The following supplement accompanies the article

Modelling ecological change over half a century in a subtropical estuary: impacts of climate change, land-use, urbanization and freshwater extraction

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Supplement. Estimating sediment and nutrient loads from sub-catchments

The most useful dataset for estimating loads was that of Eyre (1998b), which has been used here to demonstrate that the concentration of total suspended solids (TSS) at the top of the estuary was approximately proportional to the river discharge into the estuary (Fig. S1A). This is a particular instance of the general log discharge-concentration regression relationship identified in other systems (Letcher et al. 2002, Drewry et al. 2009). The flux (F) of TSS was therefore proportional to the square of the river discharge (D) rate:

$$F_{\mathrm{TSS}} = c_1 D^2, \quad (D < 2000 \text{ m}^3 \text{ s}^{-1}) \qquad \text{(S1a)}$$

where $c_1 = 0.105$ g m^{-6} s is an empirical constant. For discharge rates exceeding 2000 m^3 s^{-1} there was considerable variability in TSS, but no consistent trend. Under these conditions daily averaged TSS at the top of the estuary was assumed to plateau at 210 g m^{-3}, implying that:

$$F_{\mathrm{TSS}} = c_2 D, \quad (D \geq 2000 \text{ m}^3 \text{ s}^{-1}) \qquad \text{(S1b)}$$

where $c_2 = 210$ g m^{-3}. This was considered to be an adequate representation given that little photosynthesis would be expected to occur in the estuary under these highly turbid conditions. Applying Eq. (S1) to the discharge time series for the duration of 1996 gave an annual load at the top of the estuary of 415 thousand tonnes or about half of the total export from the mouth in the year reported by Eyre (1998b).

Unfortunately there was no information available on TSS loads from individual sub-catchments. However, since the loads were similar for all land-uses apart from cropping (Table S1), Eq. (S1) was scaled directly with the sub-catchment area not under crops, with an additional enhancement factor for the area under crops. The TSS flux in each sub-catchment, $F_{\mathrm{TSS\_sub}}$, was then given by:

$$\frac{F_{\mathrm{TSS\_sub}}}{F_{\mathrm{TSS}}} = \frac{A_{\mathrm{sub}}}{A_{\mathrm{upper}}} \chi_{\mathrm{TSS}} \qquad \text{(S2)}$$

where A_{upper} was the area of the upper catchment, A_{sub} was the area of the sub-catchment and

$$\chi_{\mathrm{TSS}}(t) = \frac{[A_{\mathrm{bush}} + A_{\mathrm{pasture}} + 30A_{\mathrm{crop\_conv}} + 3A_{\mathrm{crop\_green}} + A_{\mathrm{urban}}]}{\chi[A_{\mathrm{bush}} + A_{\mathrm{pasture}} + A_{\mathrm{crop\_conv}} + A_{\mathrm{crop\_green}} + A_{\mathrm{urban}}]} \qquad \text{(S3)}$$

The land-use coefficients in the numerator of Eq. (S3) were taken from Table S1. The denominator represented the total land area of the sub-catchment and was therefore constant. Any land-use distribution that did not include cropping gave $\chi_{\mathrm{TSS}} = 1$, while 100% conventional cropping gave the maximum value of $\chi_{\mathrm{TSS}} = 30$. This formulation assumed that the erosion characteristics of the sub-catchments surrounding the estuary were similar to the average of those for the upper catchment. While ignoring the associate differences in rainfall and landscape represented only a very rough approximation, the contribution from these sub-catchments was likely to be relatively small. One possible exception was the Clarence River Coastal catchment, where during the 1990s approximately 12000 ha or 30% of the land area was under sugarcane (with conventional harvesting), and therefore this catchment may have made a disproportionate contribution to sediment loads.

We assumed that land-use changes were linear throughout the historical period (apart from imposing the lower limit of $\chi_{\mathrm{TSS}} = 1$). While all catchments showed some increase, the Clarence River Coastal sub-catchment contribution rose from around 2% to almost 10% over the historical period due to the replacement of pasture with sugarcane plantations.

Data from the upper estuary (Eyre 1998b) was also used to test a range of empirical relationships for the dependence of dissolved inorganic nitrogen (DIN) loads into the upper estuary on the corresponding river discharge. A simple linear relationship was finally adopted:

$$F_{\mathrm{DIN}} = aD \tag{S4}$$

where F_{DIN} was the DIN flux (g s^{-1}), D was again the river discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$), and a was an empirical constant. This was equivalent to constant concentration in the river discharge, which was again a form of the general log discharge-concentration regression relationship (Letcher et al. 2002, Drewry et al. 2009). Fitting 1996 monthly nutrient load data reported by Eyre (1998b) for $D < 100\ \mathrm{m}^3\ \mathrm{s}^{-1}$ gave $a = 0.042\ \mathrm{g\ m}^{-3}$ with a mean error of 84% (Fig. S1B). Earlier data summarising nutrient concentrations in terms of discharge regimes were also consistent with this relationship (also shown in Fig. S1B). Limited data from higher discharge rates (Eyre 1998b) suggested that the response became nonlinear under flood conditions. However, nonlinear models yielded a poorer fit at low discharge rates (when primary productivity was most likely to the nutrient limited) and, in the model, tended to generate excessive nutrient concentrations downstream.

