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Identifying the sources of non-point source pollution: Research progress and emerging challenges – A review

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Abstract

Soil erosion remains a major threat to sustainable agricultural production and environment. More recent studies have highlighted the role of soil erosion in soil, water and environmental degradation. Many authors, in their research efforts, identified fertilizers and other agricultural inputs as the major driving forces of water quality impairment. Although, this assertion is true when efforts are not enough to curtail the chief driving force "erosion" itself. The efforts to link soil erosion as the main driving force to water pollution rather than fertilizers overuse is still debatable. Although, models are less expensive and produce more rapid estimates, but they rely on measured data to provide confidence in predictions. This paper therefore synthesizes the most recent available knowledge and data on major players of non-point source pollution. This effort will spur a site-specific research in various scientific communities to address the sources, mechanisms and pathways of agricultural non-point source pollution and prioritize the knowledge gaps.

Keywords: Soil erosion; agricultural diffuse pollution; pollution sources; agricultural inputs

1. Introduction

Soil erosion remains a major threat to sustainable soil and water conservation (Are et al., 2018). It is a dynamic process connected with detachment of topsoil and causing a number of unfavorable changes in the environment and river pollution in agricultural areas (Mularz and Drzewiecki, 2007; Niazi et al., 2015). Globally, it was reported that about 2.8 tonnes of soil are lost per hectare annually (Borrelli et al. (2017). Therefore, water erosion is widely occurring and is acknowledged as a serious problem in many agricultural areas. However, various approaches and models linking soil erosion by water to non-point source (NPS) pollution are available in literatures (Roberts et al., 2017; Shao et al., 2018; Panagos et al., 2018) but few are considering the mechanism and forms of nutrients polluting the aquatic ecosystems. Non-point source pollution has been considered a severe threat to aquatic environments and is a primary contributor to eutrophication and other water pollution problems (Rosendorf et al., 2016; USEPA, 2019). Not only the safety of aquatic ecosystems that water pollution affects but also restrict the development of human society and economy. Thus, NPS pollution is a term used to describe pollution resulting from many diffuse sources, in contrast to point source (PS) pollution which comes from a single source.

Non-point source pollution from the runoff generated from agricultural land, particularly manured land, has received global attention over the last 20 years (Yin et al., 2018; Ogbeide et al., 2018). Soil erosion by water and over-use of fertilizers are the two major factors identified to be accelerating the discharge of nitrogen (N) and phosphorus (P) from agricultural fields to surface water (Oshunsanya et al., 2019). Erosion preferentially transports soil components during rainfall events in greater concentrations at or near the soil surface, including C, N, and P in both organic and inorganic forms with most of which are deposited in the streams (Roberts et al., 2017; Berhe et al., 2018). However, pollutants associated with nitrogen (N) and phosphorus (P) from agricultural NPS account for over half of total nutrients loading to the environment in many regions, resulting in serious environmental pollution, human health damage and global warming (Erisman et al., 2013). Previous research by Rattan et al. (2017) showed that land-based activities such as fertilizer application, livestock density and sewage were critical factors influencing total nitrogen (TN) and total phosphorus (TP) concentrations in Canadian prairie streams. China for instance, has made great achievements in increasing crop productivity to feed its growing population, partly attributed to increased use of mineral fertilizers, containing N and P, since 1980s (Zhang et al., 2011). Unfortunately, erosion mobilizes these nutrients from agricultural production systems and thereafter deposits them to natural water bodies, thereby causing eutrophication. Apart from crop production sector, livestock farms contributed considerably to anthropogenic N and P losses, which can be explained by poor manure management practices (Chadwick et al., 2015: Hou et al., 2018). Nitrogen in mineral fertilizers and animal manure is vulnerable to losses via emissions of ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_X) to the atmosphere and via leaching of nitrate (NO_3) and other soluble N forms to groundwater and surface waters. NH_3 may form fine particulate matter (PM) in the atmosphere, which can be transported over large distances and may negatively affect human health (Hou et al., 2018). However, most of the P that is laterally distributed in the terrestrial ecosystem by soil erosion is transported in particulate form as P bound to soil particles (Berhe et al., 2018). There is evidence that erosion can change distribution of P among different pools (mineral associated, occluded, organic, and bioavailable), leading to higher stock and availability of P in depositional landform positions (Quinton et al. 2010). It is therefore, apparent globally that sustainable N and P resource management in crop and livestock production systems is urgently needed to ensure food security and safety and improve environmental quality.

