Localized erosion affects national carbon budget

Durelle T. Scott,[1,2] W. Troy Baisden,[1] Rob Davies-Colley,[3] Basil Gomez,[4] D. Murray Hicks,[5] Michael J. Page,[1] Nicholas J. Preston,[1,6] Noel A. Trustrum,[1,7] Kevin R. Tate,[1] and Ross A. Woods[5]

Received 13 September 2005; revised 11 November 2005; accepted 16 November 2005; published 11 January 2006.

[1] Small mountainous rivers discharge disproportionate amounts of sediment and carbon to the Earth's oceans. Our New Zealand data demonstrates that localized erosion plays a greater role in C budgets than has been recognized in national and global studies. We estimate that New Zealand's rivers export 4 ± 1 Mg C km^{-2} yr^{-1} of dissolved organic carbon (DOC) and 10 ± 3 Mg C km^{-2} yr^{-1} of particulate organic carbon (POC) (2 and 6 times the global average), which is equivalent to 40% of New Zealand's fossil fuel emissions. Under intact native vegetation in mountain-belt hot spots, POC export greatly exceeds CO_2 consumption from mineral weathering. Moreover, deforestation of fertile steepland greatly accelerates POC loss, evidenced by 1.7% of New Zealand's land area which generates 20% of exported POC. Thus, localized erosion deserves increased attention in C budgets and accounting. **Citation:** Scott, D. T., W. T. Baisden, R. Davies-Colley, B. Gomez, D. M. Hicks, M. J. Page, N. J. Preston, N. A. Trustrum, K. R. Tate, and R. A. Woods (2006), Localized erosion affects national carbon budget, *Geophys. Res. Lett.*, *33*, L01402, doi:10.1029/2005GL024644.

1. Introduction

[2] Rivers play an important role in the transport of C between land and the atmosphere, oceans and sediments [*Ludwig et al.*, 1996; *Mayorga et al.*, 2005; *Richey et al.*, 2002; *Stallard*, 1998]. The Marrakech Accords do not require that human-induced riverine C fluxes be accounted for under Articles 3.3 or 3.4 of the Kyoto Protocol during 2008–2012, yet more complete C accounting regimes could include riverine C transport where changes in land-use and management influence net C balance. The possibility of high C mobilization through erosion has particular relevance for countries around the tectonically active Pacific Rim, which contribute as much as 35% of the global sediment and POC flux to the oceans from only 3% of Earth's land area [*Kao and Liu*, 1997; *Lyons et al.*, 2002; *Milliman and Syvitski*, 1992]. The greatest POC fluxes occur in areas where rapid uplift exposes soft or highly fractured rocks to frequent large storms [*Gomez et al.*, 2003; *Hovius et al.*, 2000; *Kao et al.*, 2003]. Over geologic timescales (~10^6 yr), POC burial around the Pacific Rim may also influence paleo-atmospheric CO_2 levels [*Lyons et al.*, 2002], by helping to determine the mass of CO_2 contained in the biosphere/atmosphere/hydrosphere system. Tectonic uplift drives CO_2 consumption by exposing new crust to mineral weathering and facilitating subsequent oceanic carbonate burial [*Berner et al.*, 1983], as well as by contributing nutrients that influence the rates of oceanic production and burial of phytoplankton-derived organic C [*Berner*, 2003]. A strong relationship exists between tectonism and paleo-atmospheric CO_2 [*Berner*, 2003; *Berner et al.*, 1983]; however, high rates of POC delivery from the Pacific Rim [*Gomez et al.*, 2003; *Kao and Liu*, 1997; *Lyons et al.*, 2002] suggest there is a need to evaluate the effect preservation of buried organic C associated with largely unweathered terrigenous sediment derived from young mountain belts [*France-Lanord and Derry*, 1997] has on the global C-budget.

[3] To address these questions about the role of rivers in C budgets, we quantified riverine C exports from New Zealand (267,304 km^2), which lies on the active boundary of two major tectonic plates. We estimated long-term riverine POC and dissolved organic C (DOC) yields from 47 and 44 catchments, respectively, representing ~45% of New Zealand's land area. The hydrophysical characteristics of these catchments were used as a basis for extrapolating C yields across the entire country (Table 1).

