

# Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area

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## Abstract

Clearing of native vegetation and replacement with cropping and grazing systems has increased nutrient exports to the Great Barrier Reef (GBR) to a level many times the natural rate. We present a technique for modelling nutrient transport, based on material budgets of river systems, and use it to identify the patterns and sources of nutrients exported. The outputs of the model can then be used to help prioritise catchment areas and land uses for management and assess various management options. Hillslope erosion is the largest source of particulate nutrients because of its dominance as a sediment source and the higher nutrient concentrations on surface soils. Dissolved nutrient fractions contribute 30% of total nitrogen and 15% of total phosphorus inputs. Spatial patterns show the elevated dissolved inorganic nitrogen export in the wetter catchments, and the dominance of particulate N and P from soil erosion in coastal areas. This study has identified catchments with high levels of contribution to exports and targeting these should be a priority.

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## 1. Introduction

Widespread clearing of native vegetation and replacement with intensive agriculture has been linked to degraded water quality of streams and receiving water bodies such as estuaries, coastal waters and coral reefs (Walker and McComb, 1992; Zann, 1995; Carpenter et al., 1998; Wilkinson, 1999). Interest in reducing or reversing this trend has increased, but in situations where large rivers discharge to the marine environment, there is a need to prioritise rehabilitation efforts by identifying the sub-catchments and processes that contribute the bulk of the exported nutrients. Limited rehabilitation funds can then be used more effectively to target these source areas and reduce exports. In large

and diverse catchments there are a multitude of possible sources, but spatial modelling offers a technique to both identify source areas and investigate the effectiveness of particular management options. Here we present a technique for modelling nutrient transport in catchments, based on material budgets of river systems, and apply it to identify the patterns and sources of nutrient exported to the Great Barrier Reef World Heritage Area (GBRWHA).

The Great Barrier Reef World Heritage Area contains the world's largest marine protected area (the Great Barrier Reef Marine Park) and is bordered by a catchment of 423,000 km<sup>2</sup> (Fig. 2a). River nutrient load monitoring has revealed the scale of export to the reef from a limited number of catchments. Sampling of the Normanby, Barron, Johnstone, Tully, Herbert, Burdekin and Fitzroy Rivers was initiated in 1987 by the Australian Institute of Marine Science (AIMS; Furnas, 2003). Monitoring provides the only actual

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measurements of nutrient concentrations and loads, but not all rivers have been monitored and so some form of modelling or extrapolation is required to assess the patterns of export from the GBR catchments.

As detailed in the companion paper on modelling sediment transport in the GBR catchments (McKergow et al., in press) monitoring needs to be complemented by modelling of nutrient transport to extrapolate through time from limited monitoring conditions, and spatially to identify sources within the large river basins, and to identify sources and exports in ungauged catchments. The modelling needs to account for the diversity of environments that inevitably occur in large catchments. The GBR catchments range from small steep, high energy rivers in the Wet Tropics dominated by sugar cane and rainforest land covers, to vast catchments of savannah grazing, various cropping land uses and extensive low energy floodplains that store much sediment and nutrients in the dry tropics.

While nutrient sources are well documented in small catchments (e.g. Beaulac and Reckhow, 1982; Caitcheon et al., 1995; McKee and Eyre, 2000), the sources and fate of nutrients in large catchments are less well understood. A major challenge to reliably predict nutrient transport in surface waters of large areas is to account for the variety of sources and removal processes. Many models have been developed to predict nitrogen and phosphorus sources and export from catchments, and Alexander et al. (2002) review the main approaches used in large catchments. At a regional scale, suitable modelling approaches include regression (Cohn et al., 1992; Peirels et al., 1991), export coefficients (Caraco and Cole, 1999; Johnes and Butterfield, 2002), mass balance models (Jaworski et al., 1992; Jordan and Weller, 1996; Howarth et al., 1996) and physically-based models (de Wit, 2000). Hybrid models, which contain some or all of these modelling approaches, have been used for regional scale modelling of water quality. For example, the empirical model, SPARROW uses process-based functions with spatially distributed components and mass balance constraints (Alexander et al., 2002).

Empirical relationships have been used to model exports draining to the Great Barrier Reef (Moss et al., 1992; Rayment and Neil, 1997; Wasson, 1997; Furnas and Mitchell, 2001; Brodie and Furnas, 2003; Furnas, 2003). However, a new approach is required to identify the location and magnitude of nutrient sources in the landscape and facilitate scenario modelling. Given the size of the GBR region a macro-scale model is required, preferably without the need for calibration at the catchment scale. A model based on physical representation of processes is preferable for prediction purposes so that it will react correctly to changes imposed (Arnell, 1999).

This project used a hybrid modelling approach to identify nutrient sources and exports to the GBR. The spatially distributed model places mass balance con-

straints on nutrient sources derived from empirical relationships and literature based nutrient concentrations, and physically based transport rules. The nutrient model, ANNEX (Young et al., 2001), is a component of the *SedNet* (*Sediment River Network Model*) suite of programs (Prosser et al., 2001a). It constructs material budgets of particulate and dissolved nutrients through river systems based upon an extension of a tested sediment budget model. It includes deposition and transformations of nutrients as they are transported through river systems. The guiding principle behind these budgets is that the load of material carried by any stretch of river is determined by the rate of supply from various erosion processes and land uses, less deposition and transformations during transport. A balance of inputs and stores or losses is calculated in each river link sequentially from the source streams to the mouth of the catchment, gradually accumulating load. The principles of this approach are described in Prosser et al. (2001b).