The mechanism of the redistribution of soil by erosion is important in determining the nutrient cycling in farmland ecosystems during rainfall events. Meanwhile, about 95% of N is found in the topsoil, being eroded through surface and subsurface processes, and transported as particulate and dissolved N to the river systems (Berhe et al., 2018). Key research in the past has highlighted the role and processes of soil erosion in nutrient cycling of N and P. It is therefore important to note that the rate of distribution and loss of N is mainly affected by factors of rainfall intensity and slope gradient. For instance, in a year with a greater influence of rainfall generated runoff, Wu et al. (2018) reported that a large share of P loads and to a lesser extent N loads were in the dissolved form, although both the adsorbed TN and TP were relatively small when the rainfall intensity was small, and the percentage was large when the rainfall intensity was heavy. However, the adsorbed TP was always the main form of soil phosphorus loss regardless of slope gradient or rainfall intensity while that of dissolved TN concentration had a decreasing tendency with increased rainfall intensity under the same slope gradient. This implies that small rainfall intensity may have great effect on dissolved TN loss concentration at different slopes.

Meanwhile, determination of nonpoint sources agricultural pollution is not limited to surface sources. For this reason, they are difficult to control because the nutrient contributions from different parts of a watershed can vary substantially (Wang et al., 2018). Most research has focused on surface sources because the pollutant sources contributing to surface runoff losses are often visible while those contributing to groundwater losses are hidden and difficult to measure directly (Schilling et al., 2018). Previous studies show that the assessment of groundwater contribution to NPS loads at a watershed scale is typically conducted using basin-wide stream sampling during baseflow (e.g Aquilina et al., 2012), groundwater vulnerability indicators (e.g. Pavlis et al., 2010), statistical modeling (e.g. Schilling and Zhang, 2004) or watershed models (e.g. Kourakos et al., 2012). In all cases, it has been difficult to match the appropriate method to the scale of investigation. Estimating NPS groundwater loads at a watershed scale can be approached from either the top-down or bottom-up. With the top-down approach, baseflow estimates at the watershed outlet provide an integrated groundwater signal. However, the use of baseflow does not allow for identifying potential sources of pollutant loads (Schilling & Zhang, 2004). The bottom-up approach estimates pollutant loading at the field level, which can be scaled up to a watershed (Schilling, et al., 2016). This can require several wells and may not be practical. However, the combined bottom-up and top-down approaches adopted by Schilling, et al. (2018) to assess groundwater loading appeared suitable at large scale level. With the several research findings, it will be of interest in this review to look at the following: (i) recent research findings in agricultural NPS pollution in relation to sources, mechanisms and forms of the pollutants in the runoff water, and (ii) emerging challenges in quantifying agricultural non-point source pollution

2. Recent research progress on non-point source agricultural pollution

Series of studies on agricultural non-point source pollution were reported and published by some scholars in the recent years. It was found that in spite of enormous research carried out and recommendations made in the past, agricultural non-point source pollution caused by soil erosion is increasingly serious. It is obvious that the runoff-bound N and P contribute considerably to the agricultural NPS pollution. This review now considered different studies on the factors contributing to runoff and nutrient losses, the factors increasing the loss of N and P, the forms of N and P in the runoff and water bodies and some empirical models developed/evaluated to assess impact of agricultural non-point source pollution at a large-scale level.

