Environmental Pollution 239 (2018) 648–660

Contents lists available at ScienceDirect

Environmental Pollution

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

Current and future hot-spots and hot-moments of nitrous oxide emission in a cold climate river basin[☆]

Narayan Kumar Shrestha, Junye Wang[*]

Athabasca River Basin Research Institute (ARBRI), Athabasca University, 1 University Drive, Athabasca, Alberta, T9S 3A3, Canada

ARTICLE INFO

Article history:
Received 11 February 2018
Received in revised form
15 April 2018
Accepted 15 April 2018

Keywords:
Cold climate river basin
N_2O hot-spots and hot-moments
ARB
SWAT

ABSTRACT

An ecosystem in a cold climate river basin is vulnerable to the effects of climate change affecting permafrost thaw and glacier retreat. We currently lack sufficient data and information if and how hydrological processes such as glacier retreat, snowmelt and freezing-thawing affect sediment and nutrient runoff and transport, as well as N_2O emissions in cold climate river basins. As such, we have implemented well-established, semi-empirical equations of nitrification and denitrification within the Soil and Water Assessment Tool (SWAT), which correlate the emissions with water, sediment and nutrients. We have tested this implementation to simulate emission dynamics at three sites on the Canadian prairies. We then regionalized the optimized parameters to a SWAT model of the Athabasca River Basin (ARB), Canada, calibrated and validated for streamflow, sediment and water quality. In the base period (1990–2005), agricultural areas (2662 gN/ha/yr) constituted emission hot-spots. The spring season in agricultural areas and summer season in forest areas, constituted emission hot-moments. We found that warmer conditions (+13% to +106%) would have a greater influence on emissions than wetter conditions (−19% to +13%), and that the combined effect of wetter and warmer conditions would be more offsetting than synergetic. Our results imply that the spatiotemporal variability of N_2O emissions will depend strongly on soil water changes caused by permafrost thaw. Early snow freshet leads to spatial variability of soil erosion and nutrient runoff, as well as increases of emissions in winter and decreases in spring. Our simulations suggest crop residue management may reduce emissions by 34%, but with the mixed results reported in the literature and the soil and hydrology problems associated with stover removal more research is necessary. This modelling tool can be used to refine bottom-up emission estimations at river basin scale, test plausible management scenarios, and assess climate change impacts including climate feedback.

1. Introduction

Cold climate regions, such as the Athabasca River Basin (ARB) in western Canada, are some of the most sensitive eco-regions in the world and the slightest of the changes in climate would lead to significant alterations in snow-melt dominated hydrologic, sediment and nutrient transport processes, freeze-thaw cycles, and soil water and temperature (Eum et al., 2017; IPCC, 2007, 2014; Kurylyk et al., 2014). There is much evidence showing an accelerated release of GHGs (Helbig et al., 2017; Schuur et al., 2015), changes in the composition of bacterial communities (Rofner et al., 2017), and the mobilization and export of dissolved organic carbon (Olefeldt and Roulet, 2014; Tesi et al., 2016) due to thawing of permafrost in these regions. Changes to these environmental variables could also significantly affect N_2O emissions (Butterbach-Bahl et al., 2013; Voigt et al., 2017). To date, contrasting results are presented on how much the inevitable effects of climate change would influence N_2O emissions (Abalos et al., 2016; Del Grosso and Parton, 2012; Iqbal et al., 2018; Kanter et al., 2016). Understanding nutrient cycle responses to warming-induced environmental changes, such as permafrost thaw and glacier retreat, is critical to evaluating their influences on soil biogeochemical cycles and N_2O emissions in a cold climate river basin as the large-scale, cold climate river basin is a natural water system boundary and represents a complex organized system, such as an ecosystem or a society, as a macrocosm region.

Site-based measurements are able to capture the N_2O dynamics

---

[☆] This paper has been recommended for acceptance by Dr. Jorg Rinklebe.

[*] Corresponding author.

E-mail address: junyew@athabascau.ca (J. Wang).

https://doi.org/10.1016/j.envpol.2018.04.068

quite well at a localized scale. However, these measurements are cumbersome and continuous emission measurements are practically impossible unless an automatic and online system is available (Liao et al., 2013; Smith and Dobbie, 2001). Furthermore, these point measurements might include considerable uncertainties as the drivers of N_2O flux vary both spatially and temporally (Butterbach-Bahl et al., 2013; Raich and Tufekciogul, 2000). Moreover, could not be up-scaled due to spatial heterogeneity at the river basin or regional scale. Hence, there is also a growing realization of the need to monitor N_2O emissions hot-spots and hot-moments in river basins (Groffman et al., 2009). Recent studies suggest that much attention has been paid in capturing these emission hot-moments, such as during freeze-thaw cycles, as they seem to dominate the annual emission budget of cold climate river basins (Flechard et al., 2005; McClain et al., 2003; Pelster et al., 2013). However, identification of emission hot-spots, which might be more challenging and costly, is equally important (Groffman et al., 2009). Usually, N_2O estimations at the river basin scale have been carried out using the IPCC inventory with “emission factors” (IPCC, 2006). However, such simplistic methods are often inaccurate as they can't incorporate variations of land management practices (e.g. tillage operation) and the dynamics of environmental variables (e.g. soil moisture and temperature) at a finer temporal scale. Furthermore, such “top-down inventories” have shown to significantly underestimate the level of emissions (Eric, 2014; Turner et al., 2015).