## 2. Methods

Nutrient budgets for the GBR catchment were modelled with a modified version of ANNEX (Young et al., 2001). ANNEX is an extension of SedNet (Prosser et al., 2001b); it is not a stand alone model. SedNet and ANNEX were first developed and applied to the Australian National Land and Water Resources Audit (NLWRA; Prosser et al., 2001b). ANNEX produces spatial budgets of mean annual phosphorus (P) and nitrogen (N) loads in rivers. Particulate nutrient loads are based on sediment loads determined by SedNet (McKergow et al., in press). Dissolved nutrient loads were calculated from mean concentrations based on land use and mean annual flow. ANNEX includes several nutrient loss or exchange terms, which modify the loads during transport to the coast. Full details of methodology can be found in Brodie et al. (2003).

Modifications made to ANNEX in this study include (1) calculating dissolved nutrients using mean event-flow concentrations, (2) modifying reservoir deposition and (3) including nutrient speciation. Here we give a brief overview of the nutrient budgets and outline the data sources and modifications used in the application to the GBR catchment. Estimation of the sediment loads and SedNet are discussed in detail in McKergow et al. (in press).

The basic unit of calculation in SedNet is a river link, which is a section of river between adjacent stream junctions (Fig. 1). Each link has an internal catchment area, which is the area contributing runoff directly to the river link, and not through a tributary (Fig. 1).

In each link of the river network (*i*, Fig. 1) the mean annual yield of nitrogen or phosphorus ( $Y_i$ ;  $\text{t y}^{-1}$ ) is:

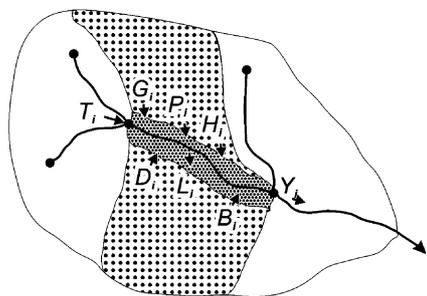


Fig. 1. Conceptual diagram of the mean annual nutrient budget ( $t/y$ ) for a link of a river network and its associated internal catchment (light shade) and floodplain (dark shade). Budget terms are defined in the text.

$$Y_i = T_i + H_i + G_i + B_i + D_i + P_i - L_i$$

where  $T_i$  is tributary particulate and dissolved input;  $H_i$  is particulate input from hillslope erosion;  $G_i$  is particulate input from gully erosion,  $B_i$  is particulate input from riverbank erosion,  $D_i$  is diffuse dissolved input,  $P_i$  is point source dissolved input and  $L_i$  is net loss of particulate and dissolved forms during transport through the river link.

ANNEX considers only physical nutrient stores and transport processes, and assumes that on an annual basis the net biological inputs and outputs are small by comparison. Nitrogen and phosphorus are treated independently in the model and both particulate and dissolved forms (dissolved inorganic nitrogen (DIN), dissolved organic nitrogen (DON), filterable reactive phosphorus (FRP) and dissolved organic phosphorus (DOP)) are included. Each form of nitrogen is transported independently in the model, while exchange between particulate P and FRP is allowed in each river link.

### 2.1. Particulate loads

Mean annual particulate nutrient inputs were calculated as the product of mean annual erosion rate and soil nutrient concentration. Mean annual hillslope, riverbank and gully erosion were determined by SedNet and are discussed in more detail in McKergow et al. (in press). Hillslope erosion was predicted using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). Gully density was predicted with an empirical model and was converted to a mean annual rate of erosion using typical values for gully age and cross sectional area. Riverbank erosion was estimated from a conceptual relationship based on stream power, riparian vegetation and extent of alluvial floodplains.

The nutrient loads sourced from riverbank and gully erosion are the product of sediment yield and soil nutrient concentration. Subsoil nutrient concentrations for the GBR catchment are not available, so spatially uniform values of  $0.25 \text{ gPkg}^{-1}$  and  $1 \text{ gNkg}^{-1}$  were used,

based on limited samples of gully and riverbank materials (Jon Olley, pers. comm.).

Concentrations of nutrients associated with hillslope erosion were derived from soil property mapping of Australia (Henderson et al., 2001). The soil mapping provides bulk nutrient concentrations for surface soils, but nutrients are more strongly associated with the finer sediment fractions, which are more likely to be delivered to the stream than the coarser particles. This behaviour can be incorporated through a nutrient enrichment ratio. In the absence of comprehensive data on enrichment ratios a simple conceptual model was implemented. It was assumed that nutrients were transported attached to the clay fraction and that deposition of sediment on hillslopes deposits the coarsest fraction first. Deposition is modelled through a hillslope sediment delivery ratio (HSDR), globally set to 0.1 for the GBR (McKergow et al., in press). Thus, if HSDR is less than the proportion of clay, only clay is delivered and the enrichment ratio is the inverse of the proportion of clay. In the few cases the proportion of clay is  $<10\%$  the nutrient enrichment ratio is the inverse of HSDR (10 in this study). The enrichment ratios calculated in this way were consistently higher than those observed in river and soil erosion monitoring (Furnas, 2003) and so we halved all values. This suggests either that considerable amounts of nutrients move with coarser particles, that nutrient concentrations were consistently overestimated, or that sediment sorting is not as effective as simplified here.

### 2.2. Dissolved load

Dissolved nutrient loads were calculated from mean concentrations based on land use and mean annual flow. Nutrient concentrations of DIN, DON, FRP and DOP were assessed from water quality studies that had one dominant land use and are summarised in Table 1. Event mean concentrations (EMCs) were derived, but for some datasets they could not be calculated so 80 percentile values from the complete datasets were used. No distinctions were made between surface runoff and subsurface flow. For each river link the load is the product of mean annual flow and mean nutrient concentration for the internal catchment area of the link.