2.1 Mechanisms of nutrient losses: the role of soil erosion

Soil erosion will become a greater issue for the future as population growth continues to expand and land resources are more intensively used with unstable farming practices (Are et al., 2018). Soil erosion processes are in three stages according to Römkens *et al.* (2002): detachment of soil particles from the soil mass; transportation of detached particles by surface runoff water or wind along the slope, and deposition of eroded materials/detached particles, when transportation energy reaches a low level. In water erosion, detachment of soil particles generally occurs under the impact of striking raindrops or by the scouring action of flowing water (whether laminar or turbulent) over the soil surface (Hillel, 2004). As it runs down the slope, the flow (surface runoff or overland flow) carries the detached particles in suspension. However, the actual amount of soil loss from an area is dependent on the transporting capacity of any overland flow generated by rainfall (Bhattacharyya *et al.*, 2010). When runoff water finally comes to rest in a low-lying area, it deposits its suspended load, known as sediment. Soil detachment is therefore an important sub-process of erosion by water since the detachment of soil materials by raindrops has to precede transportation by overland flowing water. But transportation does not always follow detachment. This means that detachment is essentially an independent variable but transportation depends on detachment. However, each of these three distinct phases of erosion can affect the nature and distribution of elements in the soil (Berhe et al., 2018).

The role of soil erosion in the redistribution of soil nutrients or their dynamics is characterized by a first-order kinetics model modified from the original model of Jenny (1941) for eroding landscapes. The original model states that:

$$\frac{dX}{dt} = I - \ k_0 X$$

where X is the stock of the nutrient element of interest (e.g., C, N, or P, in g cm−2), *t* is time (in yr), *I* is the rate of input of the nutrient element of interest into the soil system (in g cm^{-2} $yr.^{-1}$), and *k*o is a coefficient for first-order the nutrient loss through decomposition (in $yr.^{-1}$).

To account for the lateral transportation of eroded nutrients, Berhe et al (2008) further introduced additional loss constant for the nutrient element from the soil poo, or input from deposition of eroded soil, depending on the landform position considered as:

$$\frac{dX}{dt} = I - \ (k_0 + k_c)X$$

where k_c is the coefficient for first-order nutrient element loss by erosion (+ve, for eroding landform positions) or nutrient addition by deposition (–ve, for depositional settings).

2.2 Influence of precipitation and drainage on non-point source pollution

In the work of Rattan et al. (2019), they examined the impact of hydrological variability on the timing and magnitude of nutrient export from seven agriculturally-dominated watersheds in the Red River Valley, Manitoba, Canada. They compared the hydroclimatic variables of the seven sub-watersheds between the two study years (2013 and 2014) as they influenced the magnitude of runoff and forms of nitrogen (N) and phosphorus (P) concentrations in the runoff. They identified precipitation as a main factor determining the form(s) of N and P delivered by runoff water. Their comparison shows that greater precipitation (snow + rain) during 2013 (433 mm) resulted in higher total P (TP), particulate P (PP), total dissolved P (TDP), and soluble reactive P (SRP) fractions than 2014 with precipitation of 367 mm. Although, irrespective of the precipitations, there was no significant differences in the annual concentrations except PP that was significantly higher than in 2013 than 2014. The annual loss of N show that Total N (TN), particulate N (PN) and total dissolved N (TDN) concentrations were higher in 2013 than 2014. However, the ammonium (NH_4^+-N) concentrations were lower in 2013 than 2014. This implies that there is an inverse relationship between the amount of precipitation and dissolved NH_4^+-N. They concluded that the intensity of precipitation vents has influence on nutrient delivery, including the quantity and forms of nutrients.

Wu et al. (2018) employed artificial simulated rainfalls (six rainfall intensities and five slope gradients) to quantify the coupling loss correlation of runoff-sediment-adsorbed and dissolved nitrogen and phosphorus on bare loess slope in China. They obtained significant fluctuations in dissolved total nitrogen (TN) and dissolved total phosphorus (TP) concentrations with rainfall intensity and slope gradient, and the dissolved TP concentration was far less than dissolved TN. Nitrate nitrogen (NO_3^--N) accounted for 39.8% of dissolved TN loss while ammonia nitrogen (NH_4^+-N) accounted for 5.7% of dissolved TN. The NO_3-N was the main loss pattern of TN in runoff. Under the double influences of rainfall intensity and slope gradient, the percentage loss of adsorbed TN was relatively small when the rainfall intensity was small, and the percentage was large when the rainfall intensity was heavy, whereas, the adsorbed TP was always the main form of soil phosphorus loss regardless of slope gradient or rainfall intensity. At higher rainfall intensities and slope gradients, they found that the dissolved TP concentration was extremely volatile while the concentration of dissolved TP in runoff is far less than dissolved TN.

