in IMPACT World+, and ReCiPe 2016 excludes this impact category altogether.

Cosme et al. advance LCA's ability to assess marine eutrophication impacts by providing the first set of global, regionally differentiated fate, effect, and damage factors for 66 LMEs.^{63,64} Cosme et al. also introduce new soil and freshwater FFs for N emissions across 5,772 global river basins.⁶² The authors note, however, that the annual time-step and LME size restrict the ability to reflect the temporal and spatial reality of real-world hypoxic events.¹⁷

Of the six watershed models, NEWS 2, SWAT, and IMAGE-GNM provide the best opportunity to yield further improvements in eutrophication LCIA. He et al. does not provide a comprehensive option as it lacks representation of F&T pathways for P releases, which is essential to the estimation of freshwater eutrophication impacts. SPARROW is limited by the need for high-quality global monitoring data and by challenging model calibration when the model is run over large spatial extents.

NEWS 2 has demonstrated its usefulness in developing soil and surface freshwater FFs, but is currently limited to the spatial scale of basins as defined in the STN-30p river network. Still, basin-level resolution may be sufficient for LCA studies when the exact location of emissions is unknown. Additionally, NEWS 2 FFs are based only on DIN export; there is potential for further development based on transport of DON or PN, as estimated by other NEWS 2 submodels.

SWAT estimates the yield of ON, OP, nitrate, and DIP to each stream reach within a watershed, and could be used to calculate spatially differentiated CFs at the resolution of user-defined hydrologic response units (HRUs).⁷⁶ Feasibility of applying SWAT in an LCA context is limited by the fact that SWAT is run at the basin scale, though studies have demonstrated that wide geographic coverage across multiple basin scales can be achieved.⁷⁷

IMAGE-GNM provides the most comprehensive option to develop global, spatially differentiated soil and freshwater FFs for both N and P at the 0.5° x 0.5° grid scale, as was observed by Cosme et al.¹⁷ The model calculates discharge to surface water grid cells, N and P soil budgets, ammonia emissions from soil, and wastewater discharge to surface freshwater. IMAGE-GNM also estimates nutrient concentration in surface freshwater bodies facilitating validation with monitoring data and estimation of annual export fractions for use in the development of FFs, using an annual average or marginal approach.

The surface freshwater models WASP and AQUATOX provide detailed mechanistic representation of nutrient F&T, transformation processes, and biological interactions that link nutrient loading information to organic matter growth and subsequent ecological effects, often as functions of dual-nutrient limitation, light availability, and temperature. AQUATOX stands out among the reviewed models in that it estimates endpoint impacts in the form of

ammonia toxicity and lethal and non-lethal effects of low oxygen. These considerations are largely absent from current LCIA methods and the reviewed watershed models. However, the data collection burden and limited geographic coverage of WASP and AQUATOX limit their potential to directly generate FFs or EFs with global applicability.

The hydrodynamic models NCOM, FVCOM, and EFDC could resolve the issues of spatial and temporal mismatch noted by Cosme et al., however the level of effort required to achieve global coverage makes implementation more challenging. The structure of these models allows for simplifications that could reduce the modeling effort to a reasonable level, as is demonstrated by current efforts to develop an FVCOM model of the entire Atlantic Ocean basin.⁷⁸ When linked with water quality modules, these models operate at a time-step (in minutes) that can capture the temporal scale of real-world eutrophication events, with the potential to open new lines of inquiry within the scope of LCA.

Within the atmospheric compartment, the approach of Roy et al. (2012) exemplifies the use of a complex, global F&T model to develop FFs using the SRM approach. These FFs represent the 2005 data year, which is believed to be representative of average conditions for the preceding period, but patterns of NO_x emissions are shifting rapidly,^{79–81} necessitating frequent updating. Despite this caveat, the implementation of atmospheric N F&T modeling in eutrophication LCIA closely aligns with the goals of being global, spatially differentiated, and representative of the most recent science.

