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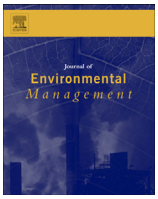

Effects of nitrogen inputs on freshwater wetland ecosystem services – A Bayesian network analysis

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ABSTRACT

Increased nitrogen (N) inputs to freshwater wetlands potentially affect the interaction between nitrous oxide (N_2O) emissions and outflow water quality. The purpose of this study is to evaluate the influence of N inputs on N removal, as well as the interaction between N_2O emissions and outflow water quality, using a Bayesian Belief Network (BBN). The BBN was developed by linking wetland classification, biogeochemical processes, and environmental factors. Empirical data for 34 freshwater wetlands were gathered from a comprehensive review of published peer-reviewed and gray literature. The BBN was implemented using 30 wetlands (88% of the case file) and evaluated using a single test file containing 4 wetlands (12% of the case file). The BBN implies it is not average annual total N load entering the wetland, but the N removal efficiency that influences the interactions between N_2O emissions and outflow water quality. Even though the network has a very low error rate indicating a high predictive accuracy, additional testing and larger training and testing datasets would increase confidence in the model's ability to provide robust predictions and to reduce the uncertainty resulting from an incomplete dataset and knowledge gaps regarding the interactions between N_2O emissions and outflow water quality.

1. Introduction

Nitrogen (N) removal is an intermediate ecosystem service that influences both water quality regulation and climate change mitigation. Although wetlands play a much larger role in climate change mitigation through the carbon cycle, there is a concern that N removal may have a negative influence through N_2O emissions, especially at higher N loading rates (Engle, 2011). Nitrogen is removed from wetlands via interactions between sedimentation, microbial processes, and plant assimilation (Saunders and Kalff, 2001). Plant assimilation per se provides only temporary removal unless plant harvesting occurs, but it is also a route to denitrification through decomposition and mineralization of organic N compounds in plant tissues. Nitrogen is removed over the long term by sedimentation and permanently by denitrification (Hemond and Benoit, 1988). The purpose of this study is to develop a Bayesian Belief Network (BBN) to investigate the effects of N inputs on ecosystem services (N removal, N_2O emissions, and water quality). Relationships between wetland classification, biogeochemical processes, and environmental factors can be used to explore the effects of N inputs on the interaction between N_2O emissions and outflow water quality.

Bayesian Belief Networks are powerful tools for modeling complex ecosystems and natural resource management decisions (Peterson et al., 2008; Dlamini, 2010; Nash et al., 2010; Stewart-Koster et al., 2010; Ticehurst et al., 2011), although this tool has not been used to evaluate the effects of nutrients on interactions between ecosystem services. Bayesian Belief Networks are models that graphically illustrate a system as a network of interactions between variables using probability to account for the uncertainty within the system. These models use directed arcs (depicted as arrows) to link nodes (probabilistic variables depicted as circles or boxes) together to portray causal relationships, which are quantified using conditional probability distributions. Nodes with no incoming arcs (root nodes) have an unconditional probability distribution. Nodes that are predecessors to other nodes (parents) link to a "child" node to form joint probability distributions. Each child node state has a calculated probability for each combination of states for its parent node(s) which is mapped onto a conditional probability table. Once the conditional probability tables are generated and the network is compiled, the prior probabilities (initial beliefs) for each node are displayed throughout the network. As likelihood scenarios are explored, the prior probabilities are adjusted and the distributions for target node(s) (i.e., variable(s) of interest) are examined. These networks allow for (1) more flexibility when compared to traditional statistical approaches (Marcot et al., 2006), (2) the combination of scientific

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knowledge in the form of quantitative and qualitative data collected using various sampling methods (Uusitalo, 2007), and (3) a more comprehensive representation of what is known about the ecosystem (Borsuk et al., 2004).

Denitrification is a vital microbial process responsible for removing nitrate (NO_3) from the soil and water column, which influences the delivery of NO_3 to downstream ecosystems (Robertson and Groffman, 2007). During the denitrification process, NO_3 is reduced to an intermediate N_2O gas prior to being released to the atmosphere as dinitrogen (N_2) gas. Most wetlands are N-limited ecosystems with adequate organic matter to promote N_2 as the end product during the denitrification process (Reddy and DeLaune, 2008). Additional NO_3 inputs from nitrified secondary effluents and runoff from agricultural and urbanized land uses (Kadlec and Wallace, 2009) increase production of N_2O during incomplete denitrification (Verhoeven et al., 2006). Nitrous oxide is a greenhouse gas with a global warming potential about 153–310 times more powerful than carbon dioxide depending on the time horizon (Forster et al., 2007); moreover, N_2O has been predicted to be the dominant stratospheric ozone-depleting substance in the 21st century (Ravishankara et al., 2009).

