Journal of Cleaner Production 177 (2018) 474–482

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

A life cycle impact assessment method for freshwater eutrophication due to the transport of phosphorus from agricultural production

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ARTICLE INFO

Article history:
Received 19 June 2017
Received in revised form
27 December 2017
Accepted 29 December 2017
Available online 30 December 2017

Keywords:
Life cycle assessment
Eutrophication potential
Phosphorus discharge
Agriculture
Impact category
Fertilizer

ABSTRACT

In life cycle assessment (LCA), the freshwater eutrophication potential (EP) of agricultural systems is difficult to assess. In common practice, the EP is assessed using release factors that reflect average soil and receiving water conditions in a particular region, typically Western Europe. Local conditions are highly variable, and generic release factors do not provide an accurate assessment in locations where conditions deviate significantly from the average conditions in Western Europe. We present a method to assess the freshwater EP of phosphorus discharge from agricultural systems using estimates of annual phosphorus loss and phosphorus loss reduction due to flow through riparian zones. The method combines an annual phosphorus loss estimator, the Revised Universal Soil Loss Equation (RUSLE), the runoff curve number, and a simple riparian zone model; which together represent the most important mechanisms controlling the release of P from agricultural systems. All required data are publicly available. The method is evaluated by comparing its predictions with reference results from five test cases derived from three studies that used calibrated and validated process-based modeling tools to estimate phosphorus loss. Results of a common LCA impact method (i.e. using a site-generic factor) are also compared with the reference studies. Relative to the estimates of the detailed reference studies, the predictions of a common LCA method were inaccurate (percent relative error up to −86%), showing significant underestimation (percent bias = 79), and a root mean square error to observations standard deviation ratio (RSR) of 2.17. The proposed method reproduced the reference studies' predictions with a lower percent relative error (less than 27%), a relatively small underestimation (percent bias = 5.2%), and a significantly reduced error (RSR = 0.38). Predictions from the proposed method are significantly better correlated, as quantified by the coefficient of determination (RSQ), with the reference values (RSQ = 0.869) than those from using a site-generic factor (RSQ = 0.001). The evaluation indicated that the proposed method provides more accurate estimates of EP from agricultural use of phosphorus than the common practice of using a site-generic factor. Because the method uses simple equations based on the factors governing phosphorus loss, it is easily integrated into LCA and provides more accurate and reliable estimates of freshwater eutrophication potential from agricultural use of phosphorus.

1. Introduction

Freshwater eutrophication is a global problem caused primarily by phosphorus (P) discharges from human activities, particularly agricultural use of P fertilizer (Withers et al., 2014). Phosphorus enrichment is the main cause of freshwater eutrophication because P is the limiting nutrient in most inland waters, as opposed to marine waters in which nitrogen (N) is most often the limiting nutrient. In the U.S., agriculture contributes 47–50% of total P discharged into rivers and lakes (Carpenter et al., 1998). Phosphorus is an essential plant macronutrient required for plant growth and reproduction. It is classified as a major nutrient, meaning that it is required in substantial amounts and it is frequently unavailable for plants in agricultural soils; therefore, it must be supplied in relatively large amounts to achieve the crop yields required to meet demand for food and feed. Not all phosphorous applied to agricultural land will be taken up by plants or retained in the soil. A fraction of it will reach surface waters and contribute to eutrophication, a leading cause of impairment of many freshwater ecosystems. Eutrophication reduces biodiversity in aquatic ecosystems,

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https://doi.org/10.1016/j.jclepro.2017.12.255
0959-6526/

limits the use of potable water, and diminishes land values near impaired water bodies (Dodds et al., 2009). Eutrophication is one of the most prevalent environmental impacts of agricultural production (Alexander et al., 2008).

Life cycle assessment (LCA) is an environmental assessment method used to evaluate products from cradle-to-grave by quantifying emissions and discharges that potentially cause environmental effects, such as climate change, ozone depletion, acidification, and eutrophication. Although eutrophication is a commonly used LCA impact category, the existing methods of assessing freshwater eutrophication reflect average conditions in Western Europe, where they were developed and do not consider variations in key factors as required for local and regional assessments. A more accurate and flexible method of estimating regional freshwater eutrophication potential (EP) from agricultural products is needed.

Unlike climate change and ozone depletion impacts that occur on a global scale, freshwater eutrophication is always a local or regional impact. Unfortunately, currently available methods of assessing the impact of P discharge, such as a site-generic factor that is implemented as a multiplier of phosphorus application rate, do not capture how impact varies with local conditions (Mutel and Hellweg, 2009). Existing methods use a single site-generic factor to represent the fraction of P fertilizer applied to soil that will reach a local waterbody. Currently available site-generic factors are based on average conditions of P discharge in Europe (Mutel and Hellweg, 2009). These site-generic factors assume that for a given application rate, P discharges from land occur at the same rate everywhere independent of local conditions (Potting and Hauschild, 2006).