Whereas CAMx and CMAQ offer increased spatial resolution and better source apportionment methods compared to GEOS-Chem, these benefits can only be realized in a single, regional model run. Targeted validation of simulated deposition sensitivity to these factors is required to justify the effort of pursuing developments with these models.

Recommendations for improvement of LCIA modeling for eutrophication

The recommendations (Table 5) seek to: (1) fill gaps in existing characterization models, (2) provide greater spatial differentiation of FFs, and (3) add F&T mechanisms as needed to improve the environmental relevance and scientific robustness of eutrophication LCIA methods.

First and foremost, we propose separating freshwater and marine eutrophication LCIA methods.

This is in line with recent method updates, e.g. ReCiPe 2016 and IMPACT World+, and with the findings of the 2013 LC-Impact report.⁸² The simplifying assumptions that P and N are limiting in surface freshwater and marine waters, respectively; the improved availability of FFs, XFs, and EFs; and the differences in oxygen depletion mechanisms affecting biomass growth, hypoxia, and endpoint effects all support this recommendation.

For freshwater eutrophication, we recognize Helmes et al. 2012 as the best available source of freshwater FFs.

Factor values are provided at a 0.5° x 0.5° grid scale allowing aggregation of FFs with state, province, watershed, or country boundaries. Both ReCiPe 2016 and IMPACT World+

aggregate FFs at the country level. We recommend a reaggregation of FFs for the U.S. at the state-scale, in addition to the currently available watershed factors. Further performance validation of the Helmes et al. F&T model will ensure appropriate, regionalized characterization. Comparison with the results of NEWS 2 and SPARROW should also be feasible based on annual nutrient export fractions. The outcome of this model comparison can guide future model developments.

An opportunity exists to expand characterization of the freshwater cause-effect chain by adapting the oxygen depletion midpoint indicator of Cosme et al. for freshwater systems.

This indicator would reduce the distance between the midpoint indicator and ecological effects without introducing the uncertainty associated with estimates of species-response. Gaps in characterization would persist, such as the inability to estimate HAB occurrence.

For marine eutrophication, we recognize the work of Cosme et al. as the best available LCIA method,

as it fills previously existing gaps in the characterization model and provides full coverage of the cause-effect chain. Integrating the Cosme et al. method with the atmospheric FFs from Roy et al. (2012) would close additional gaps in the characterization model.

The use of linked hydrodynamic water quality F&T models could increase spatial and temporal resolution of the resulting midpoint and endpoint CFs.

These models could refine residence time estimates in coastal waters for LMEs (or a smaller spatial unit) and could help refine the Cosme et al. marine eutrophication method. They could likely also help generate marine FFs and XFs. Feasibility of implementation could be assessed via case study for a region where detailed coastal modeling is already available, e.g. the Louisiana Coastal Shelf.⁴⁸

Terrestrial F&T of land-applied nutrients requires further research, as terrestrial eutrophication modeling is largely absent from LCIA despite its importance to agricultural and other land use sectors.⁸²

The assumption by ReCiPe 2016 that 10% of land-applied P reaches surface waters is currently the best available approach without overburdening the user with data collection requirements. Cosme et al. provide soil and freshwater FFs for N based on the NEWS 2 model, spatially differentiated at the 30-minute (STN-30p) river basin scale. More specific guidance needs to be developed for landscape characteristics such as soil type, climate, and proximity to freshwater (as given in EDIP 2003) to better estimate terrestrial export fractions associated with land-applied nutrients.

Finally, we recommend the development of new soil and freshwater FFs based on IMAGE-GNM, given the global availability of data at the 0.5° x 0.5° grid scale.

This approach would improve upon the general soil F&T guidance of ReCiPe 2016, increase spatial resolution compared to N FFs from the NEWS 2 model, and provide a consistent framework for dealing with N and P F&T in soil and surface freshwater.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.
Fate and transport considerations relevant for eutrophication modeling

Table 1

Summary of coverage offered by surveyed models across multiple media. Geographic scope refers to the spatial extent of the model’s application.

