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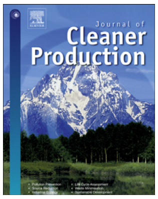

Linking substance flow analysis and soil and water assessment tool for nutrient management

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ABSTRACT

Improper soil management and inefficient use of nutrients in agricultural systems causes significant loss of nutrients, leading to many environmental impacts. Different spatial and temporal environmental conditions such as soil type, physical geography, weather and differing agricultural practices can affect the release of nutrients to the environment. Management of nutrients in agricultural systems using conventional substance flow analysis cannot account for the spatial variability of nutrient flows accurately. This research introduces a framework to link substance flow analysis and the soil and water assessment tool to reveal the spatial variability of nutrient flows in áreas with different climate and land conditions, and having various agricultural management practices. The spatially allocated flows can be agglomerated to quantify the total quantity of nutrients during a specific time to conduct substance flow analysis more accurately. Substance flow analysis of nutrient in maize production system in Phayao, Thailand is used to demonstrate the framework. Several improved agricultural management practices were simulated and evaluated. The results showed that both Nitrogen and Phosphorus balances in the system in the case study area were negative because of the large amount of nutrient loss through several ways. No-till farming was the most effective option to reduce N loss. However, crop rotation with beans, optimising fertilizer application and applying more manure could reduce large amount of chemical fertilizer use. Combining all the practices was found to be the most effective option to reduce P loss.

1. Introduction

Agriculture is a major source of livelihood in many developing countries. The world population growth and growing demand of food have accelerated the demand for crop production (FAO, 2011). However, unsustainable crop production can lead to significant adverse environmental impacts including deforestation, soil erosion, and nutrient and water pollution (FAO, 2011). In addition, improper and inefficient use of fertilizers causes significant loss of nutrients (Sutton et al., 2013). Around 80% of N and 25–75% of P are lost to the environment through run-off, leaching and off-gas emissions causing environmental impacts such as eutrophication and global warming and leaving insufficient nutrients in the soil for cropping (Sutton et al., 2013). It also triggers the demand for chemical fertilizers significantly; four times over the past forty years and the increasing trend still continues (Sutton et al., 2013). P fertilizer is made from phosphate-rock which is a limited non-renewable resource. N fertilizer can be produced by fixing N_2 from the atmosphere; however, it requires large amount of energy to process, which in turn leads to large emissions of greenhouse gases (Gronman et al., 2016). Therefore, proper and efficient use of nutrients is urgently required for increasing soil fertility and yield, reducing environmental impacts, conserving non-renewable materials like phosphate rock and saving agricultural production cost. To do so, a tool is required to track the flow and balance of nutrients in order to reduce the loss and environmental impacts.

Substance flow analysis (SFA) has been applied to track nutrient flows and manage nutrients in several applications at the regional scale (Zhang et al., 2016; Wu et al., 2016; Cordell et al., 2009). Moreover, management of nutrient along the supply chain has been conducted and a new method of nutrient footprint has also been introduced in Gronman et al. (2016). A more comprehensive tool, life cycle assessment (LCA) has also been applied to assess the impacts of agricultural nutrient emissions like eutrophication,

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acidification and global warming (Ashworth et al., 2015; Mu et al., 2016). To do an LCA, the life cycle inventory (LCI) step is needed to account for nutrient inputs and outputs throughout the agricultural system in order to assess the related environmental impacts. Several SFA and LCI applications mentioned previously estimate nutrient outputs of the system based on average of several field data. However, monitoring of nutrient pollution in the field requires significant time and budget. Moreover, using the average data from several fields in different areas with varying environmental conditions such as soil type, physical geography, weather and differing agricultural practices that affect the release of nutrients to the environment may be less meaningful. Therefore, LCA may not be representative of the specific location being studied. Many LCIs estimate nutrient outputs of the system using the tier one equation in the methodology of Ecoinvent where many of the factors are based on European circumstances (Nemecek and Kagi, 2007; Nevison, 2000), and may therefore not represent the result of the local area of interest, especially in the Asian region.