Nutrient concentration datasets for catchments with one dominant land use and event concentrations are uncommon in Queensland. For rainforest, concentrations were derived from a small number of studies in the Wet Tropics and two studies in the Mackay-Whitsundays (Table 1). It is difficult to verify that savannah/woodland catchments have not been grazed during the last 150 years, so nutrient concentrations were estimated from studies on sites which are ungrazed at present or subject to a very light grazing

Table 1  
Concentrations of DIN, DON, FRP and DOP in runoff from land uses within the GBR catchments

Land use	Region/catchment	DIN ( $\mu\text{g l}^{-1}$ )	DON ( $\mu\text{g l}^{-1}$ )	FRP ( $\mu\text{g l}^{-1}$ )	DOP ( $\mu\text{g l}^{-1}$ )	Source
Rainforest	Wet Tropics	40	150	10	10	Brasell and Sinclair (1983), Butler et al. (1996), Cogle et al. (2000, 2002), Devlin et al. (2001), Faithful (1990), Faithful and Brodie (1990), Furnas (2003), Hunter et al. (2001), Pearson et al. (1998)
Ungrazed savannah/woodland	Mackay-Whitsundays	60	150	30	10	Faithful (2002), Pearson and Clayton (1993)
		100	100	20	10	Furnas (2003), Jackson and Ash (2001), O'Reagain et al. (2001), Prove and Hicks (1991), Schmidt and Lamble (2002)
Grazing		200	250	50	12	O'Reagain et al. (in press), Furnas (2003), Nelson et al. (1996), Noble and Collins (2000), O'Reagain et al. (2001), Prove and Hicks (1991)
Sugar cane	Johnstone	900	250	20	20	Armour et al. (1999), Baskeran et al. (2002), Bauld et al. (1996), Biggs et al. (2000, 2001), Bohl et al. (2000, 2001), Bramley and Muller (1999), Bramley and Roth (2002), Brodie et al. (1984), Clayton and Pearson (1996), Congdon and Lukacs (1996), Devlin et al. (2001), Eyre and Davies (1996), Hunter and Armour (2001), Hunter et al. (1996, 2001), Mitchell and Furnas (1997), Mitchell et al. (2001), , Moody et al. (1996), Pearson et al. (2003), Rasiyah and Armour (2001), Rasiyah et al. (2003), Reganzani et al. (1996), Verberg et al. (1998), Weier (1999), White et al. (2002), Mitchell et al. (in press), Wilhelm (2001)
	Mossman, Barron, Russell-Mulgrave	900	250	20	20	
	Tully	1100	250	20	20	
	Herbert	1100	350	40	30	
	Mackay-Whitsundays	900	250	30	30	
	Burnett, Mary	900	250	30	30	
Horticulture		500	200	30	20	Cogle et al. (2000, 2002), Hashim et al. (1997)
Urban/Industry		1650	300	120	20	Chiew and McMahon (1999), Chiew and Scanlon (2001)
Bananas	Wet Tropics	700	250	100	20	Hunter (1997), Hunter et al. (1996, 2001), McKergow et al. (2004), Mitchell et al. (2001), Moody et al. (1996)
Cotton		700	200	80	20	Carroll et al. (1992), Noble et al. (1997), Noble and Collins (2000), Noble, pers. comm.
Grains		500	300	60	20	Dilshad et al. (1996), Noble et al. (1997), Noble and Collins (2000), Noble, pers. comm.
Forestry		150	150	8	8	Bubb et al. (2002), Bubb and Croton (2002)

Note the Wet Tropics region contains the catchments between the Herbert and Normanby River basins, and the Mackay Whitsundays region is between the Fitzroy and Burdekin basins (see Fig. 2a).

regime (O'Reagain et al., 2001). Concentrations for grazing lands were derived from several small catchments studies (Prove and Hicks, 1991; O'Reagain et al., 2001) and larger catchment studies dominated by grazing (>90%).

Many water quality studies have been carried out on sugar cane lands. However, only a few have sampled runoff events and these were used to derive nutrient concentrations (Clayton and Pearson, 1996; Bramley and Muller, 1999; Mitchell et al., in press; Hunter et al., 1996, 2001; Pearson et al., 2003). Concentrations were checked against other sugar cane studies, including DIP and DIN subsurface flow concentrations, which are similar to event surface runoff concentrations. There were few studies found for the other land uses (horticulture, urban, cotton, grains, forestry and bananas) but some data was available for all of them.

### 2.3. Point sources

Point sources in the model are those included in the National Pollutant Inventory 2001, which provides estimates of nutrient loads discharged from industrial and other major urban point sources during 1999–2000. Only point sources that were located within five kilometres of a river link were included, and it was assumed that these loads discharged directly into the nearest river link.

### 2.4. Nutrient losses and exchange

ANNEX includes four nutrient loss or exchange terms: (1) deposition of sediment associated nutrients on floodplains, (2) storage of all forms of nutrients in

reservoirs, (3) denitrification of DIN on floodplains, in the river and in reservoirs, and (4) P exchange in the river between FRP and sediment. The particulate nutrient load deposited on floodplains and in reservoirs is the product of deposited suspended sediment and nutrient concentration, which is tracked through the river network as sediment is added and removed. Dissolved nutrient storage in reservoirs is the product of concentration and runoff volume stored. It was assumed that the bulk of the nutrient load is transported during floods and that 20% of the reservoir capacity is available to store floodwater.

Denitrification of dissolved inorganic nitrogen was modelled as an exponential decay process:

$$\text{DIN}_{\text{out}} = \text{DIN}_{\text{in}} \exp\left(-\frac{kA}{Q}\right)$$

where,  $\text{DIN}_{\text{out}}$  is DIN leaving the link,  $\text{DIN}_{\text{in}}$  is DIN entering the link,  $k$  is an assimilation rate coefficient,  $A$  is an area function and  $Q$  is a flow function. For links where bedload was deposited  $k$  is  $0.0001t$ , where  $t$  is the mean annual water temperature ( $^{\circ}\text{C}$ ), which is assumed to equal the mean annual air temperature of the catchment (available across Australia as a continuous data surface). In the absence of bedload deposition,  $k = 0.0002t$ . These values of  $k$  are based on measurements of denitrification in Australian rivers (Ford, pers. comm.).

