A method to identify likely sites for denitrification in semi-arid floodplain rivers

Leo Lymburner, Senior Research Officer, Australian Centre for Tropical Freshwater Research, James Cook University, Townsville, Australia

Peter Hairsine, Stream Leader, CSIRO Land and Water, Canberra, Australia

Jeff Walker, Senior Lecturer, University of Melbourne, Melbourne Australia

Alex Held, Head of COSSA, CSIRO, Canberra, Australia

Abstract

Water quality in semi-arid floodplain rivers such those found in northern Australia is being impacted by human activities. One impact is the increase in the amount of dissolved inorganic nitrogen carried by streams and rivers. Denitrification provides a mechanism whereby dissolved inorganic nitrogen can be converted into atmospheric nitrogen and removed from the river network. However the timing, spatial distribution and influence of land management on denitrification in semi-arid floodplain rivers remains poorly understood. This paper presents an algorithm that combines remote sensing data, terrain analysis and stream gauging station data to predict where within the catchment denitrification is likely to be taking place. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery was used to generate a map of riparian vegetation (closed forest, open forest, woodland, open woodland) and land cover (grassland, cropping). These vegetation and land cover classes were used to estimate the distribution of water soluble carbon. Terrain analysis was used to generate a stream channel network and a map of colluvial and alluvial soils. The flow characteristics of the stream channel network and innundation frequency of the floodplain were calculated from an analysis of stage height records from stream guaging stations. The stage height records were analysed to determine how frequently stage height exceeded a certain level for more than 3 days (the time required for denitrification to begin) or for more than 8 days (the time required for all available reserves of water soluble carbon to be consumed). This combination of a map of soluble organic carbon with a stream network GIS that describes the probability of denitrification occuring in different soil horizons represents a new method for calculating the likelihood and distribution of denitrification. Results from this approach are presented for two subcatchments of the Fitzroy river in Queensland, the Comet and Nogoa. These catchments contain extensive floodplains that surround both single channel and anastomosing river reaches. The results show that denitrification is most likely to occur in the root zones of closed forest and open forest located in the riparian zones and floodplains of 2nd and 3rd order (Strahler) streams. The model identifies these areas based on the high amounts of soil organic carbon associated with these vegetation classes and the high frequency of bank full events calculated for these stream orders. The results also show that the practice of clearing and cropping on floodplain soils has reduced the denitrification capacity within the study area by 50%. This is of concern in areas where fertilized cropping on floodplain soils potentially converts nitrate sinks into nitrate sources. The capacity to identify areas of high denitrification potential is a valuable tool for catchment managers because it enables them to identify priority areas for protection and restoration.

Introduction

The Fitzroy catchment in Queensland drains into the Great Barrier Reef Marine Park. The introduction of cropping and grazing into the Fitzroy catchment has increased in-stream concentrations of dissolved inorganic nitrogen (DIN) (Noble *et al.*, 1996) which in turn has resulted in an increase in the amount of DIN transported out of the catchment (Douglas *et al.*, 2005). Catchment generated DIN has impacted on the reef and other sensitive near-shore environments during previous flood events (Brodie and Mitchell, 1992). Consequently, there is a need to reduce the amount of DIN delivered by the Fitzroy river to protect sensitive near shore environments including the Great Barrier Reef (O'Reagain *et al*., 2005). One way of reducing the amount of DIN delivered by the Fitzroy river is to maintain and restore the denitrification capacity of riparian zones within the catchment. To do this it is necessary to identify the riparian zones and floodplains throughout the catchment in which denitrification is most likely to occur. This enables the identification of priority areas for the protection and restoration of riparian vegetation. The denitrification index (DNI) developed in this study aims to address this need.

Riparian zones can remove nitrogen from the soil and from groundwater in a variety of ways. Nitrogen can be removed via direct uptake by plants or via microbial denitrification. Microbial denitrification is of particular interest, because the nitrogen is converted into gaseous forms of nitrogen N_2O and N_2, thereby removing the nitrogen from the riparian system completely. Microbial denitrification typically occurs when denitrifying bacteria are subjected to anaerobic conditions associated with inundation/submersion, and during this period use nitrate rather than oxygen to break down dissolved organic carbon (Sigunga *et al*., 2002). This process is limited by a number of factors, including: the amount of water soluble carbon (WSC)[1] present and the contact time between the nitrate enriched water and the WSC. The concentration of nitrate can also limit this reaction. In humid areas, denitrification takes place when nitrogen enriched shallow groundwater enters the riparian zone from the adjacent hillslope, and then travels through the rooting zone of riparian vegetation towards the stream (Hill *et al*., 2004).

