Science of the Total Environment 642 (2018) 21–32

Contents lists available at ScienceDirect

Science of the Total Environment

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

Influences of agricultural land use composition and distribution on nitrogen export from a subtropical watershed in China

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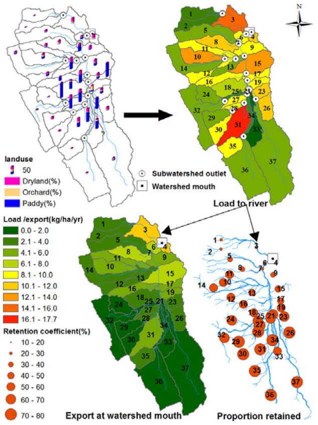
HIGHLIGHTS

- Agricultural impacts on watershed N export vary with land use types.
- Agricultural land use distribution and composition impact watershed N export.
- Both N source and aquatic N retention during transport are critical for N export.
- Model results can guide agricultural land planning to reduce watershed N export.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 6 March 2018
Received in revised form 22 May 2018
Accepted 4 June 2018
Available online xxxx

Editor: Ouyang Wei

Keywords:
Nonpoint source nitrogen pollution
Agricultural land use
Aquatic nitrogen retention
Agricultural composition
SWAT

ABSTRACT

Despite the significant impacts of agricultural land on nonpoint source (NPS) nitrogen (N) pollution, little is known about the influence of the distribution and composition of different agricultural land uses on N export at the watershed scale. We used the Soil and Water Assessment Tool (SWAT) to quantify how agricultural distribution (i.e., the spatial distributions of agricultural land uses) and composition (i.e., the relative percentages of different types of agricultural land uses) influenced N export from a Chinese subtropical watershed, accounting for aquatic N retention by river networks. Nitrogen sources displayed high spatial variability, with 40.7% of the total N (TN) export from the watershed as a whole derived from several subwatersheds that accounted for only 18% of the watershed area. These subwatersheds were all located close to the watershed mouth. Agricultural composition strongly affected inputs to the river network. The percentages of dry agricultural land and rice paddy fields, and the number of cattle together explained 70.5% of the variability of the TN input to the river network among different subwatersheds. Total N loading to the river network was positively correlated with the percentage of dry land in total land areas and the number of cattle within subwatersheds, but negatively with the proportion of paddy fields. Distribution of agricultural land uses also affected N export at the mouth of the watershed. Moreover, N retention in the river network increased with increasing N transport distance from

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https://doi.org/10.1016/j.scitotenv.2018.06.048

source subwatershed to the watershed mouth. Results provide important information to support improved planning of agricultural land uses at the watershed scale that reduces NPS nutrient pollution.

1. Introduction

Eutrophication has become the primary water quality issue for many freshwater and coastal marine ecosystems worldwide (Smith and Schindler, 2009; Strokal et al., 2014). Excessive N loading to waterways derived from anthropogenic activities is the major cause of increased eutrophication and associated water quality impacts (Sinha and Michalak, 2016). Nitrogen losses from the landscape mainly enter water systems through transport of excess N by surface runoff or subsurface drainage (Schoumans et al., 2014). Nitrogen export in a watershed is often determined by processes affecting soil N availability (Galloway et al., 2004; Howarth et al., 2011), surplus water (Kopacek et al., 2013), and biogeochemical transformations of N during transport in both terrestrial and aquatic ecosystems (Billen et al., 2009; Schulz et al., 2003; Seitzinger et al., 2006; Seitzinger et al., 2002).

Agricultural land use is a major determinant of NPS N pollution, and correlates positively with in-stream TN (Hansen et al., 2018; Ouyang et al., 2013; Ouyang et al., 2014; Xia et al., 2016). Increased nutrient loading to streams from agricultural land is associated with excess anthropogenic N that is added to soils in the form of chemical fertilizer and animal manure (Hill and Bolgrien, 2011; Kaushal et al., 2011; Rankinen et al., 2016; Shen et al., 2015; Wollheim et al., 2008). Generally, hydrological loss of TN from agricultural land increases with increasing N fertilizer application rates (Eghball et al., 2002; Zhang et al., 2015), particularly when the N application rate exceeds crop N removal rate (Gu et al., 2015; Zhou et al., 2016). Nitrogen leaching is also affected by soil microbial processes that depend on pools of organic carbon (C), and soil C/N ratios, which are influenced by agricultural management practices (Wang et al., 2015a). Dry land cropping always increases N loading to streams resulting from excessive anthropogenic inputs of N such as fertilizer or manure application (Hill and Bolgrien, 2011; Jordan et al., 1997). These increases are associated with the alterations of soil surface conditions, and other land management practices that promote runoff and soil erosion (Zhou et al., 2017).