Phosphorus exchange between the dissolved ( $P_d$   $\text{mg l}^{-1}$ ) and particulate ( $P_p$   $\text{g kg}^{-1}$ ) forms is determined by an adsorption isotherm ( $K_d$ ,  $\text{m}^3 \text{kg}^{-1}$ ):

$$P_p = K_d P_d$$

A  $K_d$  value of 40 was used for the whole region based on Australian experience (Young et al., 2001).

### 2.5. Hydrology and land use

The model requires various hydrological parameters for each river link and land use for each internal catchment area. Mean annual flow, bankfull discharge, and median flood discharge were obtained at each gauging station from time series of daily flows. The resultant values were extrapolated to ungauged river links using multiple regression relationships with catchment area and rainfall. Land use was compiled from several sources, including NLWRA, Queensland Land Use Mapping Project, catchment atlases and other studies (Brodie et al., 2003).

### 2.6. Natural vegetation cover

To understand the impact of land use and management practices on nutrient transport, current exports must be put in the context of those under natural vegetation cover. Nutrient supply under native vegetation was calculated using the same procedure as above. Nat-

ural vegetation cover was derived from the National Vegetation Information System (NLWRA, 2001). Natural nutrient inputs from hillslope erosion were calculated as the product of erosion rate and soil nutrient concentration. The erosion rate was calculated using the RUSLE with C factors guided by measured erosion rates. No change to the soil nutrient concentration was made, as this is negligible compared with the change in erosion rate. Rates of natural riverbank erosion were predicted using 95% riparian vegetation cover and no change was made to the nutrient concentrations. The natural nutrient budget assumed no sediment supply from gullies. For dissolved nutrient inputs, vegetation was classified as either rainforest or savannah/woodland and assigned nutrient concentrations from Table 1. This simplifies the patterns of nutrient source but is all that is possible with the current lack of data. The influence of reservoirs and flow regulation was removed.

## 3. Results and discussion

### 3.1. Nutrient sources

Hillslope erosion is the largest source of particulate nutrients (Table 2) because of its dominance as a sediment source (McKergow et al., in press) and nutrient enrichment of surface soils. Channel erosion makes up less than 10% of the total nutrient sources (Table 2). Dissolved nutrients in runoff supply about 30% of TN and 15% of TP loads to rivers (Table 2). Overall, point sources of nutrients are insignificant compared to the diffuse component of total load. Point sources can be significant in small river basins with urban centres, such as the town of Mackay in the Pioneer River catchment.

Within the overall budgets there are some strong regional patterns. The patterns of diffuse total P

Table 2  
Components of the nutrient budget for the GBR catchment

Nutrient budget item	Predicted mean annual rate ( $\text{kt y}^{-1}$ )	
	Total N	Total P
Hillslope to stream delivery	64	17
Gully erosion	5.5	1.4
Riverbank erosion	1.5	0.4
Dissolved runoff (includes point sources)	29	3.2
<i>Total supply</i>	<i>100</i>	<i>22</i>
Floodplain and reservoir storage	37	11
Denitrification	<1	–
Particulate export	36	10
Dissolved export	27	1
<i>Total losses</i>	<i>100</i>	<i>22</i>
Total export	63	11