Williams et al. (2018) studied nutrient transport pathways and examined key components driving nutrient delivery processes during storm events in four nested agricultural watersheds in the western Lake Erie basin of the Midwestern US. They found that mobilization of NO_3-N in soil water due to rising shallow groundwater tables and the availability of NO_3-N throughout the growing season exerted a strong influence on NO_3-N transport by erosion. They also reported that the watersheds with a higher intensity drainage transported water with higher concentrations, but delivered the NO_3-N-rich water later in the storm event compared to watersheds with lower intensity drainage. However, the particulate P (PP) transport was dominated by upland sources and processes (i.e., surface runoff) at smaller spatial scales and a combination of both upland and in-stream sources at larger spatial scales. Their results also suggest that the relative contributions of runoff and instream processes on PP transport may vary depending on the time of year. They recommended that conservation practices that decrease both upland flow and in-stream erosion as well as practices that decrease hydrologic connectivity between fields and streams will be needed to address PP loss. While dissolved reactive P (DRP) loss requires a combination of both nutrient management and practices that decrease hydrologic connectivity will be needed.

2.3 Influence of fertilizers

Yi et al. (2018) evaluated the application of three different fertilization regimes (no fertilizer; CK, farmer's fertilization practice; FFP, and site-specific nutrient management; SSNM) in a long-term chili (Capsicum spp. L.) production to study their effects on nitrogen (N) and phosphorus (P) runoff losses in Yuhang County, in northern Zhejiang Province, China. The TN losses in the runoff from the different fertilization regimes show that FFP treatment led to the highest N loss (15.52 kg N ha^{-1}) during the experimental period. This was 22.6% more than that from the SSNM treatment. They observed that the dissolved N (NH_4^+-N and NO_3^--N) was more than the particulate N (PN), while accounting for more than half (62.5%) of N losses in the runoff irrespective management practices. Also, they reported that NH_4^+-N losses were more than NO_3^--N in the runoffs from FFP and SSNM because of the large amount of organic fertilizer applied in both practices. However, in CK, where no organic fertilizer was used, NO_3^--N concentrations were higher than NH_4^+-N in the runoff. Their results also show that P losses followed similar trends in N losses but total P was far less the total N in the runoffs. The dissolved P accounted for 77.5% of the total P losses leaving 22.5% as runoff particulate P.

In a survey conducted by Smith et al. (2018), it was found that agriculture activities in the Maumee River watershed is a major contributor of P to western Lake Erie. They found than many farmers use science-based nutrient management recommendations with regard to soil testing as a guide for P fertilizer applications. The data collected showed that in over 90% of the fields surveyed, P fertilizer applications either met or were below fertilizer recommendations from soil testing. Ultimately, the survey indicated that many producers had voluntarily implemented, at some level, scientifically appropriate P management practices, yet the anticipated benefits have yet to be realized.

In ecological network analysis (ENA) of soil nitrogen cycling in economic and natural forests of the Miyun Reservoir watershed of Beijing Municipality, Xu et al. (2018) found that soil N cycling of the chestnut forest was more intensive than that of the Chinese pine forest. Meanwhile, N loss in the chestnut forest soil (dominated by the output of NO_3^-N) was more serious than that in the Chinese pine forest soil (dominated by the output of NH_4^+N and organic N). The chestnut forest was over-fertilized under the fertilization mode being considered. Fertilization mode was identified as the main factor affecting soil N export, thereby recommending a fertilization mode of 162.50 kg N/year offered by manure.

In the work of Wang et al. (2018) on integrated N–P index model involving multiple sources and transport factors to evaluate N and P losses, they identified critical source areas of nonpoint-source pollution linking to fertilizers. Wang et al. (2018) reported that the integrated index model developed in their study is useful to have in-depth knowledge of the distribution of nutrient loss across a large watershed. Compared with traditional N and P index models, the integrated index assessment model provided the following improvements: (i) combination of several nonpoint sources in one model, (ii) automatic classification of transport factors using natural breaks based on conditions of the study watershed, and (iii) more intuitive analysis of nutrient loss through using nutrient load as a source factor in the integrated index. Validation of the integrated index model in the study watershed appears that the model performed reasonably well in evaluating nutrient losses, despite some uncertainties. The model could identify critical source areas, which could help in prioritizing management activities.