Model Criteria	Model Name																		
	#	ReCiPe 2016	IMPACT World+	CARMEN	He et al. 2011	NEWS 2	SWAT	IMAGE-GNM	SPARROW	WASP	AQUATOX	Cosme et al.	NCOM- CGEM	FVCOM- WQM	FVCOM- GEM	EFDC- WQM	CMAQ	CAMx	GEOS- Chem
Model Type						Watershed			Water Quality				Marine		Atmosphere				
Geographic Scope	Global ¹	-	●	●	●	●	●	●	●			●					○	○	●
	Regional	-			●	●	●	●	●	●	●		●	●	●	●	●	●	
	Country	-	●	●															
Spatial Resolution	Watershed	-				●			●			●							
	Reach	-							●	●	●								
	Grid, degrees	-			●	●	●	●					●	●	●	●	●	●	●
Modeling Approach	Mechanistic	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	Empirical ²				○	○	○	●	●	○	○								
	Deterministic	●	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●
Uncertainty	Probabilistic							●	●										
	N	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	P	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	
Total Form Chemical Coverage	DO						●			●	●	●	●	●					
	Surface Freshwater	①	●	●	●	●	●	●	●	●	●	●	●	●	●				
	Soil and Groundwater ³	①	○	●	●	●	●	●	●			●							
Compartments	Marine ⁴	①	①	①							① ⁵			●	●	●	●	●	●
	Atmosphere	①	●	●													●	●	●

Notes: Superscripts refer to the row (i.e. model criteria); circle symbols refer to the particular model in the row. ● – Criterion included in model.

¹○ - Have global capacity when nested with global models.,

²○ - Incorporate minor empirical elements.,

³○ - Provide guidance, but no CFs.,

⁴● - Provide CFs, but incorporate no compartment specific F&T.,

⁵● - AQUATOX has a sub-module specific to the estuarine environment.,

* CML pertains to the global average. Geographic scope and spatial resolution do not apply.

Table 2

Comparison of freshwater F&T mechanisms and coverage of nutrient species for models that include nutrient cycling [(+) or (-) refers to an increase or decrease, respectively, in concentration of associated species in the water column]

Category ¹	Characteristic	Model Name		
		SWAT	WASP	AQUATOX
Sources of Aquatic Loading	Point Source: User Specified	N, P	N, P	N, P
	Non-Point Source: User Specified	-	N, P	N, P
	Leaching	NO ₃	-	-
	Surface Runoff	PO ₄ , NO ₃	-	-
	Shallow Groundwater	NO ₃	-	-
	Erosion	PIP, POP, PON	-	-
Freshwater Nutrient Pools	Nitrogen	ON, NH ₄ , NO ₂ /NO ₃ , BN	NH ₃ , NO ₃ , DON, BN, DN	NH ₃ /NH ₄ , NO ₃ , DN, BN
	Phosphorus	OP, PO ₄ , BP	PO ₄ , DOP, BP, DP, PIP	PO ₄ , DP, BP, PIP
	DO	DO	DO	DO
	Advection	N, P	N, P	N, P
Transport and Removal Mechanisms	Diffusion	-	-	N, P
	Biological Fixation	-	-	BN (+)
	Sediment Exchange	NH ₄ (+/-), PO ₄ (+/-)	-	NO ₃ (+), NH ₃ (+), PO ₄ (+)
	Settling	ON (-), OP (-), BN (-), BP (-) ²	BN (-), BP (-), DN (-), DP (-), PIP (-)	BN (-), BP (-), DN (-), DP (-)
	Resuspension	N (+), P (+)	DN (+), DP (+), PIP (+)	DN (+), DP (+), BN (+), BP (+)
	Use	N (-), P (-)	-	-
Nutrient Cycling Processes (within grid cells)	Denitrification	-	NO ₃ (-)	NO ₃ (-)
	Mineralization	OP (-), PO ₄ (+)	DON (-), NH ₃ (+), DOP (-), PO ₄ (+)	NH ₃ (+), PO ₄ (+), DN (-), DP (-), BN (-), BP (-)
	Nitrification	NO ₃ /NO ₂ (+), NH ₄ (-), DO (-)	NH ₃ (-), NO ₃ (+), DO (-)	NO ₃ (+), NH ₃ (-), DO (-)
	Dissolution, hydrolysis	ON (-), NH ₄ (+)	DN (-), DP (-), DON (+), DOP (+)	-
	Decomposition, microbial	DO (-) ³	-	DN (-), DP (-), NH ₃ (+), PO ₄ (+), DO (-)