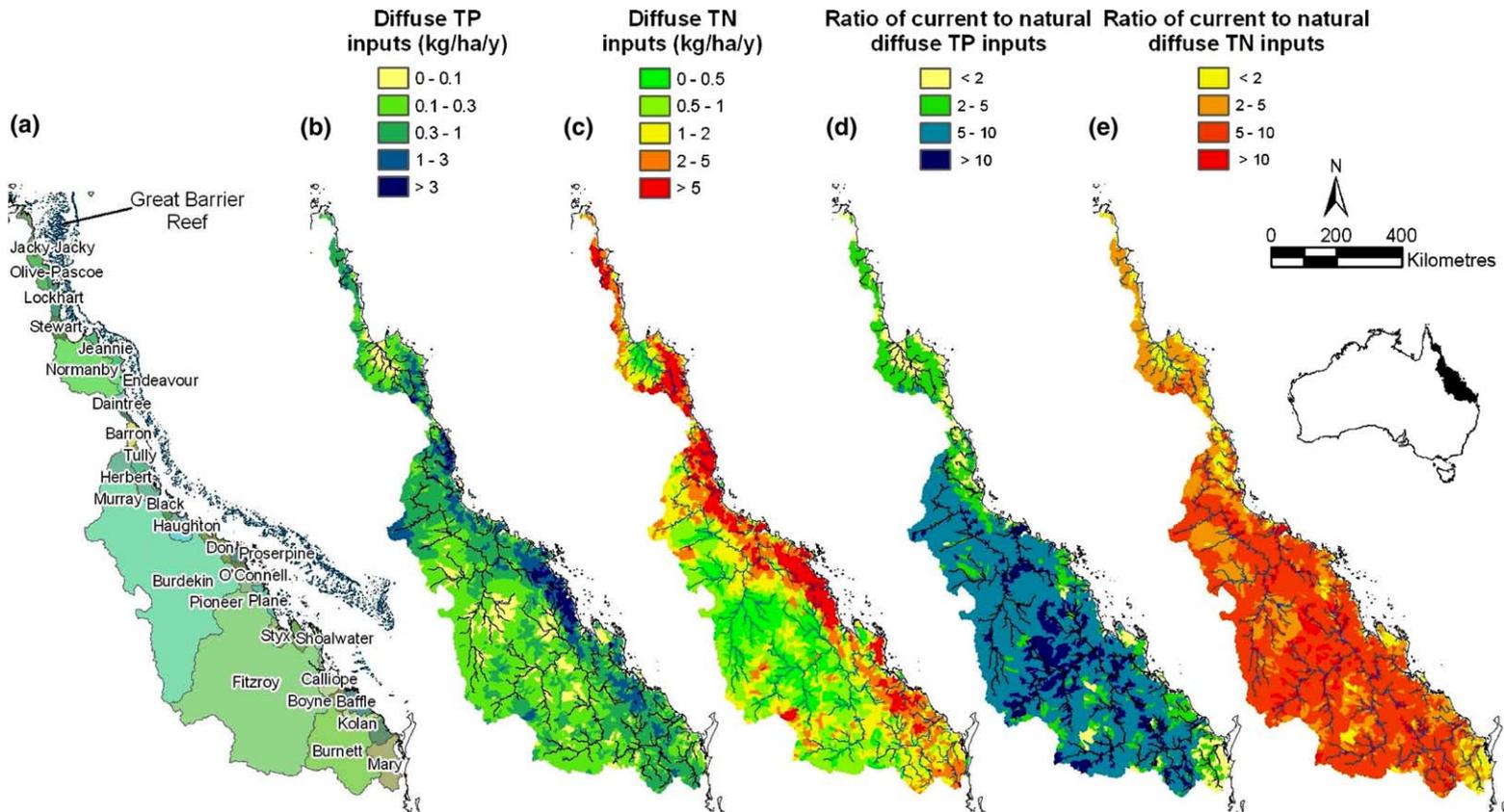


Fig. 2. (a) GBR catchments, (b) diffuse TP inputs in each sub-catchment of the GBR, (c) diffuse TN inputs from each sub-catchments of the GBR, (d) ratio of current to natural contribution to TP diffuse export and (e) ratio of current to natural contribution to TP diffuse export.

contributions largely reflect the hillslope erosion predictions (Fig. 2b) so that the Mackay-Whitsunday coast (between the Fitzroy and Burdekin River basins) and coastal parts of the Fitzroy and Burdekin River basins are significant nutrient sources. The Wet Tropics (between the Herbert and Normanby River basins) are larger sources of nutrients than expected from the sediment results (McKergow et al., *in press*) because of high dissolved losses from both rainforest and sugar cane lands. Inland areas are predicted to have low phosphorus supply because of low hillslope erosion, relatively low nutrient concentrations and limited diffuse runoff.

The Wet Tropics (between the Herbert and Normanby river basins) are larger sources of nutrient than expected from the sediment results because of high dissolved losses from both rainforest and sugar cane lands. Inland areas are predicted to have low phosphorus supply because of low hillslope erosion, relatively low nutrient concentrations and limited diffuse runoff.

The pattern for total N is also dominated by coastal sources (Fig. 2c) but is predicted to be much more evenly distributed along the coast. This is because of the much greater contribution of dissolved N to the total inputs. The model predicts that dissolved forms dominate N inputs from both grazing and cropped areas along the Wet Tropics coast. Dissolved N is also a significant source in parts of the Normanby River basin because of low soil erosion rates and significant runoff.

Areas with high nutrient inputs must be placed in the context of sources under natural vegetation cover. For most of the GBR catchment, nutrient inputs have increased at least five times (Fig. 2d and e). The areas of highest increase (>10 times natural inputs) are isolated parts of the Burdekin, Fitzroy and Burnett River basins. Much of the Wet Tropics and Cape York (north of Black River) show low increases in nutrient input compared to natural cover, because of low intensity land use. There are small areas of high increase in the intensively used lowlands of the Wet Tropics (between Herbert and Normanby).

### 3.2. Nutrient exports

Nutrient sources are only translated into coastal impacts if they are transported along the river network and discharged to the coast. The modelled nutrient budgets for the region predict that 63% of total nitrogen and 50% of total phosphorus are exported (Table 2). Floodplain and reservoir deposition of particulate nutrients are the main stores and these are most significant in the larger catchments. The bulk of nutrient supplied to rivers is exported from the small coastal catchments. Denitrification in rivers is predicted by the model to be insignificant across the region, in terms of its influence

on mean annual loads, because of the short travel times and assumption that the bulk of the load moves with large floods. About a third of the dissolved inputs of P are predicted to become attached to sediment during transport and thus can be deposited.

Nutrient exports to the GBR are commonly summarised by Australian Water Resources Council River Basins (Fig. 3). The Burdekin and Fitzroy Rivers dominate nutrient exports because they are the largest catchments. Patterns of area-specific nutrient load (mean annual nutrient load divided by the upstream catchment area) show the intensity of nutrient transport in each river link. Area specific nutrient exports are high from the Mackay Whitsunday (O'Connell, Pioneer, Plane) and Wet Tropics river basins (Russell-Mulgrave, Johnstone, Tully; Fig. 3a and b).

The pattern of P export mirrors sediment exports because of the dominance of hillslope erosion (Table 2). There are high P exports in the Russell-Mulgrave, Johnstone, Pioneer and Plane River basins because of high sediment P concentrations, presumably as a result of more fertile soils in those basins (Fig. 3a). Dissolved P exports are significant in the Wet Tropics (Murray to Barron River basins) and in the Pioneer River (Fig. 3a).

Current phosphorus exports by river basin are predicted to be 3–30 times higher than natural rates, with the biggest increases occurring on several of the Mackay-Whitsunday river basins (O'Connell, Pioneer, Plane; Fig. 3a). The TP export from the GBR catchment is predicted to have increased from 2 to 11 kt y<sup>-1</sup>.