The Soil and Water Assessment Tool (SWAT) is a process based model that has been adopted for in watershed modelling and management. The model's simulation schemes are based on the area-represented information (ie: soil type, slope, weather and agricultural practice) that results in spatial variability of nutrient balance and flow (Gassman et al., 2007). The model can account for spatial variability and uncertainty of flow arising from different climate and land conditions and agricultural management practices in different areas. Therefore, linking SFA and SWAT can overcome the limitation of SFA described in the previous section, and can assist in the management of the nutrients considering the local conditions. It can also facilitate the application of SFA and LCA to account for the local conditions more accurately, and save money and time. However, spatial and temporal issues and complexity of the SWAT model analysis and output results (associated with hydrological, soil, nutrient and pesticides modelling) can cause confusion. The spatial and temporal data output from the SWAT model has to be assigned, selected and extracted consistent with the objective of SFA model. Moreover, the ouput flows that are spatially allocated in the SWAT model have to be combined to obtain the total nutrient flow of the whole system boundary for the SFA model. Interlinking of input and output of specific spatially allocated substances between SWAT and SFA can be difficult to determine for the SFA practitioner who is not familiar with SWAT model but needs to use the results from the model.

This research introduces the framework to link SFA and SWAT to obtain the spatially variable local condition results more accurately. The framework can guide and facilitate SFA practitioners not familiar with SWAT model to use the results from the SWAT model. This research demonstrates the framework through SFA of Nitrogen (N) and Phosphorus (P) in the maize production system in Phayao, Thailand. The results can enable user and stakeholder to visualize and analyse the pathway of nutrient loss. The simulation of the improved nutrient management scenario was conducted for assessing the practice to reduce nutrient loss to the environment.

2. Method

2.1. Substance flow analysis

Substance Flow Analysis (SFA) is a tool used to quantify and track useful substances or toxic species through anthropogenic or geogenic processes in order to manage substance recovery and reduce environmental impacts (Brunner and Rechberger, 2004). The SFA method is based on the mass balance principle that calculates stock or balance by subtracting the outputs from the inputs. Input flow and output data can be obtained from statistics data or field data collection. Output flow can also be calculated using transfer efficient factor or using model (Brunner and Rechberger, 2004). The SFA method comprises of several iterative steps including: problem definition, system definition, determination of flows and stocks, balancing of goods, determination of concentrations, balancing of substances, illustration and interpretation (Brunner and Rechberger, 2004).

2.2. SWAT model

The Soil and Water Assessment Tool (SWAT) is a public domain watershed-level mathematical model developed by the U. S. Department of Agriculture (USDA) Agriculture Research Service (ARS) and has been widely used globally as a simulation approach for over 40 years (Williams et al., 2008). The model can evaluate both in-stream processes and land phase. The SWAT model has been used widely for hydrology, water quality and also in agricultural management (Vigiak et al., 2015; Rocha et al., 2015), reforestation (Wangpimool et al., 2013) and climate change studies (Cousino et al., 2015). The SWAT has capability to adjust and edit several parameters in both biochemical and physical aspects or even management practice parameters (Arnold and Fohrer, 2005). The main structure of SWAT consists of hydrological cycle equations, erosion evaluation, nutrient and pesticides modelling (Neitsch et al., 2011).

2.3. Framework to link SFA and SWAT

The concept of integration is that within the SFA framework, once system definition of SFA and the SWAT model have been settled consistently, the SWAT model can be aided in quantifying the input flows and calculating the stock and output flows of substances spatially. The spatial and temporal data output from the SWAT model has to be assigned, selected and extracted consistent with the objective of SFA model. The framework to link SFA and the SWAT model is shown in Fig. 1 and described as per following steps:

The method starts firstly with the SFA framework, the problem of interest that needs to be analyzed and solved must be defined. Secondly, based on the problem definition, system definition in the SFA framework is defined including determination of substances, determination of system boundary (geographical (spatial) and time (temporal boundary) and determination of related processes and goods. Here, the SWAT model can be set according to SFA system definition by adding all the related data – geographical data, meteorology data, soil data, slope data in geo-spatial format or shape file in the defined system boundary. Moreover, detailed data related to land management practices or factors that influence the output results have to be collected and set in the SWAT model.

In the linking process, the watershed, sub-watershed outlets and reservoir locations have to be determined corresponding to the study area information and boundary. After the sub-watersheds are created, the soil groups map, land use and land cover map are input to create hydraulic response units (HRUs) which contain the different characteristics of soil, land cover and slope in each sub-watershed. All the simulation schemes are based on the area-represented information such as geological information, soil data, land cover, plant growth and land management which have been spatially subdivided and overlaid into Hydrologic Response Units (HRUs). Finally, the HRUs which have different characteristics are interacted with several time-series data of climate including precipitation, solar radiation and others to obtain the simulation result (Neitsch et al., 2011). Here, all the data are automatically and spatially allocated and simulated (as per HRU) to calculate the inputs to the SWAT model.

Thirdly, related flow and stock of the substances has to be pre-