2. Data Collection and Model Description

[4] Samples were collected for 1 year at monthly intervals for DOC, POC, and total suspended sediment (TSS) concentrations from 44 National Institute of Water and Atmospheric Research (NIWA) water quality stations within New Zealand [*Smith et al.*, 1996]. These stations have a 12-year record of monthly water-quality measurements, and provide good spatial coverage of the entire country. High-flow sampling was also performed within the Manawatu, Waipaoa, and Motueka catchments, and the Waipaoa dataset was augmented by previous research [*Gomez et al.*, 2003].

[5] Annual POC yields were estimated using 2 approaches. The 1st method applied the relationship between %C and TSS (model 1a and 2) in conjunction with 20-year daily TSS records generated from sediment rating curves [*Hicks et al.*, 2004]. The 2nd approach applied the relationship between %C and total organic nitrogen (TON)/Turbidity for each region (model 1b) in conjunction with flow and sediment 20-year records. For DOC, DOC concentrations for each station from the 1-year sampling

[1] Landcare Research, Palmerston North, New Zealand.
[2] Now at Department of Geosciences, University of Nebraska-Lincoln, Lincoln, Nebraska, USA.
[3] National Institute of Water and Atmospheric Research, Hamilton, New Zealand.
[4] Geomorphology Laboratory, Indiana State University, Terre Haute, Indiana, USA.
[5] National Institute of Water and Atmospheric Research, Christchurch, New Zealand.
[6] Now at School of Earth Sciences, Victoria University, Wellington, New Zealand.
[7] Now at Institute of Geologic and Nuclear Sciences, Lower Hutt, New Zealand.

0094-8276/06/2005GL024644$05.00

Table 1. Models for Scaling POC and DOC Export

Model	Yield	Approach[a]
1a, 1b	POC	$Y_{POC} = \beta + \alpha_1(MAP) + \alpha_2(ET_{731} + ET_{732}) + \alpha_3(ET_{731} + ET_{732}) \times (MAP)$
2	POC	$Y_{POC} = (\alpha_1 + \alpha_2 ET_{731} + \alpha_3 ET_{732}) \times MAP^{1.7}$
3	DOC	$\log_{10} Y_{POC} = \beta + \alpha_1 \log_{10}(MAP) + \alpha_2 \log_{10}(MAS) + \alpha_3 \log_{10}(MAT) + \alpha_4 \log_{10}(slope) + (\log_{10} MAP)^2$

[a]Values of POC and DOC from 47 river stations were extrapolated to the national scale. Y_{POC} and Y_{DOC} represent the POC and DOC yield (Mg C km^{-2} y^{-1}), MAP is mean annual precipitation, MAS is mean annual solar radiation, MAT is mean annual temperature, slope is obtained from a 25-m digital elevation model (DEM), α and β are regression parameters, and ET_{731} and ET_{732} represent the proportion of area in landslide and earth flow/gully susceptible terrains, respectively. Models 1a and 1b differ in using %C in TSS and TON/Turbidity, respectively, as surrogate variables for estimating the yield at the station.

campaign were extrapolated across the 12-year dataset using filtrate absorption coefficients at 340 nm and a regional coefficient. DOC yields were then estimated at each station using the relationship between DOC concentration and discharge across the 20-year flow record.

[6] The estimated DOC yields from each station were then used to build a log-linear regression model to extrapolate DOC yields across the landscape. Several variables (e.g., mean annual temperature (MAT), mean annual precipitation (MAP), mean annual solar radiation (MAS), soil C content, P-retention, catchment slope) were then tested to develop a spatial prediction model. Significant variables included MAP, MAT, MAS and slope.

[7] For POC, 3 models (2 linear, 1 power-law) (Table 1) were applied to the dataset to obtain a statistical relationship suitable for scaling the variability to produce a national POC estimate. MAP was the primary variable in all 3 models, and a geomorphological variable was required to capture the high POC fluxes within the East Cape region of New Zealand, where large gully systems provide sediment and organic C to the river network.