Category ¹	Characteristic	Model Name		
		SWAT	WASP	AQUATOX
	Growth, photosynthesis	BN (+), NO ₃ (-), NH ₄ (-), PO ₄ (-), BP (+), DO (+)	NH ₃ (-), NO ₃ (-), PO ₄ (-), BN (+), BP (+), DO (+)	NH ₃ (-), NO ₃ (-), PO ₄ (-), BN (+), BP (+), DO (+)
	Mortality	ON (+), BN (-), OP (+), BP (-)	BN (+/-), BP (+/-), DN (+), DP (+), NH ₃ (+), PO ₄ (+)	BN (-), BP (-), DN (+), DP (+), NH ₃ (+), PO ₄ (+)
	Ingestion	-	BN (+/-), BP (+/-), DN (+), DP (+), NH ₃ (+), PO ₄ (+)	DN (-), DP (-), BN (+/-), BP (+/-), NH ₃ (+), PO ₄ (+)
	Excretion	-	-	NH ₃ (+), BN (-), BP (-), DN (+), DP (+), PO ₄ (+)
	Colonization	-	-	DN (-), DP (-), NH ₃ (+), PO ₄ (+)
	Adsorption	-	PO ₄ (-), PIP (+)	PO ₄ (-), PIP (+)
	Respiration, metabolism	ON (+), OP (+), BN (-), BP (-), DO (-)	BN (-), BP (-), NH ₃ (+), PO ₄ (+), DO (-)	DO (-), NH ₃ (+), PO ₄ (+), BN (-), BP (-)
	Reaeration	DO (+)	DO (+)	DO (+)
	Sediment Demand	DO (-)	DO (-)	DO (-)

¹P - phosphorus, N - nitrogen, DON - dissolved organic nitrogen, ON - organic nitrogen, OP - organic phosphorus, DOP - dissolved organic phosphorus, DO - dissolved oxygen, PIP - particulate inorganic phosphorus, POP - particulate organic phosphorus, PON - particulate organic nitrogen, NO₂ - nitrite, NO₃ - nitrate, NH₄ - ammonium, NH₃ - ammonia, PO₄ - phosphate, DN - detrital nitrogen, DP - detrital phosphorus, BN - biological nitrogen, BP - biological phosphorus

²SWAT includes specific mechanisms for sediment routing within river channels that are not present in most models. NEWS2 also considers a form of sediment routing for TSS.

³Decomposition of carbonaceous biochemical oxygen demand (CBOD) in water column

Table 3

Comparison of soil F&T mechanisms for mechanistic watershed models. Loading sources are excluded from the table as they are generally consistent for all models, including fertilizer, manure application, and atmospheric deposition of N. All models that span multiple media, except for CARMEN, consider biological N fixation. F&T processes that move nutrients into and out of the soil compartment are distinguished from those that transform nutrients between nutrient forms.