Nitrous oxide production reduces the delivery of NO_3 to downstream ecosystems, but increases the risk for N_2O emissions to the atmosphere. Few wetland studies have attempted to evaluate the environmental risks associated with NO_3 removal and the balance between water quality impairment and N_2O emissions (Freeman et al., 1997; Hefting et al., 2003; Zaman et al., 2008). It is documented that increased N loads potentially strengthen the risk for N_2O emissions (Stadmark et al., 2009). Freshwater wetlands are capable of releasing considerable amounts of N_2O (Smith et al., 1983; Yu et al., 2006).

Higher N inputs increase the potential for the outflow of water from wetlands to exceed water quality recommendations (Kadlec and Wallace, 2009). A meta-analysis of many wetland studies worldwide did not find evidence supporting a declining efficiency model, but instead found a linear increase in N removal as a function of N loading (Jordan et al., 2011). However, N removal efficiencies for freshwater wetlands located near the Gulf of Mexico were observed to decline as the N inputs increase (Engle, 2011).

Even though wetlands are efficient in removing N, increases in N turnover and outputs potentially reduce the capacity for wetlands to balance both water quality regulation and climate change mitigation. In order to prevent detrimental interactions between N_2O emissions and water quality, wetlands need to be efficient in removing excessive N inputs from polluted waters to reduce eutrophication in downstream receiving water bodies, while emitting negligible amounts of N_2O during incomplete denitrification (Verhoeven et al., 2006). We hypothesized that excessive N inputs would increase the likelihood for higher N_2O emissions and decrease the probability that the outflow of water from freshwater wetlands would meet water quality criteria. The goals for this study were: (1) to develop, implement, and evaluate a BBN model using both quantitative and qualitative data reported in the literature; (2) to explore scenarios demonstrating the effects of N inputs on N removal and the interactions between N_2O emissions and outflow water quality; and (3) to identify gaps in scientific knowledge and data. The BBN constructed in this study was synthesized from pre-existing data and knowledge.

2. Methods and materials

2.1. Bayesian network development

2.1.1. Data collection and criteria for model development

A comprehensive review of published peer-reviewed and gray (i.e., academic institution and government agency) literature was conducted to compile data characterizing surface-flow freshwater wetlands located around the world. Literature databases (e.g., Web of Science, Science Direct, Agricola, Biosis, CAB Abstracts, JSTOR, Springer) were queried using keyword combinations. Additional ad hoc internet searches were executed using the same keyword combinations. The reference sections of peer-reviewed literature were screened to find potential articles containing usable data.

There were several criteria the data had to meet in order for a study to be included in the freshwater wetland case file:

1. Input and output N loads or input and output concentrations with flow rates to calculate the load
2. Input loading rates greater than output loading rates
3. Values quantifying N losses via multiple transformation processes (i.e., denitrification, soil N accumulation, and aboveground biomass uptake)
4. A minimum sample collection period of one year, because the biogeochemical processes associated with regulating and supporting ecosystem services change slowly over time (Millennium Ecosystem Assessment, 2005)
5. Sufficient information for the units to be converted to $g\ m^{-2}\ yr^{-1}$.

Empirical data for 34 freshwater wetland cases were found during the literature search. Due to the lack of data, some of the wetland cases contained missing values. When a study contained an incomplete N budget, additional studies conducted on the same wetland monitored during the same time of the year were aggregated to minimize the number of missing values. The first 30 freshwater wetland cases (88% of the total dataset) found during the literature search were entered into a spreadsheet and used to train the BBN. Subsequently four additional freshwater wetland cases (12% of the total dataset) were found in the literature and used to test the BBN (Korb and Nicholson, 2011). The training dataset was used to establish the conditional probability tables within the model. The testing dataset was used to provide an estimate of the generalization accuracy of the model's ability to predict the interaction between N_2O emissions and outflow water quality outcomes for new freshwater wetland cases (Korb and Nicholson, 2011).

2.1.2. Network structure

A freshwater wetlands BBN was developed using guidelines from a combination of several published procedures (Cain, 2001; Marcot et al., 2006; Chen and Pollino, 2012). A conceptual diagram was designed to link the wetland characteristics and biogeochemical processes associated with N removal to total N inputs. The conceptual diagram was reviewed by several scientists during each step of the refinement process. The finalized conceptual diagram was converted into a BBN structure (Fig. 1a).

A total of 11 nodes was included in the model (Fig. 1a); a detailed description of each node is contained in the Supplementary Material. These nodes were discretized into no more than three states to minimize the network size (Cain, 2001). The node states were selected based on established classification systems, ecological critical limits, and environmental management thresholds provided in the literature or by experts (Table 1).

The target node for this BBN is ecosystem service interaction (i.e., N_2O emission versus reduction in outflow N concentration). Due to the lack of N_2O emission measurements for the wetlands used to train this model, the ecosystem service interaction node was based on a deterministic relationship between N_2O emissions and outflow water quality rather than a probabilistic relationship. The ecosystem service interaction node represented whether the interaction between N_2O emissions and outflow water quality was