[8] The spatial DOC & POC models were then applied across the landscape at 1-km grid resolution to estimate New Zealand's DOC & POC yields. Predicted and surrogate yields were largely in agreement for each model (Figure 1). The predicted POC yields between models 1a, 1b, and 2 provided a range in POC yield, and were used to generate a standard deviation.

3. Results

[9] We estimate that New Zealand's rivers discharge 2.7 ± 1.0 Tg C yr^{-1} of POC (10 ± 3 Mg C km^{-2} yr^{-1}) and 1.1 ± 0.3 Tg C yr^{-1} (4 ± 1 Mg C km^{-2} yr^{-1}) of DOC to the ocean. These yields are 2 and 6 times the global average POC [*Ludwig et al.*, 1996; *Meybeck*, 1993; *Stallard*, 1998] and DOC [*Aitkenhead and McDowell*, 2000; *Ludwig et al.*, 1996] fluxes, respectively, distinguishing New Zealand's tectonically active setting from typical continental environments. The total riverine POC yield is a C flux equivalent to 30% of the country's total 2002 fossil fuel CO_2 emissions; globally this ratio is less than 5%. These results demonstrate that, compared with most other land masses, New Zealand's riverine POC flux is relatively more important to both the global C cycle and aspects of C accounting that relate land-use change and forestry to industrial activities.

[10] Maps of POC and DOC (Figure 2) yield indicate that, just as there are hot spots of riverine C export on a global scale [*Lyons et al.*, 2002], local hot spots of POC and DOC yield exist within New Zealand, characterized by a 10,000-fold range in POC yield and a 1000-fold range in DOC yield. We define a threshold of 20 Mg C km^{-2} y^{-1} as a change in soil organic C stock of similar magnitude to other land-use changes relevant to the global C budget [*Tate et al.*, 2003]. About 3% of New Zealand's land area has a DOC yield exceeding this threshold, and this area accounts for 25% of New Zealand's total DOC yield to the ocean. Similarly, 9% of New Zealand has a POC yield in excess of

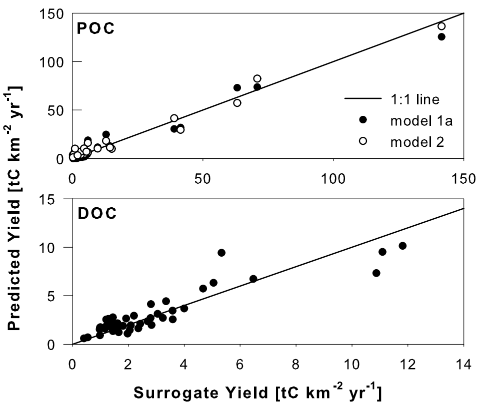

Figure 1. Comparison between modelled and measured POC and DOC yields for monitored catchments.

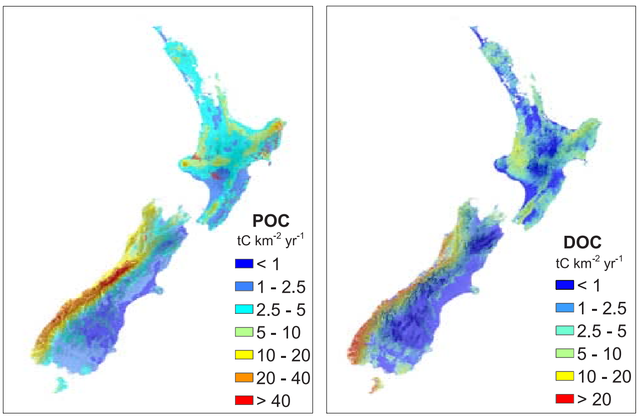

Figure 2. Particulate and dissolved organic carbon yields spatially distributed across New Zealand based on data for 47 and 44 stations, respectively. POC yields were estimated by applying a power-model that used mean annual precipitation and an adjustment for cells containing highly erodible terrain. DOC yields were estimated by applying a log-linear model that used mean annual precipitation, mean annual solar radiation, mean annual temperature, and slope.