The partitioning of DIN in the upper estuary based on the data of Eyre (1998b) was $[\mathrm{NO_x}]/[\mathrm{NH_4}] = 2.0 \pm 0.6$. (mean ± SD) Data from earlier years (Williams 1987) yielded a similar estimate of 1.7 ± 0.9 (ignoring one anomalously low ammonium reading under medium flow conditions). For consistency we used the Eyre (1998b) data, so that the ammonium flux was set at $0.33F_{\mathrm{DIN}}$, and the combined nitrate and nitrite flux was set at $0.67F_{\mathrm{DIN}}$.

While most of the DIN entering the Clarence River Estuary arrives via the upper estuary, approximately 22% is derived from the local sub-catchments (Baginska et al. 2004). Since very limited data was available for the smaller tributaries, an alternative approach was required to estimate their nutrient inputs. Average annual total nitrogen loads were available for each sub-catchment from model estimates based on data collected from 1990 to 2002 (Baginska et al. 2004). We assumed that DIN loads from the sub-catchments followed the same proportions as the total nitrogen loads. We further assumed that Eq. (S4) holds for each sub-catchment after being scaled down in proportion to the total nitrogen loads. The DIN flux in each sub-catchment, $F_{\mathrm{DIN\_sub}}$, was then given by:

$$\frac{F_{\mathrm{DIN\_sub}}}{F_{\mathrm{DIN}}} = \frac{TN_{\mathrm{sub}}}{TN}\chi_{\mathrm{DIN}} \tag{S5}$$

where TN was the average total nitrogen load to the upper estuary and TN_{sub} was the average total nitrogen load from the sub-catchment (Table S2). The land-use factor $\chi_{\mathrm{DIN}}(t)$ took into account that TN_{sub} was estimated by Baginska et al. (2004) based on land-use distributions in the 1990s and that these distributions were significantly different in other decades. The fraction of the total DIN flux into the estuarine system from each catchment was then:

$$F_{\mathrm{DIN\%}} = \frac{(F_{\mathrm{DIN\_sub}}/F_{\mathrm{DIN}})}{1+\sum\limits_{\mathrm{sub}}(F_{\mathrm{DIN\_sub}}/F_{\mathrm{DIN}})} \tag{S6}$$

Estimates of χ_{DIN} can be made on the basis of land-use dependent export coefficients (mass of substance generated per unit land area per unit time), which have been estimated for a number of catchments in New South Wales (NSW) (Young et al. 1996, Baginska et al. 2004) and Queensland (Young et al. 1996, Brodie and Mitchell 2005). Export coefficient estimates for total nitrogen can easily vary by a factor of 2 or 3 between catchments due to differences in catchment characteristics and data availability. However, their ratios are generally much more consistent across catchments (within 50%). Ratios consistent with the studies referenced above are listed in Table S1. It was also assumed that the export coefficient ratios for DIN increase as total nitrogen ratios to the power of 1.5, consistent with the finding from Harris (2001) that, in NSW coastal estuaries, the proportion of total nitrogen in the form of DIN was higher for land-uses with larger total nitrogen loads. Applying the export coefficient ratios from Table S1 implied:

$$\chi_{\mathrm{DIN}}(t) = \frac{[A_{\mathrm{bush}} + 3A_{\mathrm{pasture}} + 90A_{\mathrm{crop\_conv}} + 8A_{\mathrm{crop\_green}} + 42A_{\mathrm{urban}}]_t}{[A_{\mathrm{bush}} + 3A_{\mathrm{pasture}} + 90A_{\mathrm{crop\_conv}} + 8A_{\mathrm{crop\_green}} + 42A_{\mathrm{urban}}]_{1996}} \tag{S7}$$

where the symbols for relative areas of each land-use are defined in Table S1. By definition, $\chi_{\mathrm{DIN}}(1996) = 1$, with 1996 being chosen as the reference year because of the relatively large quantity of nutrient data collected in that year.

Historical land-use data were available from 1942, the 1960s, 1989 and 2005. The 1989 and 2005 datasets were very similar and were averaged to estimate 1996 values used in Eq. (S7). While there were major gaps in the 1942 data, the 1960s data was more comprehensive. With only 2 relatively reliable points (1965 and 1996), we assumed that χ_{DIN} changed linearly throughout the historical period (1950–2004). A further constraint on χ_{DIN} was that it could not fall below the value given by Eq. (S7) when the entire area was assumed to be bushland (potentially relevant when projecting back in time). In the case of the Clarence River Coastal sub-catchment, there was sufficient data from 1942 to set a lower limit above this minimum ($\chi_{\mathrm{DIN}} = 0.198$).

The percentage of DIN from each of the sub-catchments estimated from Eqs. (S4) to (S7) is provided in Table S2 for the years 1965 and 1996. While all sub-catchments showed some increase in relative load, the largest increases (>100%) occurred in the Wooloweyah Lagoon sub-catchment (clearing in the southern part of the sub-catchment) and Clarence River Coastal sub-catchment (replacement of pasture with sugarcane plantations).