[(+) or (–) refers to an increase or decrease in concentration of associated species in the water column]

Criteria ¹	Model Name						
	CARMEN	He et al. 2011	NEWS 2	SWAT	IMAGE-GNM		
Soil Nutrient Pools	Nitrogen	TN	BN, DN, HN, NH ₄ , NO ₃	DON, DIN, PN	NH ₄ , NO ₃ , DN, HN, PON, BN	TN	
	Phosphorus	TP	-	DOP, DIP, PP	DP, HP, PO ₄ , POP, BP, PIP	TP	
Transport and Removal Mechanisms (into and out of grid cells)	Export, Retention	-	N (-)	DIP, DIN, DON, DOP	-	-	
	Surface runoff	TN	NO ₃	-	NO ₃ , PO ₄	TN, TP	
	Lateral flow	TN	NO ₃	-	NO ₃	TN	
	Erosion	TP	-	PN, PP	PIP, PON	TN, TP	
	Deep groundwater	TN	-	-	NO ₃ (-)	-	
	Revaporization	-	-	-	NO ₃ (+)	-	
	Volatilization	-	NH ₄ (-)	-	NH ₄ (-)	TN (-)	
	Nitrification	-	NO ₃ (-)	-	-	-	
	Denitrification	-	NO ₃ (-)	-	NO ₃ (-)	TN (-)	
	Vegetative Cycling	TN (-), TP (-)	NH ₄ (-), NO ₃ (-), BN (+/-), DN (+)	DIN (-), DIP (-)	NO ₃ (-), PO ₄ (-), BN (+), BP (+), DN (+), DP (+)	TN (-), TP (-)	
	Groundwater use	-	-	-	NO ₃ (-)	-	
	Nutrient Species Transformation Processes (within grid cells)	Adsorption	TP (-)	-	-	PO ₄ (-)	-
		Weathering	-	-	DIP (+)	-	TP (+)
		Mineralization	-	DN (-), HN (-), NH ₄ (+)	-	PO ₄ (+), DN (+/-), DP (+/-), HN (-), HP (-), NO ₂ /NO ₃ (+)	-
Nitrification		-	NH ₄ (-), NO ₂ /NO ₃ (+)	-	NH ₄ (-), NO ₂ /NO ₃ (+)	-	

<i>Criteria¹</i>	<i>Model Name</i>				
	CARMEN	He et al. 2011	NEWS 2	SWAT	IMAGE-GNM
Humus Stabilization	-	DN (-), HN (+)	-	DN (+/-), DP (+/-), HN (+/-), HP (+/-), PIP (+/-)	-
Decay	-	-	-	DN (-), DP (-), HN (+), HP (+)	-
Groundwater decay	-	-	-	NO ₃ (-)	-

¹TP - total phosphorus, TN - total nitrogen, DON - dissolved organic nitrogen, DIP - dissolved inorganic phosphorus, DOP - dissolved organic phosphorus, PP - particulate phosphorus, PN - particulate nitrogen, NO₂ - nitrite, NO₃ - nitrate, NH₄ - ammonium, NH₃ - ammonia, PO₄ - phosphate, BN - biological nitrogen, BP - biological phosphorus, DN - detrital nitrogen, DP - detrital phosphorus, HN - humic nitrogen, HP - humic phosphorus, POP - particulate organic phosphorus, PON - particulate organic nitrogen

Table 4

Comparison of F&T mechanisms and nutrient species coverage for marine eutrophication models.

[(+) or (-) refers to an increase or decrease, respectively, in concentration of associated species in the water column]