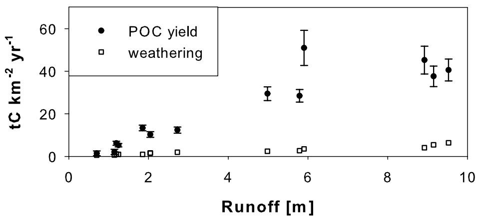

Figure 3. Comparison between CO_2 consumption due to weathering and POC yields highlight the greater POC yields from this region. The CO_2 consumption rates are from ref (26), and POC export is the mean and standard deviation of models 1a, 1b and 2 in Table 1.

the threshold, accounting for 65% of total POC export to the ocean.

4. Discussion

[11] These POC and DOC 'hot spot' terrains are primarily blanketed in natural vegetation cover – mainly primary forests, secondary forests, subalpine tussock grasslands and alpine herbfields. POC and DOC fluxes from these areas can largely be considered representative of conditions prior to human disturbance. The principal exception is steep (typically >26°) terrain representing 1.7% of New Zealand's land area, typically underlain by soft mudstones and crushed sedimentary rocks [*Jessen et al.*, 1999; *Page et al.*, 2004]. These soft-rock steeplands have a specific yield of 110 Mg C km^{-2} y^{-1}, in agreement with previous estimates [*Page et al.*, 2004], and deliver 20% of New Zealand's POC to the ocean. Over half this terrain is in pastoral agriculture, and a large portion of the remainder once cleared for pasture has been recently reforested with indigenous or exotic species. Evidence that erosion rates in this terrain are elevated in pastoral agriculture relative to forest vegetation [*Blaschke et al.*, 1992] suggests the associated C fluxes can be considered relevant to Articles 3.3 and 3.4 of the Kyoto Protocol because they can be considered 'human-induced'. Determining the fate of this large human-induced POC flux is therefore highly relevant to New Zealand's Kyoto commitments and policies.

[12] Understanding the specific greenhouse gas implications of POC and DOC losses can be difficult because traditional land-atmosphere C exchange measurements only record losses of CO_2 from the ecosystem, while inventory-based methods will not record C losses if the soil C pool recovers before the subsequent measurement. The net impact of POC and DOC on land-atmosphere C exchange depends on the proportion of the C subsequently oxidized and returned to the atmosphere as CO_2.

[13] Carbon lost from terrestrial ecosystems to rivers as DOC and DIC is likely to be returned to the atmosphere as CO_2 through a combination of photo-oxidation, heterotrophic decomposition [*Amon and Benner*, 1996] and evasion [*Richey et al.*, 2002], causing potential errors in terrestrial land-atmosphere CO_2 exchange measurements. However, POC delivered to the ocean by high-yielding rivers is more likely to be protected from oxidation by rapid burial [*Sommerfield et al.*, 1999], which also hinders biological degradation associated with bioturbation [*France-Lanord and Derry*, 1997]. Thus, high POC export causes errors in both land-atmosphere CO_2 exchange and C inventory, which can be further confounded by recovery of soil C stocks on eroded land [*Harden et al.*, 1999; *Stallard*, 1998]. When combined, POC export and burial therefore paradoxically represent a C sink.

[14] The significance of POC export and burial goes beyond present-day C budgets. If burial protects a significant fraction of POC from oxidation, the relative importance of POC burial versus CO_2 consumption by weathering must be re-examined vis-à-vis paleo-atmospheric CO_2 levels. Figure 3 compares recently observed rates of CO_2 consumption by weathering [*Jacobson and Blum*, 2003] with map-based POC yields derived using approaches 1a, 1b and 2 (Table 1). The weathering rates plotted in Figure 3 describe CO_2 delivery to rivers from both silicate and carbonate weathering rather than the rate of $CaCO_3$ burial. Thus, the protection of even a small fraction of POC by burial is likely to represent a greater sink for CO_2 than weathering consumption. These results therefore lend strong independent support to previous suggestions that mountain building primarily influences atmospheric CO_2 through POC burial, rather than silicate weathering [*France-Lanord and Derry*, 1997]. The data in Figure 3 can be assumed representative of the geologic past because POC delivered from high-yielding areas of South Island does not result from human land-use change.