The pattern of TN exports is similar, with high specific exports from the Wet Tropics (Russell-Mulgrave, Johnstone, Tully River basins) and Mackay-Whitsunday (O'Connell, Pioneer and Plane River basins) catchments (Fig. 3b). Dissolved N exports dominate in the Wet Tropics, with up to 2/3 of TN exported as either DIN or DON. Cape York has lower exports, but around half of the nitrogen is exported in dissolved forms. The Burdekin and Fitzroy Rivers have low specific nitrogen exports (Fig. 3b). The Burdekin River is predicted to be a higher source of N than the Fitzroy River, whereas for P they are predicted to have approximately equal exports (Fig. 3a). The higher N export from the Burdekin River may be due to both slightly higher N concentration on soils and a greater amount of runoff producing a larger dissolved load. Overall, across the GBR catchment, the Australian Soil Resource Information System (ASRIS) database shows a slight increase in N concentration in soils with a decrease in latitude (Henderson et al., 2001).

Current total N export is predicted to be 2–13 times the natural export across river basins (Fig. 3b). The total N export has risen from 14 to 63 kt y<sup>-1</sup>; approximately a fivefold increase, but less than for sediment and phosphorus.

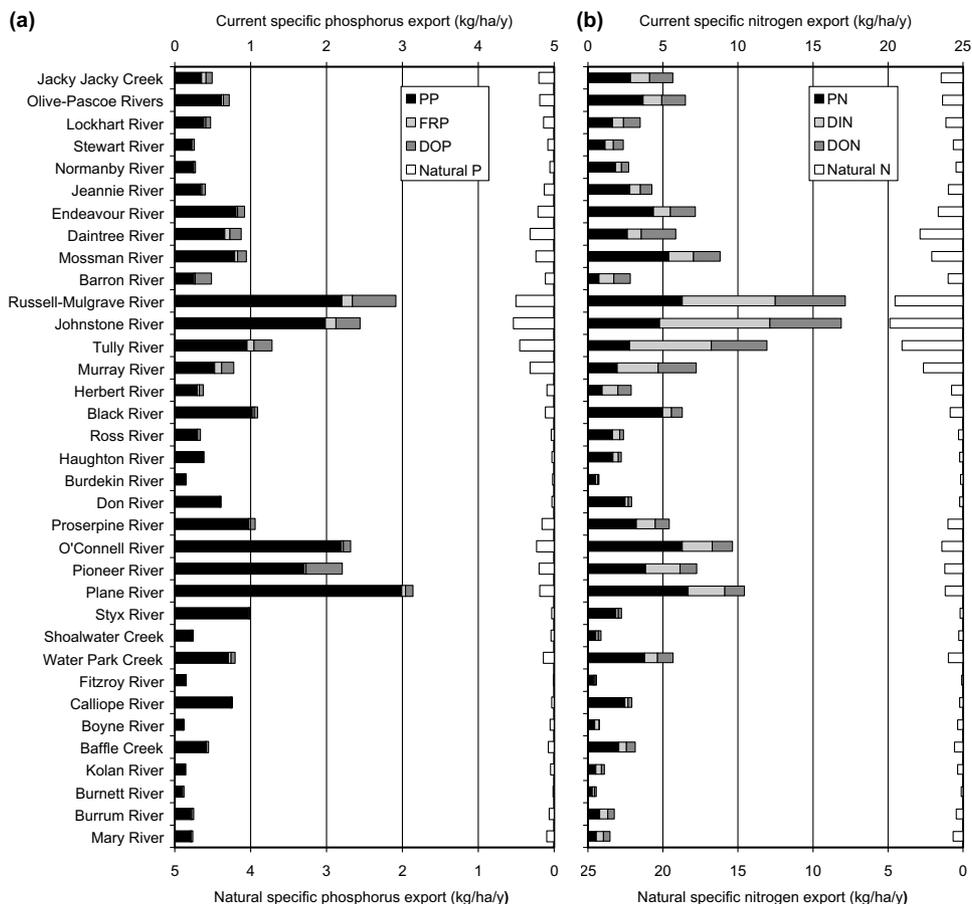


Fig. 3. (a) Specific TP export by source for each AWRC basin under current and natural vegetation cover, and (b) specific TN export by source for each AWRC basin under current and natural vegetation cover.

Table 3

Comparison of previously modelled estimates of current and 1850 TP and TN annual loads from the GBR catchment with the current modelling

Model	Current P (kt)	1850 P (kt)	Current N (kt)	1850 N (kt)
Belperio (1983)	13.7		89	
Moss et al. (1992)	7.6		49.6	
Neil and Yu (1996)	14	3.7	91.1	23.9
Furnas and Mitchell (2001)	1.7		47	
Furnas (2003)	7.09	2.4	43	23
NLWRA (Prosser et al., 2001a)	10.9		53.6	
Current model	11	1.8	63	14.5

### 3.3. Comparison with previous studies

Total nutrient exports estimated in this study, of  $11 \text{ kt TP y}^{-1}$  and  $63 \text{ kt TN y}^{-1}$  are similar to previously published estimates which vary between 7 and  $14 \text{ kt TP y}^{-1}$  and 43 and  $91 \text{ kt TN y}^{-1}$  (Table 3; excluding Furnas and Mitchell, 2001). These other results are based upon more direct extrapolation from monitoring results, the most comprehensive of which is Furnas (2003). Our study systematically over-predicts TP and TN in comparison to Furnas (2003) (Table 3).

Much of the difference is attributable to higher particulate exports, despite the closer match for suspended sediment exports (McKergow et al., in press). This suggests that the difference lies in either overestimation of soil nutrient concentrations or nutrient enrichment ratios. There is particularly scant data available from the region for nutrient enrichment ratios and little ability to model spatial patterns in this component. Clearly, this is an area that needs improved data and methods for extrapolation to unmeasured sites.