Category	Characteristic	AQUATOX-Estuary	Cosme et al.	Model Name		
				NCOM-CGEM	FVCOM-WQM	FVCOM-GEM
Freshwater Nutrient Pools	Nitrogen	NH ₃ , NO ₃ , BN, DN, PON	DIN, BN, DN	NO ₃ , NH ₄ , BN, DN	NH ₃ /NH ₄ , NO ₃ , DN, BN	NH ₄ , NO ₃ , NO ₂ , DN
	Phosphorus	PO ₄ , PIP, BP, DP, PON	-	PO ₄ , BP, DP	PO ₄ , DP	PO ₄ , DP, DOP, BP, PIP
Transport and Removal Mechanisms	Advection	N, P	DIN	N, P	N, P	N, P
	Diffusion	N, P	-	N, P	N, P	N, P
	Biological Fixation	BN (+)	-	-	-	-
	Sediment Exchange	NO ₃ (+/-), NH ₃ (+/-), PO ₄ (+/-)	-	NH ₄ (+), PO ₄ (+)	NO ₃ (+/-), NH ₃ (+/-), PO ₄ (+/-)	NO ₃ (+/-), NH ₃ (+/-), PO ₄ (+/-)
Nutrient Cycling Processes (within grid cells)	Active Vertical Transport	BN (+/-), BP (+/-)	BN (+/-)	-	BN, BP (+/-)	BN (+/-), BP (+/-)
	Settling	BN (-), BP (-), DN (-), DP (-)	DN (-), BN (-)	DN (-), DP (-)	BN (-), BP (-), DN (-), DP (-)	DP (-), DN (-), BP (-), BN (-), DP (-)
	Resuspension	DN (+), DP (+), PON (+), POP (+)	-	-	NH ₄ (+), NO ₃ (+), PO ₄ (+)	DN (+), DP (+), DN (+), PIP (+), BN (+), BP (+)
Nutrient Cycling Processes (within grid cells)	Denitrification	NO ₃ (-)	DIN (-)	NO ₃ (-)	NO ₃ (-)	NO ₃ (-)
	Mineralization	NH ₃ (+), PO ₄ (+), DN (-), DP (-), BN (-), BP (-)	-	DN (-), DP (-), NH ₄ (+), PO ₄ (+)	NH ₄ (+), PO ₄ (+), DN (-), DP (-)	DOP (-), PO ₄ (+), DON, (-), NH ₄ (+)
	Nitrification	NO ₃ (+), NH ₃ (-), DO (-)	-	NH ₄ (-), NO ₃ (+), DO (-)	NO ₃ (+), NH ₄ (-)	NH ₄ (-), NO ₃ (+), DO (-)
	Dissolution/Hydrolysis	-	-	-	DN (-), DP (-)	DN (-), DP (-)
	Decomposition, microbial	DN (-), DP (-), NH ₃ (+), PO ₄ (+), DO (-)	DN (-)	-	DN (-), DP (-)	-
Mortality		BN (-), BP (-), DN (+), DP (+)	BN (-), DN (+)	BN (-), BP (-), DN (+), DP (+)	BN (-), BP (-), DN (+), DP (+)	-

Model Name							
Category	Characteristic	AQUATOX-Estuary	Cosme et al.	NCOM-CGEM	FVCOM-WQM	FVCOM-GEM	EFCD-WQM
Biological Uptake	Biological Uptake	NH ₃ (-), NO ₃ (-), PO ₄ (-), BN (+), BP (+), DO (+)	DIN (-), BN (+)	NH ₄ (-), NO ₃ (-), PO ₄ (-), BN (+), BP (+), DO (+)	NH ₄ (-), PO ₄ (-), NO ₃ (-), BN (+), BP (+), DO (+)	NH ₄ (-), PO ₄ (-), NO ₃ (-), BN (+), BP (+)	PO ₄ (-), NH ₄ (-), NO ₃ (-), BN (+), BP (+), DO (+)
Predation/Ingestion	DN (-), DP (-), BN (+/-), BP (+/-)	BN (+/-)	BN (+/-), BP (+/-), DN (+), DP (+)	BN (+/-), BP (+/-), DN (+), DP (+)	BN (+/-), BP (+/-), DN (+), DP (+)	DOP (+), DP (+), PO ₄ (+), DON (+), DN (+), NH ₄ (+), BN (-), BP (-)	
Colonization	DN (-), DP (-), NH ₃ (+), PO ₄ (+)	-	-	-	-	-	-
Adsorption	PIP (+), PO ₄ (-)	-	-	-	-	-	PO ₄ (-), PIP (+)
Respiration/metabolism	NH ₃ (+), PO ₄ (+), BN (-), BP (-), DO (-)	DN (-)	NH ₄ (+), PO ₄ (+), BN (-), BP (-), DO (-)	NH ₄ (+), PO ₄ (+), BN (-), BP (-), DO (-)	NH ₄ (+), PO ₄ (+), BN (-), BP (-)	DOP (+), POP (+), PO ₄ (+), DON (+), PON (+), NH ₄ (+), BN (-), BP (-), DO (-)	
Excretion	NH ₃ (+), BN (-), BP (-), DN (+), DP (+), PO ₄ (+)	BN (-), DN (+)	NH ₄ (+), PO ₄ (+), DN (+), DP (+)	-	DOP (+), POP (+), PO ₄ (+), DON (+), PON (+), NH ₄ (+), BN (-), BP (-)		
Reaeration	DO (+)	-	DO (+)	-	DO (+)	DO (+)	
Sediment Demand	DO (-)	DO (-)	DO (-)	DO (-)	DO (-)	DO (-)	