2.4. Other factors and socio-economy of the farmers in agricultural non-point source pollution

In Nigeria, Ogbeide et al. (2018) monitored pesticide concentrations on monthly basis in samples of surface water and sediments across the selected sites for 18-months in agrarian catchments. Pesticide behaviour and sorption-likelihoods were examined using partition coefficients K_d (sediment-water coefficient), K_{oc} (sediment-water coefficient normalized for organic carbon) and Log K_{ow} (octane-water coefficient); while the relationship between K_d and K_{oc} was also examined. The study shown that the percentage clay and organic fractions of each site are strongly associated with the partitioning of pesticide species between surface water and sediment. Co-factors to this effect included the concentration of pesticide species detected on each site which was believed to be associated with the type of crop being grown in the area, and seasonal effects. It was concluded that the high availability of pesticides in sediment across sites was associated with high mobility of pesticide-laden sediments into stream water during the rainy season. This implies that a potential higher magnitude of risks for humans and biota in the rainy season than dry season. As such, pesticides irrespective of solubility would end up in surface water, increasing risks for pelagic biota and humans sourcing river water for domestic use.

Fan et al. (2019) considered the research on agricultural non-point source pollution mainly focus on technologies to assess and control water quality impairment. They were however of the opinion that most of these technologies fail or having low adoption because the socioeconomic constraints from different stakeholders were overlooked. They used the approach of experimental economics to investigate the effects of group size, communication, and length of the right to farm on the cooperation of resource users in the context of agricultural NPS pollution mitigation. They considered the length of the right to farm into account because farms are national properties in some countries like China and Israel, and the length of the right to farm may affect agricultural sustainability. Their socioeconomic survey shown that reducing the number of farms can promote the cooperation among farmers when communication is allowed, which would benefit the mitigation of agricultural NPS pollution. They also recommended that extending the tenure of the land right to farmers can help to sustain the communication-and-group-size effects on the mitigation of agricultural pollution. Their conclusion was that regulations on the farm size, communication, and length of farm property rights are crucial for agricultural sustainability in countries with numerous small farms and in which farms are national properties.

3. Emerging challenges in agricultural non-point source pollution

It is a known fact that agricultural activities contribute considerably to NPS pollution through inadequate conservation plan, but farmers must produce food crops and rear animals for food production. In the same vein, N and P are the major contributors to agricultural NPS pollution coming from fertilizers, manures and animal wastes through erosion. Although, series of research has been carried out with many findings on extent of agricultural NPS and controls, but there are issues yet unresolved that the scientific community must address. Here a brief summary of some of the issues.

3.1. Data required for assessment of erosion-induced agricultural non-point source pollution

Soil erosion is a critical long-term problem that needs solutions in the short term. Scientists must reach a consensus on what should be measured when they refer to soil erosion, and on the data that can be used to develop universal models. Studies on the relationships between the on-site and off-site consequences of soil erosion are essential to our holistic understanding of the nature of this problem. The relationship between agricultural production and damages to and from water quality are complex. The challenges in monitoring agricultural NPS pollution is not only chasing the storm events but also the identification of safe and representative sampling locations, catchments, selection of relevant runoff quality parameters and acceptable test procedures. In spite of recent development in agricultural NPS pollution research, many of the research considered the estimation of total P, total N or both in experimental or modelling. Majority of these studies did not explicitly account for N and P fractions (particulate and dissolved N and P) in the runoff or in aquatic ecosystem, which are the major pollutants causing water quality impairment. Most research studies are not detailed enough to identify the fractions of N and P but rather overestimating or underestimating the pollutants in the waterbodies.