Estimating P discharges from agriculture is a challenge because they depend on highly variable local conditions, transport mechanisms, soil P concentrations, conservation measures such as managed riparian zones, and how fertilizer is incorporated into the soil (Eghball and Gilley, 2001). The amount of P input to an agricultural system in a particular year (yr) may be a small part of what determines the freshwater EP. When deposited in soil, P enters a complex dynamic process of moving from a pool of plant-accessible P to a more stable form and vice versa. Once P is in a bioavailable form it is also easily dissolved in water, making it vulnerable to loss in runoff and subsurface drainage. More stable forms of P that are attached to soil particles are also susceptible to transport off the field through both wind and water erosion. The greatest P loss will occur under conditions of high soil P concentration, high runoff, and high erosion (Sharpley and Beegle, 2001). Generally, when the P concentration in the soil is high, the total P discharge is dominated by the overland movement of soil particles rather than the subsurface movement of dissolved P (Hart et al., 2004). Loss of P to inland waters is also affected by riparian zones (i.e., the vegetated interface between the land and a river, stream or lake). Healthy riparian zones can reduce P discharges by up to 97% (Fox and Penn, 2013). The effectiveness of P loss reduction by riparian zones depends on multiple characteristics such as width, vegetation type (e.g., grasses, trees), slope, and soil physical properties such as hydraulic conductivity (Fox and Penn, 2013). The many factors controlling the discharge of P to local waterbodies cannot be captured in a single site-generic factor.

Sophisticated mechanistic models can estimate P discharges accurately, but are often impractical for use in LCA due to a level of complexity requiring user expertise and considerable effort to manage large data sets, software configuration, and calibration. Generally, due to constraints on budget and personnel, LCA studies assessing multiple impacts over the full lifecycle require less complicated methods that do not require large quantities of input data or detailed model calibration. LCA methods, like all modeling exercises, must balance the accuracy required by the objectives of the study with method complexity, so that capturing important details in modeling the environmental impact of a product's life cycle is achievable with available resources (Hellweg and Canals, 2014).

Recent research has focused on increasing the geographic resolution of EP methods for LCA by assessing the endpoint impact in the waterbody (Azevedo et al., 2013; Cosme et al., 2014; Helmes et al., 2012). These studies, however, do not address important limitations in currently available methods related to estimating the size of P discharges. A few published LCA methods have included procedures to estimate regionalized P discharges associated with different land uses. Scherer and Pfister (2015) proposed estimating soil-related P loss from fertilizer input and existing P in soil. The P loss pathways considered in Scherer and Pfister (2015) were surface runoff, erosion, drainage, and groundwater. Scherer and Pfister (2015) did not, however, consider the effect of fertilizer application practice (e.g., incorporation into soil or broadcast) or the effect of riparian zones, both of which are critical factors controlling P discharge at the water's edge. Early work by Gallego et al. (2009) proposed an analysis framework including a transport factor representing the fraction of P reaching the water's edge and a plant uptake factor. Gallego and colleagues developed this approach to estimate more accurately the P discharges from agriculture and to understand spatial variation. Although Gallego and colleagues recognized the need to account for transport and plant uptake, their work did not include a procedure to account for the major factors influencing the transport of phosphorus into inland waters such as erosion, runoff, and fertilizer incorporation. This work develops a method to estimate P discharge that accounts for all of the principal factors governing P discharge from agricultural fields. The method is intended for LCA practitioners, but is also useful for assessing the effectiveness of conservation practices.

We introduce a midpoint method of estimating freshwater EP due to P discharge that considers site characteristics, application practices, and transport mechanisms, and thus more accurately describes P discharges from agricultural land. We demonstrate the accuracy of the method by comparing P discharge estimates with the results of 5 test cases derived from three validated studies of P loss from agricultural soils in the US. The goals of this study are to both describe the proposed method and test its performance by comparing estimated P discharges to predictions made with validated models from the reference studies and the commonly used site-generic factor method used in LCA. The proposed method accounts for major factors influencing P discharges; thus, it can be used to assess multiple methods of land application of P (e.g. broadcast, incorporated, partial incorporation) and cropping systems. Because the method accounts for P changes in the soil, the method makes it possible to evaluate a system for a period longer than a year, such as when crops are grown in a rotation system with different amounts of P fertilizer applied in each phase of the rotation.

2. Materials and methods

In LCA, eutrophication potential is usually evaluated as a midpoint impact category indicator (Bare et al., 2000; Seppälä et al., 2004). A midpoint impact analysis assesses the magnitude of the characterized and aggregated discharges or emissions that potentially contribute to an environmental consequence, but it does not quantify the actual damages or the endpoint consequences of the environmental effect. Typically, the EP is quantified in mass units of phosphate or phosphorus equivalents (i.e. kg PO_4^{3-} eq. or kg P eq.) per product functional unit. The equivalence unit (e.g. kg PO_4^{3-} eq. or kg P eq.) functions as a common unit to aggregate different discharges with the corresponding potential eutrophication effects