Table S1. Ratio of export coefficients relative to that of bushland and unimproved pasture based on nutrient export coefficients from the nearby Tweed and Richmond River catchments (Baginska et al. 2004) and total suspended solids (TSS) export coefficients from the Johnstone River catchment in Queensland (Brodie & Mitchell 2005). These are largely consistent with earlier data from Young et al. (1996)

	Total N	DIN	TSS	Symbol for area
Bushland or unimproved pasture	1	1	1	A_{bush}
Improved pasture	2	3	1	A_{pasture}
Cropping – conventional harvesting	20	90	30[a]	$A_{\mathrm{crop\_conv}}$
Cropping – green harvesting[b]	4	8	3	$A_{\mathrm{crop\_green}}$
Urban[c]	12	42	1	A_{urban}

[a] Estimate based on experience in Queensland catchments suggesting an order of magnitude difference between sediment inputs from conventional and green harvesting (Rayment 2003)

[b] Harvesting green sugarcane with trash blanketing (GCTB) and minimum tillage – values estimated from Brodie & Mitchell (2005)

[c] A value based on medium density development was adopted because there are no significant high density urban developments in the Clarence Valley and loads from low density development were likely to be enhanced by the widespread use of septic systems

Table S2. Total nitrogen loads (*TN*) for each sub-catchment from Baginska et al. (2004) and estimated percentage of DIN flux ($F_{\mathrm{DIN\%}}$) from each sub-catchment in 1965 and 1996 (the remainder arriving from the upper reaches via the main river channel)

Subcatchment	**TN_{sub} (kg yr^{-1})**	**$F_{\mathrm{DIN\%}}$ (1965)**	**$F_{\mathrm{DIN\%}}$ (1996)**	**$\Delta F_{\mathrm{DIN\%}}$ (%)**
Coldstream Creek	12839	1.29	2.33	81
Lower Orara River	14129	2.37	2.56	8
Swan Creek	6842	0.62	1.24	100
Clarence Tidal Pool	9300	1.43	1.69	18
Alumy Creek	3103	0.52	0.56	8
Shark Creek	7141	0.87	1.29	48
Clarence Coastal	27358	2.23	4.95	122
Stockyard Creek	10270	1.71	1.86	9
Sportsman Creek	13553	1.98	2.45	24
Wooloweyah Lagoon	4556	0.36	0.82	128
The Broadwater	6228	0.88	1.13	28
Esk River	13915	1.78	2.51	41
Total	129234	16.04	23.40	46

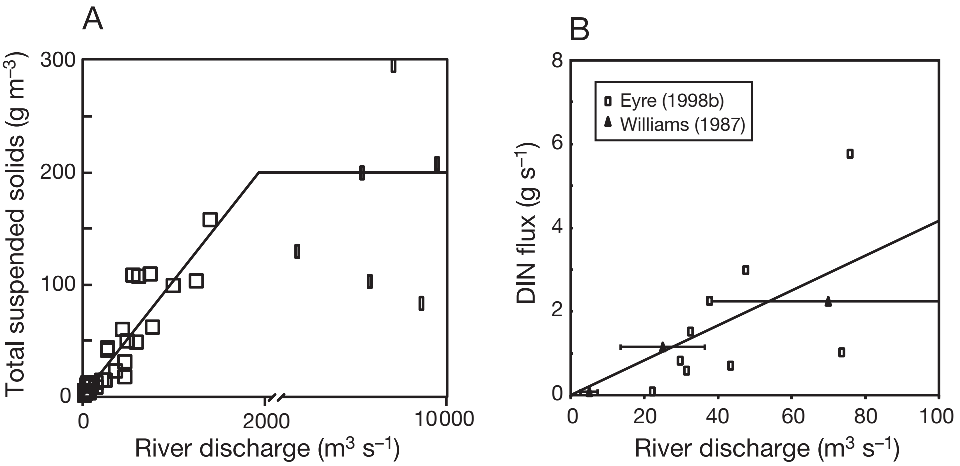

Fig. S1. (A) Total suspended solids (TSS) measured near the upstream boundary of the model plotted against river discharge during 1996 from Appendix 2 in Eyre (1998b). The linear fit (for river discharge <2000 m^3 s^{-1}) corresponds to TSS = 0.105 F_{water} where TSS is expressed in units of g m^{-3} and F in m^3 s^{-1} ($R^2 = 0.83$). TSS was lagged by one day to allow for differences in the measurement locations of TSS and flow. The values for higher river discharges were recorded in the Stockyard Creek sub-catchment and helped set a nominal plateau concentration for TSS inputs in the model. (B) Dissolved inorganic nitrogen flux (nitrate and ammonia) measured in the upper estuary plotted against flow during 1996 from Eyre (1998b). The line is Eq. (S4) with a = 0.042 g m^{-3}. Flux estimates derived from earlier data (Williams 1987) are also consistent with the empirical fit

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