In semi-arid regions, such as the study area which is located in the dry tropics, denitrification occurs via the same mechanism, but under different circumstances (Schade, *et al*., 2002). In these regions denitrification is likely to occur when nitrogen enriched water enters the root zone of vegetation adjacent to the channel during the rising arm of the hydrograph, spends a period of time in the root zone, and then returns to the channel during the falling arm of the hydrograph (Schade *et al*., 2002). Denitrification can also occur when flow goes overbank, and water infiltrates into the floodplain (Caraco and Cole, 2001). This occurs when the flood duration is sufficient so that the dissolved oxygen levels drop to the point where microbes start to metabolise nitrate (Sigunga *et al*., 2002). Under these circumstance denitrification can occur at any location throughout the floodplain, if dissolved organic carbon is available (Hill *et al*., 2000), and provided that the soil remains wet enough for denitrification to occur. Studies of denitrification in semi-arid areas with vertisol soils (similar climate and soil type to those encountered in the study area of this research) have found that denitrification occurs when the water holding capacity (WHC) of the soil exceeds 60% for more than twenty hours and occurs rapidly when WHC exceeds 80% (Sigunga *et al*., 2002). Once WHC exceeds 60% there is a lag period of twenty hours whilst available oxygen is used up (Sigunga *et al*., 2002), after which denitrification begins to take place. In a study of denitrification in vertisols, Powlson *et al.* (1988) found that 25% of denitrification took place in the first two days (after the initial lag) and all denitrification took place (*i.e.* available carbon supplies were consumed) within seven days.

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[1] which will become dissolved organic carbon in the presence of water.

Methodology

The denitrification index (DNI) is calculated using Equation 1

$$\mathrm{DNI}_x = \frac{WSC_x^{\mathrm{Current}} \times NDNE_x^{\mathrm{Current}}}{WSC_x^{\mathrm{Reference}} \times NDNE_x^{\mathrm{Reference}}} \quad (1)$$

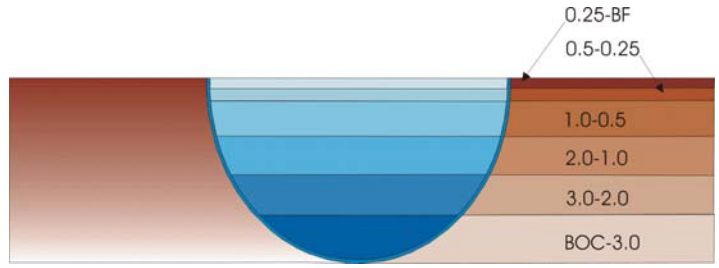

Figure 1. Channel cross section showing soil depth ranges (x)

Where WSC_x^{Current} and $WSC_x^{\mathrm{Reference}}$ represent the amount of water soluble carbon (WSC) (kg m^{-3}) that would become dissolved organic carbon in the presence of water under current vegetation/land cover and reference vegetation cover respectively, and NDNE_x represent the number of denitrification events that occur in soil depth range *x* under current and reference conditions (Figure 1, BF represents bank full and BOC represents base of channel). Having calculated DNI_x at every depth range *x* using Equation 2 it is now possible to calculate DNI using

$$\mathrm{DNI} = \sum_{x=\mathrm{BOC}}^{x=0} \mathrm{DNI}_x \quad (2)$$

To calculate the DNI it is necessary to know 1. the spatial distribution of WSC in riparian and floodplain soils; and 2. the NDNE for each *x* for riparian zones and floodplains throughout the study area. The spatial distribution of WSC was estimated using the aboveground biomass of riparian vegetation structural classes (*sensu* Specht (1970)) to infer the below ground distribution of WSC based on literature values (O'brien *et al*., 2003) that describe the relationship between aboveground biomass and WSC for the dominant vegetation types in the study area. Values for WSC in central Queensland soils subject to grazing are from Holt (1997). The NDNE for each *x* was calculated from stream gauging station data within the study area. A denitrification event was considered to have occurred if the stream stage height exceeded *x* for more than three days. The NDNE was also limited by the capacity of fine root turnover to replenish WSC in each *x*, a process that takes at least one month (Katterer, 1995). The NDNE_x values calculated in this fashion were linked to stream order (Strahler, 1964). A stream channel network with Strahler stream ordering was generated from a 25 metre digital elevation model, and this stream channel network was used to estimate the NDNE_x for riparian zones and floodplains throughout the study area. The channel network contains numerous anabranches and distributary channels on the floodplains of higher order streams (3D, 4D, 5D and 6D channels in figure 3) where a 4D channel is a distributary channel of a 4th order stream. These D class channels are assumed to have flow characteristics determined by high stage events, so the NDNE_x for the 4D channel is calculated from the high stage event characteristics of gauging stations located on 4th order streams.