Although most agricultural land tends to increase N export, there are some types of agricultural land use that result in lower N exports (Jordan et al., 1997; Ouyang et al., 2015; Takeda and Fukushima, 2006). In particular, rice paddy fields are associated with lower TN export, due largely to a higher hydraulic retention time and anoxic conditions favorable for denitrification (Krupa et al., 2011; Lee et al., 2014; Takeda and Fukushima, 2006; Wang and Gu, 2013). The location of these rice paddy fields relative to other watershed N sources could reduce downstream N fluxes. Despite the generally good understanding of the impacts of the individual land uses on water quality, few studies have investigated the impacts of the composition and distribution of different agricultural land use types on TN export from watersheds.

Total N flux at the mouth of the watershed is also influenced by biogeochemical transformations within the river network as water flows downstream from source areas to the mouth of the watershed (Aguilera et al., 2012; Alexander et al., 2002; Bettez et al., 2015; Wollheim et al., 2017). River systems are important regulators of anthropogenic N flux between land and receiving water bodies (Wollheim et al., 2014). Between 37% and 76% of N loss from terrestrial inputs can be mitigated in the river network during downstream transport (Seitzinger et al., 2002; Stewart et al., 2011; Van Breemen et al., 2002; Wollheim et al., 2008). Nitrogen removal in surface waters is influenced by several processes such as denitrification and biological assimilation (Billen et al., 2009; Grizzetti et al., 2015; Hejzlar et al., 2009; Mulholland et al., 2008). These processes are affected by temperature, in-stream nutrient concentration, transient storage, biological activity, and water residence time (Alexander et al., 2009; Botter et al., 2010; Hejzlar et al., 2009; Herrman et al., 2008; Withers and Jarvie, 2008; Zhao et al., 2015) which interact to determine TN removal (Wollheim et al., 2006). Generally, aquatic N retention increases with longer residence times. As a result, location of nonpoint N sources within the river network may also be an important factor, with sources near the mouth of watershed having less transport time and more N retention than those farther from the mouth (Mineau et al., 2015).

The linkages between TN loading to surface waters and watershed TN export are often poorly quantified because of the complexity of N transport pathways (Xia et al., 2016). Many approaches are available to quantify NPS pollutant fluxes including the export coefficient method, index method, and spatially-distributed watershed water quality models (Ouyang et al., 2017a; Shen et al., 2011; Wellen et al., 2015). In particular, spatially-distributed and process-based watershed models are increasingly used because they combine various physical and biological processes associated with N flux, including water movement, sediment transport, crop growth, and nutrient cycling, etc. Typically, these models disaggregate a watershed into multiple discrete units, namely subwatersheds or even smaller units, to represent the spatial variability of sources and controls. For example, the SWAT (Arnold et al., 2010; Liu et al., 2016) can be used to quantitatively estimate NPS pollutant loss from source areas (Chen et al., 2014b; Grizzetti et al., 2015; Shen et al., 2015). SWAT also has the capacity to quantify nutrient retention by streams and rivers within a subwatershed. However, these earlier studies did not quantify aquatic retention of N during aquatic transport after leaving the subwatershed and therefore ignored the potential of additional N retention by downstream rivers. Chen et al. (2014b) proposed an approach to account for this dynamic and therefore fully identify the N contribution of different locations to watershed N export. In this approach, the relationships between different subwatersheds in terms of N flux are identified by accounting for connectivity of reaches.

In this study, SWAT was used to estimate N inputs from source areas in the landscape, N retention in the surface water network, and the export of N at the mouth in an agriculture-dominated watershed in subtropical China. The main objectives of this study were to: 1) quantify the spatial distribution of the sources of N exported at the mouth of an agricultural watershed with two types of agricultural activities, and 2) quantify the proportion of loads retained by aquatic retention processes given the distribution of agricultural activities.

2. Materials and methods

2.1. Study watershed

The study was conducted in the Fengyu River Watershed (99.85861°–100.0294°E, 25.88000°–26.09778° N, elevation 2082–3615 m) located in Yunnan Province, Southwest China (Fig. 1). The Fengyu River Watershed is a subwatershed of the Erhai Lake Watershed. Erhai Lake is eutrophic due to excess agricultural N input. The Fengyu River Watershed (Drainage area = 219 km^2) consists of dry land agriculture and rice paddy fields in gently sloped areas, and forests and grasslands in areas with steeper slopes. The watershed has a subtropical, plateau monsoon climate with mean annual temperature of 13.9 °C and annual rainfall of 700 mm. >85% of the annual rainfall occurs between May and October. Forest and grassland areas are present upslope in the headwaters, with their streams flowing down through agricultural areas before entering the Fengyu River mainstream. Generally,