As a result, process-based modelling tools have become an attractive alternative (Li et al., 1992; Schmid et al., 2001). Such modelling tools are not only helpful in identifying emissions hot-spots and hot-moments, but are also useful in assessing the effectiveness of different management options for evaluating the impacts of climate and land-use changes (Butterbach-Bahl et al., 2013), and for climate feedback (Schuur et al., 2015). A process based model should be able to dynamically simulate the main drivers of N_2O emissions, including interactions between soil, water, vegetation, and nutrients, and should also be flexible enough to incorporate finer spatial and temporal resolution datasets, which are becoming more available through advancements in remote sensing technology (Groffman et al., 2009; McClain et al., 2003). Many such models have been developed to simulate N_2O from soils such as JULES (Best et al., 2011; Clark et al., 2011), DNDC (Li et al., 1992), DAYCENT (Del Grosso et al., 2001), CENTURY (Parton, 1996), Roth-C (Coleman and Jenkinson, 1996), etc. However, these models primarily use the vertical transfer of hydrological and substrate fluxes and lack consideration of the lateral transport of water and nutrients (Groffman et al., 2009). More importantly, typical water cycle regions are river basins acting as natural water system boundaries. Therefore, models should be able to simulate the “lateral flow and distribution of water, nitrogen and carbon within landscapes” (Groffman et al., 2009), stream flows, and sediment and nutrients runoff in river networks. Moreover, cold climate regions consist of agriculture, forests, wetland, peatland, permafrost and glacier regions, which are the most efficient terrestrial carbon stores on Earth (AWC, 2014). Such cold climate regions service multiple other ecosystem functions, such as climate regulation, water filtration, and biodiversity (Black, 1997). In such regions, the N_2O emissions during freeze-thaw conditions need to be accurately represented (Butterbach-Bahl et al., 2013; Flechard et al., 2005; Groffman et al., 2009; Kravchenko et al., 2017; McClain et al., 2003; Pelster et al., 2013). Furthermore, a model should represent special processes related to cold climate regions, such as the ability to simulate areal snow distribution, freeze-thaw cycles, stream flow and snow melt processes comprehensively. Whereas, N_2O emissions have been monitored or simulated globally, we lack sufficient data on how, or if, hydrological processes, such as flooding, drought, erosion and sediment transport, permafrost thaw and snowmelt, affect N_2O emissions in a cold climate river basin since the transport of water and nutrients are one of the most important components in the water and nutrient cycle.

In this context, a widely used process-based hydrological model – the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) has been tested for short and long-term simulations of hydrological, sediment and water quality processes all around the world, irrespective of climate or the shape and size of river basins (Abbaspour et al., 2015; Arnold et al., 2012; Kannan et al., 2006; Leta et al., 2014; Ligaray et al., 2017; Meng et al., 2018; Shrestha et al., 2013, 2014). This tool possesses all the attributes required, as pointed out by Groffman et al. (2009), for the simulation of N_2O hot-spots and hot-moments at a regional scale. While the model considers both nitrification and denitrification processes in its nitrogen-cycling algorithm (Neitsch et al., 2011), it does not explicitly estimate N_2O emissions, which could introduce uncertainty into the estimation of N and C stocks.

With this in mind, we incorporated the well-established semi-empirical equations of nitrification and denitrification processes (Parton et al., 1996, 2001) into the SWAT model, to explicitly estimate N_2O emissions from both nitrification and denitrification. These equations can be considered conceptual as they relate soil carbon, ammonia, nitrate, moisture, temperature, and pH to N_2O emissions (Butterbach-Bahl et al., 2013). The SWAT model is then tested to simulate short-term, site-based N_2O measurements from three sites (cropped, shelterbelt and grassland) in the Canadian prairies. In order to estimate N_2O emissions in the ARB: (a) a comprehensive SWAT model of the ARB was built-up using high-resolution spatial and meteorological data sets, considering both point and non-point pollution sources, and defining appropriate crop, pasture, grassland, and forest related management practices; (b) multi-variable (streamflow, sediment and water quality), multi-site (35 streamflow, 5 sediment and 10 water quality monitoring stations), and multi-objective sensitivity, calibration and validation, and uncertainty analysis has been carried out with special consideration of snow-melt processes; (c) optimized land-use type N_2O related parameters were regionalized to the ARB. Moreover, we quantified the N_2O emissions in different land-use types, seasons, and regions in the ARB to identify the N_2O hot-spots and hot-moments. Next, we assessed climate change impacts on the N_2O dynamics of the ARB using future climate data from bias-corrected spatial disaggregated high-resolution datasets from the top three Coupled Model Intercomparison Project (CMIP5) Global Circulation Models (GCMs) for the Western North America region. Finally, different fertilizer, crop residue management, and grazing scenarios were tested to evaluate the effectiveness of possible N_2O abatement methods. To our knowledge, this is the first study of its kind in which SWAT was used to estimate current and future N_2O emissions in a large cold climate region watershed and to understand how the hydrological processes affect N_2O emissions. We believe that this modelling tool can be used in other regions to refine the bottom-up emission inventories, and that results of this study can be translated into a process for managing the N_2O emissions of the ARB.

2. Material and methods

2.1. The study area

The Athabasca River Basin (ARB) runs upward in central Alberta, Canada and provides a dependable water supply source for major urban centers (Jasper, Hinton, Whitecourt, Athabasca, and Fort McMurray) and its major industries (agriculture, forestry, pulp and