Comparison of the current dissolved organic P and N predictions with those of Furnas (2003) (Fig. 4) suggest

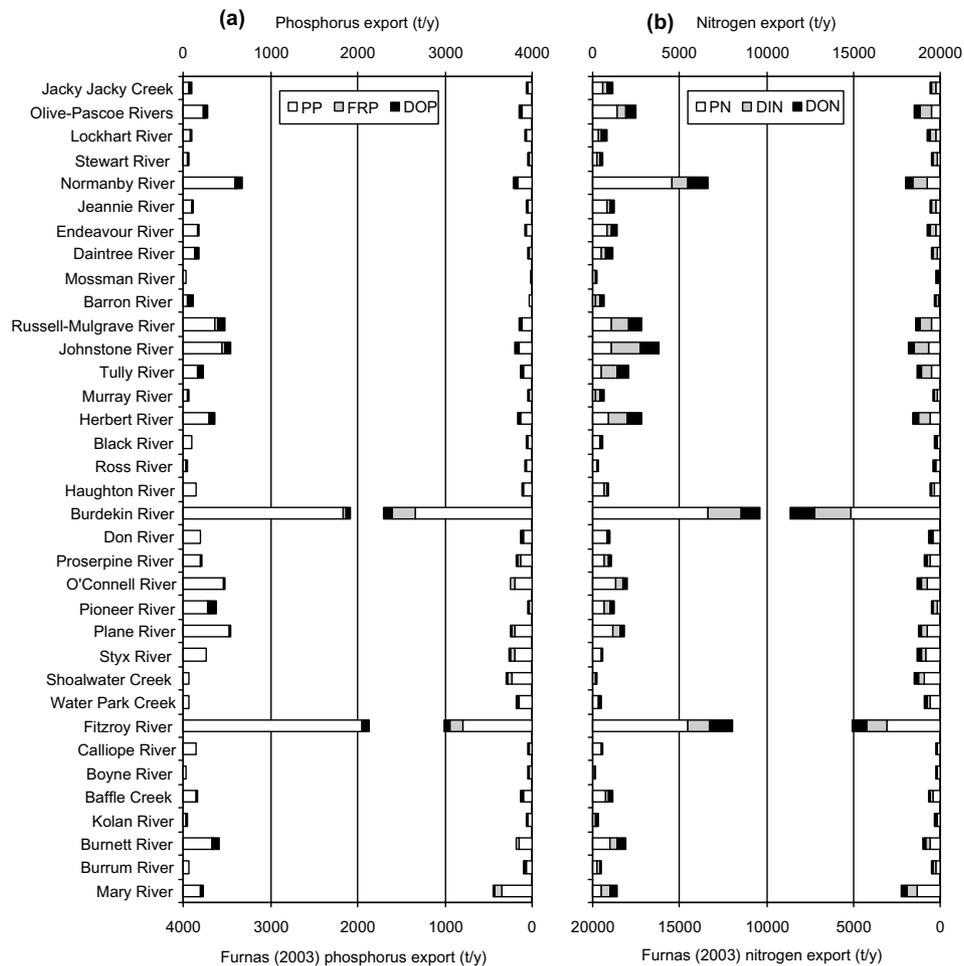


Fig. 4. Comparison between the current SedNet results and Furnas (2003) predictions for (a) phosphorus and (b) nitrogen export from each AWRC River basin.

that either the input rates used are too high, or that storage and losses are unaccounted for during transport through the river network. Information on the concentrations of DON and DOP in water running off different land uses in the GBR catchment is sparse. Where reported, they are calculated as the difference between total dissolved P or N and FRP or DIN, respectively. The concentrations used are therefore less accurate than would be desired and the incorporation of better data should improve the performance of the DON and DOP predictions. Fortunately, DON and DOP only make up a small proportion of the total export.

The inclusion of point source data in nutrient budgets is an important consideration that has been ignored by some previous studies. For example, the high DOP loss predicted for the Pioneer River ( $80\text{t yr}^{-1}$ ; Fig. 4a) compared to the Furnas (2003) estimate of  $7\text{t yr}^{-1}$  is due to the inclusion of significant point sources at Mackay. This illustrates the limitations of direct extrapolations of concentrations from monitored to unmonitored rivers.

Comparison of DIN exports between model predictions and the monitored rivers of Furnas (2003) show mixed results (Fig. 4b). Predictions for the Normanby and Burdekin rivers match well (Fig. 4b), suggesting that DIN losses from grazed catchments are well estimated. In the wetter catchments (Johnstone and Tully) the model over-predicts exports compared to the monitoring results (Fig. 4b). This suggests that DIN concentrations used in the Wet Tropics may be too high, either due to dilution in large runoff events or inadvertent bias in the measurements towards places with higher than average export. An alternative explanation is that denitrification losses are larger than the model predicts. Further research characterising DIN exports to rivers and their transport through river systems should improve model conceptualisation and performance.

### 3.4. Scenario modelling

An advantage of spatial models, such as SedNet and ANNEX, is that they provide the ability to examine

management options in detail, to predict the benefits that will follow. The main purpose of scenario modelling is to assess what the nutrient loads would be under altered land use management. It is very difficult to replicate the exact condition of the catchment for any given situation, therefore scenarios are meant as a guide only. The results provide an indication of the relative change that can be expected if land use or land management practices are altered and help guide the magnitude of change required in catchments to reach water quality targets.