Results and Discussion

The DNI indicates that denitrification is most likely to occur in stands of closed forest and open forest located in the littoral zones[2] of 2nd and 3rd order streams that are located on floodplains (Site A in Figure 2 and the first two columns of Figure 3). These channels reach bankfull stage more frequently than higher order streams, and consequently water enters the WSC rich top-soil more frequently. These flow characteristics in combination with the high amounts of WSC found in the soil beneath stands of closed forest and open forest (generated by leaf litter and fine root turnover) create the most suitable conditions for denitrification to occur (shown in dark green in Figures 2

[2] Littoral zone refers to the zone immediately adjacent to the channel

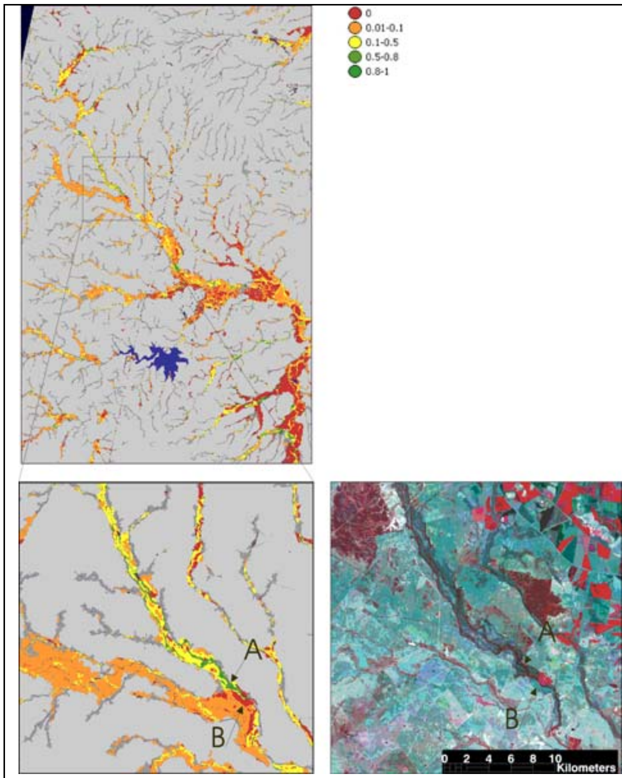

Figure 2. The spatial distribution of riparian and floodplain DNI for Theresa Ck, Lower Nogoa and Lower Comet Rivers

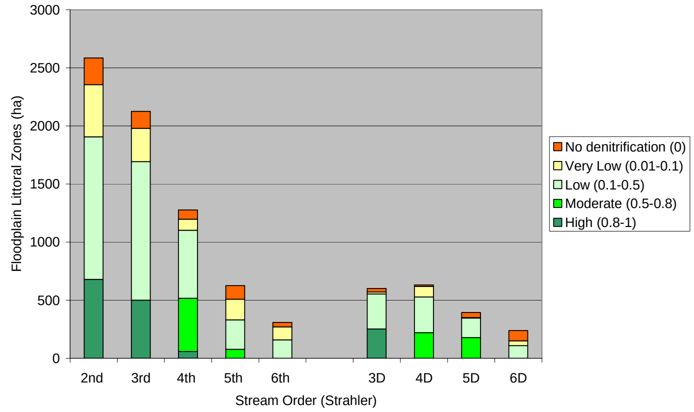

Figure 3. Range of DNI values in the littoral zone adjacent to different stream orders (excludes floodplains)

and 3). Stands of woodland and open woodland adjacent to 2nd and 3rd order streams will encounter similar flow characteristics, however the lower amount of WSC associated with these structural classes reduces the capacity for denitrification (shown as pale green in Figures 2 and 3). Areas that have been cleared of woody vegetation are assumed to contain WSC only in the topsoil layer (x =0.25-BF in Figure 1) and will therefore have a very low potential for denitrification (shown as yellow in Figures 2 and 3. Finally, the areas that have been cleared off vegetation (ie are currently under crops are shown as having no potential for dentrification based on a combination of low amounts of WSC and the possibility that nitrogen fertilizers are being applied to such areas (shown in orange in figures 2 and 3 and highlighted at Site B).

The DNI shows how land use changes in the littoral zone and on the floodplain have reduced the amount of WSC in riparian soils, thereby reducing the amount of nitrate that can be removed from the system by riparian vegetation. This has major implications for the water quality both in-stream and in the receiving waters given the increased nitrate and ammonium inputs from cropping and grazing that takes place on the floodplain (Noble *et al*., 1997). Based on the results of the DNI stands of closed forest and open forest located on the floodplains of 2nd and 3rd order streams (Site A in Figure 2) are the highest priority area in terms of protection (riparian fencing) and areas upstream and downstream of these stands would be the highest priority in terms of restoration. The DNI is suitable for prioritizing riparian protection/restoration projects aimed at maintaining and improving the denitrification capacity of catchments. However additional fieldwork will be required before the DNI is used to calculate the amount of nitrate removed by denitrification. Future studies that accurately quantify the amount of nitrate removed by stands of vegetation adjacent to different stream orders can be coupled with the approach described here, and, in combination with estimates of fertilizer inputs, would be used to develop a 'whole-of-catchment' nitrogen budget. Such a budget would provide valuable insight into the overall importance of riparian denitrification during flood and low flow conditions.

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