/ P - phosphorus, N - nitrogen, DON - dissolved organic nitrogen, ON - organic nitrogen, OP - organic phosphorus, DIP - dissolved inorganic phosphorus, DOP - dissolved organic phosphorus, POP - particulate organic phosphorus, PON - particulate organic nitrogen, NO₃ - nitrate, NH₄ - ammonium, NH₃ - ammonia, PO₄ - phosphate, BN - biological nitrogen, BP - biological P, OM - organic matter, DN - detrital N, DP - detrital P, PIP - particulate inorganic phosphorus

Table 5

Recommendations for the improvement of freshwater and marine eutrophication LCIA methods. Priority of each recommendation is assessed on a scale of 1-3, as follows: an immediate need (1), beneficial in the medium-term (2), or requires validation to justify the effort (3). The level of effort associated with each recommendation is assessed as: easy (E), medium (M), or difficult (D). Easy recommendations represent adoption of the best, currently available methods. Recommendations assessed as medium difficulty represent extensions of existing approaches. Difficult recommendations require novel modeling techniques or applications.

LCIA Method	Environmental Compartment	Priority	Level of Effort	Recommendation
Freshwater and Marine	All Compartments	1	E	Separate freshwater and marine eutrophication LCIA methods.
	Soil & Freshwater	2	D	Use IMAGE-GNM [/] to develop sub-watershed-level, spatially differentiated terrestrial and freshwater FFs.
Freshwater Eutrophication	Freshwater	1	E	Adopt freshwater FFs from Helmes et al., providing state or watershed aggregated fate factors for the US.
		2	M	Adapt O ₂ depletion midpoint indicator approach developed in Cosme et al. for freshwater systems.
		2	M	Validate performance of Helmes et al. retention rates and resulting FFs against other models and monitoring data to assess long-term needs for method improvement.
	Soil	1	E	Apply standard emission fractions to terrestrial nutrient loads, as in the ReCiPe approach (e.g. 10% land-applied P to freshwater).
		1	M	Provide spatially differentiated guidance on emission fractions based on landscape characteristics.
Marine Eutrophication	Freshwater & Marine	1	E	Adopt soil, freshwater, and marine FFs, and marine XFs and EFs, from Cosme et al., reaggregating to the state level for the US.
	Marine	2	D	Refine residence time values that serve as the basis of Cosme et al. marine fate and transport factors [/] .
		3	D	Use hydrodynamic water quality models to develop marine FFs and XFs, increasing spatial resolution beyond 66 LMEs.
	Air	2	M	Adapt the research of Roy et al. (2012) to develop global marine eutrophication FFs for atmospheric N emissions. Consider updating FFs based on more recent inventory data.
		3	D	Run a series of nested CMAQ or CAMx model runs at a regional scale using GEOS-Chem at a coarser grid resolution to provide boundary conditions. Explore options to apply the SRM approach of Roy et al. or internal source apportionment functions.

[/]This possibility was suggested in Cosme et al. (2016).