5. Concluding Statements

[15] We conclude that mountain building on New Zealand's high-standing islands has strong implications for C cycling on the timescales of land-use change and C accounting under the UNFCCC and Kyoto Protocol, as well as on geologic timescales. In the case of geological erosion in nearly pristine mountain belts such as the Southern Alps, our estimates and those made previously [*Lyons et al.*, 2002] are based on scarce data, suggesting more measurements are needed for high-yielding catchments. On timescales where 'human-induced' changes to the C cycle are a concern, further research should reveal the degree to which reforestation reduces the erosion and subsequent oxidation of POC–a critical aspect of confirming or refuting the suggestion that erosive steeplands should be a global priority for tree-planting because of the double benefit of carbon sequestration and erosion reduction. Critical uncertainties in the net greenhouse gas implications of erosion remain, including the need to better quantify the fraction of POC buried in sediments that is oxidized, the contribution of sediments to methane and nitrous oxide production, as well as the rate of soil C recovery on eroded land. Nations with hot spots of erosion will need to be aware of the uncertainties erosion introduces into the fair and equitable trading of C credits for afforestation, reforestation, and land management under the Kyoto Protocol, as these nations finalize policies to devolve C credits to individual land owners and projects.

[16] **Acknowledgments.** We thank H. Brackley, M. D'Ath and B. Rosser for technical assistance; R.H. Wilde for providing soil data; M. Jessen, I. Lynn and L Basher for assistance with terrain classification; J. Leathwick for climate data; Regional Councils for support of the stream gauging; and K. Walter for assistance with river flow data. Landcare

Research provided primary funding. Additional funding from NZ NSOF to RAW, DMH, and WTB. BG acknowledges support from National Science Foundation Grant BCS-0317570.

References

Aitkenhead, J. A., and W. H. McDowell (2000), Soil C: N ratio as a predictor of annual riverine DOC flux at local and global scales, *Global Biogeochem. Cycles*, *14*, 127–138.

Amon, R., and R. Benner (1996), Photochemical and microbial consumption of dissolved organic carbon and dissolved oxygen in the Amazon River system, *Geochim. Cosmochim. Acta*, *60*, 1783–1792.

Berner, R. A. (2003), The long-term carbon cycle, fossil fuels and atmospheric composition, *Nature*, *426*, 323–326.

Berner, R. A., A. C. Lasaga, and R. M. Garrels (1983), The carbonate-silicate geochemical cycle and its effect on atmospheric carbon-dioxide over the past 100 million years, *Am. J. Sci.*, *283*, 641–683.

Blaschke, P. M., N. A. Trustrum, and R. C. DeRose (1992), Ecosystem processes and sustainable land use in New Zealand steeplands, *Agric. Ecosyst. Environ.*, *41*, 153–178.

France-Lanord, C., and L. A. Derry (1997), Organic carbon burial forcing of the carbon cycle from Himalayan erosion, *Nature*, *390*, 65–67.

Gomez, B., N. A. Trustrum, D. M. Hicks, K. M. Rogers, M. J. Page, and K. R. Tate (2003), Production, storage, and output of particulate organic carbon: Waipaoa River basin, New Zealand, *Water Resour. Res.*, *39*(6), 1161, doi:10.1029/2002WR001619.

Harden, J. W., J. M. Sharpe, W. J. Parton, D. S. Ojima, T. L. Fries, T. G. Huntington, and S. M. Dabney (1999), Dynamic replacement and loss of soil carbon on eroding cropland, *Global Biogeochem. Cycles*, *13*, 885–901.

Hicks, D. M., J. M. Quinn, and N. Trustrum (2004), Stream sediment load and organic matter, in *Freshwaters of New Zealand*, edited by J. Harding et al., pp. 12.11–12.16, N. Z. Hydrol. Soc., Christchurch.

Hovius, N., C. P. Stark, H. T. Chu, and J. C. Lin (2000), Supply and removal of sediment in a landslide-dominated mountain belt: Central Range, Taiwan, *J. Geol.*, *108*, 73–89.