3.2. Identifying the appropriate data to input in non-point source pollution models

The appropriate use of models to assess and monitor, and at what scale, to address the problem of nutrient loading is a great challenge that require attention. Stakeholders typically place more trust in measured data but there are never enough data to feed the models developed, since development of models are time-consuming while most data cannot cover all spatial and temporal scales, and hydroclimatic conditions. For instance, accurate prediction of water flow rate and the chemical transport processes became more challenging with increases of the spatial scales (Wang and Lin, 2018). Although, models are less expensive and produce more rapid estimates, but they rely on measured data to provide confidence in predictions. According to Smith et al. (2018), models are just the only tools capable of simulating alternative practices, spatial relationships, various conditions, and future scenarios but not the actual measured data.

While modeling may, in many cases, be the best way to estimate conservation effectiveness in a large scale, watershed and water quality models are complex and require significant resources and expertise to develop and maintain (Kumwimba et al., 2018). They are best constructed with care, perhaps iteratively over time, and through collaboration with regional stakeholders who can help the modeler understand the practices occurring across the watershed. Knowledge on how to design these systems to provide a specific performance requirement is inadequate for most settings (Kalcic et al. 2018). There are many sources of model error and uncertainty, and they can severely limit the use of models in assessing conservation effectiveness. Model prediction at measuring stations, where calibration occurs, can be fairly uncertain if there is a lack of measured data. The level of uncertainty increases into the headwaters, where there is unlikely to be data to verify model performance, and may be greatest at the field scale, where assumptions about land management practices are made. For instance, most of the papers reviewed in this write up concentrates on either total N, total P or both while few dwells on the fractions in terms of dissolved and adsorbed nutrients. Kalcic et al. (2018) were of the opinion that sufficient knowledge is required to design and estimate the performance of beyond-the-field damages done by erosion, but adequate knowledge is not enough. Indeed, as some of the approaches are fairly new, site-specific knowledge is often inadequate, and the current body of literature contains mixed information that is not easy to translate into best management practice strategies. Efforts to address these short-comings are occurring in most states, but further work is needed to assess current knowledge and prioritize knowledge gaps.

4. Conclusions

Soil erosion is a long-term driving force of diffuse pollution that requires short term solutions. Globally, attention is focused on agriculture because of its contribution to non-point source (NPS) pollution. Erosion preferentially transports soil components during rainfall events in greater concentrations of nitrogen (N) and phosphorus (P) – both organic and inorganic forms, at or near the soil surface, and deposit them into the water bodies (Berhe et al., 2018). It is then obvious that the runoff-bound N and P contribute considerably to agricultural NPS pollution as shown by various studies. Research shows that over-use of fertilizers is the major contributor to runoff-bound N and P, since the amount of nutrients in fertilizer applied is higher than the plant requirements (Yi et al., 2018). However, Oshunsanya et al. (2019) identified runoff erosion, rather than fertilization, as a major driving force for agriculture-derived water pollution.

In spite of the research progress on the contribution of soil erosion to agricultural NPS pollution, there are issues that need detailed research. Considering most recent studies, it is obvious that opinion has been formed that overuse of fertilizers contributes to agricultural NPS pollution. However, records still show that soil erosion is still removing available nutrients, especially N and P in both particulate and dissolved forms, from unfertilized land while depositing them into water bodies, thus, causing pollution. The recommendations of Williams et al. (2018) for conservation practices to reduce both upland flow and in-stream erosion, and the use of vetiver hedgerows by Oshunsanya et al. (2019), indicate that if measures to curb the driving force – erosion, irrespective of fertilization regime, losses of N and P may be reduced drastically. Even then, the mechanism of soil erosion in relation to particulate and dissolved N and P are yet unraveled. Therefore, a site-specific research is required in various scientific communities to address the short-comings and prioritize the knowledge gaps.

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PUBLIC INTEREST STATEMENT

Research on identifying the sources of agricultural non-point source (NPS) pollution is important in environmental degradation assessment. Series of studies on agricultural NPS pollution have been conducted and published by some scholars in the recent years. It was found that in spite of enormous research carried out and recommendations made in the past, agricultural non-point source pollution caused by soil erosion is increasingly serious. With these several research findings, this paper looks at: (i) recent research findings in agricultural NPS pollution in relation to sources, mechanisms and forms of the pollutants in the runoff water, and (ii) emerging challenges in quantifying agricultural non-point source pollution. This will spur the scientific communities to address the short-comings and prioritize the knowledge gaps.

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