As an example of the potential for SedNet/ANNEX to analyse management scenarios, we predicted the response of TN exports in the Tully River basin to a possible reduction in fertiliser application rate on sugar cane lands. The current application rate of  $200 \text{ kg ha}^{-1} \text{ y}^{-1}$  includes fertiliser ( $140 \text{ kg ha}^{-1} \text{ y}^{-1}$ , Schroeder et al., 1998), mineralisation of sugar cane trash nitrogen ( $40 \text{ kg ha}^{-1} \text{ y}^{-1}$ , Robertson and Thornburn, 2000) and a small addition of mill mud ( $20 \text{ kg ha}^{-1} \text{ y}^{-1}$ , Barry et al., 1998). The scenario application rate of  $130 \text{ kg ha}^{-1} \text{ y}^{-1}$  has the same components, but in smaller quantities. The change in application rate was modelled as a 50% reduction in DIN concentration. This was assumed as most nitrogen lost from the paddock is derived from N that is surplus to plant requirements (approximately  $120 \text{ kg ha}^{-1} \text{ y}^{-1}$ ), i.e. that portion of the applied N between the requirement of 120 and the applied of  $200 \text{ kg ha}^{-1} \text{ y}^{-1}$ .

Approximately 13% of the Tully River basin is used for sugar cane. The TN budgets for the current conditions and scenario are summarised in Table 4. The scenario reduces the dissolved N input by 18% and dissolved N exports from the basin by 19%, illustrating the effectiveness of targeting management at a key nutrient source. The sugar cane is grown at lower elevations, so there are few opportunities for transformations to occur before the N is exported at the coast.

Table 4  
Comparison of predicted TN budgets for current conditions and a fertiliser reduction scenario

Nitrogen budget item	Predicted mean annual rate ( $\text{ty}^{-1}$ )	
	Current	Fertiliser reduction
Hillslope to stream delivery	465	465
Gully erosion	46	46
Riverbank erosion	4	4
Dissolved runoff	1645	1353
Total supply	2160	1868
Floodplain and reservoir storage	80	80
Denitrification	<1	<1
<i>Dissolved export</i>	<i>1596</i>	<i>1304</i>
Particulate export	484	484
Total losses	2160	1868

### 3.5. Improvements required

The results from this study have increased our understanding of nutrient sources and transport in the GBR catchment, but the comparison above with measured loads shows that considerable improvements are required to have better confidence in the results. Some of these were outlined in the comparison with measurements and others are considered here.

Nutrient exports predicted in this study are similar to the NLWRA estimates (Young et al., 2001), despite developments in the model. A key development included changes to the dissolved load module. The NLWRA loads were derived from Australia-wide modelling of soil water nutrient fluxes (Young et al., 2001). In this study, dissolved nutrient loads were calculated as the product of mean concentrations based on land use and mean annual flow. This development also allowed specification to be included in the model.

A major limitation of the new approach is the use of a uniform dissolved nutrient concentration for many land uses (Table 1). For sugar cane there is sufficient data to include regional variability, but for many land uses there is limited data. For example, one nutrient concentration is used for grazing land over the entire GBR catchment, despite differing pasture types and stocking rates. Cattle densities on most of Cape York are approximately 1 cow per  $\text{km}^2$ , whereas numbers on the major grazing areas of the rest of the GBR catchment (Burdekin, Fitzroy, Burnett) are often around 10 cows/ $\text{km}^2$  (Andrew Ash pers. com.). Stocking rates are associated with vegetation cover and soil erosion, which are accounted for in the model. However, nutrients may also be mobilised by grazing, digestion and excretion, which are not specifically treated in the model. Future modelling may be able to take this factor into account, by for example, varying dissolved nutrient concentration factors depending on stocking rates. New data will be required to help parameterise this factor (O'Reagain et al., 2001, in press).

Applying a uniform concentration also results in higher dissolved nutrient loads in areas of high runoff. This is one of the reasons for higher nitrogen exports in the Burdekin River basin than the Fitzroy River basin. Areas of relatively high runoff within a land use class may in reality have a lower mean concentration due to dilution. As there are insufficient data on nutrient concentrations in runoff, a uniform concentration has been used.

Even for sugar cane, where there is sufficient data to include spatial variation of nutrient concentration this can only be achieved as a simple geographical regionalisation based on the measurements. No attempt has been made to explore the environmental factors that produce the geographical variation, and thus there is no basis for extrapolation to unmeasured conditions. This contrasts

with the situation for hillslope erosion of sediment where there is a well established empirical model, the Universal Soil Loss Equation (Renard et al., 1997), applicable at the large regional scale and tested against Australian data (Lu et al., 2003). Additional data and analysis is required to advance nutrient export estimation to the same level.

Each form of nutrient is modelled as an independent budget, with the exception of FRP and PP, so ratios of loads between particular forms are not predetermined by the model structure. Rates of phosphorus exchange are poorly known, and no measurements are available for Australian tropical rivers, so to date the parameter has been largely fitted to produce observed ratios of FRP to TP. We need to establish whether the observed ratios in rivers do reflect exchange processes or whether additional mechanisms need to be included.

#### 4. Conclusions

We have assessed nutrient delivery from the GBR catchments to the Reef using spatial nutrient budgets. The bulk of the nutrient load is transported by suspended sediment derived from hillslope erosion. Dissolved inputs are locally significant, particular in the Wet Tropics basins. The modelled budgets predict that 63% of TN and 50% of TP are exported to the coast, and the bulk of this comes from small coastal catchments.

The spatial framework used in this study can help identify individual catchments that may contribute to exports. This will enable limited rehabilitation funding to be targeted to a relatively small proportion of the GBR catchment. Reducing hillslope erosion should be a priority, particularly in small coastal catchments and areas with high soil nutrient concentrations. Scenario modelling suggests that significant reductions in DIN export could be achieved by reducing fertiliser applications.

ANNEX, the nutrient module of SedNet, has greater uncertainty in predictions than the sediment model because of the greater complexity of several nutrient forms, transformations and losses during transport and fewer measurements of each process on which to derive empirical or conceptual models. Measurements are needed of nutrient processing in rivers so that they can be used in large-scale modelling. Only then can the terms of the budgets be balanced independently and tested against measurements of river exports.

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