Jacobson, A. D., and J. D. Blum (2003), Relationship between mechanical erosion and atmospheric CO_2 consumption in the New Zealand Southern Alps, *Geology*, *31*, 865–868.

Jessen, M. R., T. F. Crippen, M. J. Page, W. C. Rijkse, G. R. Harmsworth, and M. McLeod (1999). *Land Use Capability Classification of the Gisborne-East Coast Region*, *Landcare Res. Sci. Ser.*, vol. 12, 213 pp., Manaaki Whenua Press, Lincoln, N. Z.

Kao, S. J., and K. K. Liu (1997), Fluxes of dissolved and nonfossil particulate organic carbon from an Oceania small river (Lanyang Hsi) in Taiwan, *Biogeochemistry*, *39*, 255–269.

Kao, S. J., F. J. Lin, and K. K. Liu (2003), Organic carbon and nitrogen contents and their isotopic compositions in surficial sediments from the East China Sea shelf and the southern Okinawa Trough, *Deep Sea Res. Part II*, *50*, 1203–1217.

Ludwig, W., J. L. Probst, and S. Kempe (1996), Predicting the oceanic input of organic carbon by continental erosion, *Global Biogeochem. Cycles*, *10*, 23–41.

Lyons, W. B., C. A. Nezat, A. E. Carey, and D. M. Hicks (2002), Organic carbon fluxes to the ocean from high-standing islands, *Geology*, *30*, 443–446.

Mayorga, E., A. K. Aufdenkampe, C. A. Masiello, A. V. Krusche, J. I. Hedges, P. D. Quay, J. E. Richey, and T. A. Brown (2005), Young organic matter as a source of carbon dioxide outgassing from Amazonian rivers, *436*, 538–541.

Meybeck, M. (1993), Riverine transport of atmospheric carbon—Sources, global typology and budget, *Water Air Soil Pollut.*, *70*, 443–463.

Milliman, J. D., and J. P. M. Syvitski (1992), Geomorphic tectonic control of sediment discharge to the ocean—The importance of small mountainous rivers, *J. Geol.*, *100*, 525–544.

Page, M. J., N. A. Trustrum, H. Brackley, and W. T. Baisden (2004), Erosion-related soil carbon fluxes in a pastoral steepland catchment, New Zealand, *Agric. Ecosyst. Environ.*, *103*, 561–579.

Richey, J. E., J. M. Melack, A. K. Aufdenkampe, V. M. Ballester, and L. L. Hess (2002), Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2, *Nature*, *416*, 617–619.

Smith, D. G., G. B. McBride, G. G. Bryers, J. Wisse, and D. F. J. Mink (1996), Trends in New Zealand's National River Water Quality Network, *N. Z. J. Mar. Freshwater Res.*, *30*, 485–500.

Sommerfield, C. K., C. A. Nittrouer, and C. R. Alexander (1999), Be-7 as a tracer of flood sedimentation on the northern California continental margin, *Cont. Shelf Res.*, *19*, 335–361.

Stallard, R. F. (1998), Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial, *Global Biogeochem. Cycles*, *12*, 231–257.

Tate, K. R., N. A. Scott, S. Saggar, D. J. Giltrap, W. T. Baisden, P. F. Newsome, C. M. Trotter, M. R. Davis, and R. H. Wilde (2003), Land-use change alters New Zealand's terrestrial carbon budget: Reducing uncertainties associated with estimates of soil carbon change, *Tellus, Ser. B*, *55*, 364–377.

W. T. Baisden, M. J. Page, N. J. Preston, D. T. Scott, K. R. Tate, and N. A. Trustrum, Landcare Research, Private Bag 11052, Palmerston North, New Zealand. (BaisdenT@LandcareResearch.co.nz)

R. Davies-Colley, National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

B. Gomez, Geomorphology Laboratory, Indiana State University, Terre Haute, IN 47809, USA.

D. M. Hicks and R. A. Woods, National Institute of Water and Atmospheric Research, Christchurch, New Zealand.