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Short communication

Multiple indicators reveal river plume influence on sediments and benthos in a New Zealand coastal embayment

BARRIE M. FORREST
PAUL A. GILLESPIE
CHRIS D. CORNELISEN
Cawthron Institute
Private Bag 2
Nelson, New Zealand
email: barrie.forrest@cawthron.org.nz

KARYNE M. ROGERS
GNS Science
P.O. Box 31312, Lower Hutt,
Wellington, New Zealand

Abstract Multiple physico-chemical and biological indicators were used to delineate the spatial influence of the Motueka River plume on coastal surface sediments and associated biota in Tasman Bay, New Zealand. Sediments were primarily muds at nearshore sites on all transects and comprised coarser sediments at the most seaward sites in Tasman Bay. Organic carbon/nitrogen ratios, stable carbon and nitrogen isotope signatures, and certain lipid biomarkers and trace metals provided suitable indicators of terrestrial and riverine influence on subtidal sediments. Analysis of these parameters revealed a discernible catchment influence extending at least 6 km offshore in the river outwelling plume, with a pronounced signature evident at two sampling stations within approximately 2 km of the Motueka River mouth. At these two nearshore sites, nickel and chromium from natural upper-catchment sources were present at concentrations greatly exceeding sediment quality thresholds for probable ecological effects. The infaunal assemblage at these sites comprised low densities of a few opportunistic taxa, with the spatial distribution of organisms strongly correlated with trace metal concentrations. Although a causal relationship with trace metals is possible, other unmeasured influences such as gradients of salinity, depth and physical disturbance could conceivably be the primary drivers of the biological pattern. By contrast with the effects on infauna, analyses of stable carbon and nitrogen isotopes and trace metals in epibenthic shellfish did not reveal any evidence of a direct terrestrial or riverine influence. Overall, the results from this work indicate a relatively localised river plume effect on subtidal sediments and the associated infaunal assemblage. However, because previous work has shown that the river plume can extend tens of kilometres offshore during flood flows, further investigation is required to understand changes in seabed parameters within the context of spatio-temporal variation in catchment inputs and river plume discharge.

Keywords land-use effects; terrestrial organic matter; river plume; soft sediment; macrofauna; trace metals

INTRODUCTION

Coastal river plume environments are characterised by sediments, organic matter, nutrients, and trace contaminants delivered from their adjacent catchments. The quantity and quality of such materials is influenced at a range of spatial and temporal scales by variation in key factors (e.g., climatic conditions) that alter their transport and by catchment characteristics such as topography and land use (e.g., Hicks et al. 2000; Findlay et al. 2001; Justic et al. 2003; Hayward et al. 2006). In estuarine and coastal marine environments, the input of catchment-derived particulate materials via riverine point sources can have a profound effect on surface sediments and hence on the structure and function of benthic assemblages (Josefson & Conley 1997; Danovaro et al. 2000; Long et al. 2002; Lohrer et al. 2006) and associated fishery resources (Grimes 2001; Le Pape et al. 2003; Martinetto et al. 2006).

In New Zealand, much of our understanding of river plume effects on seabed habitats stems

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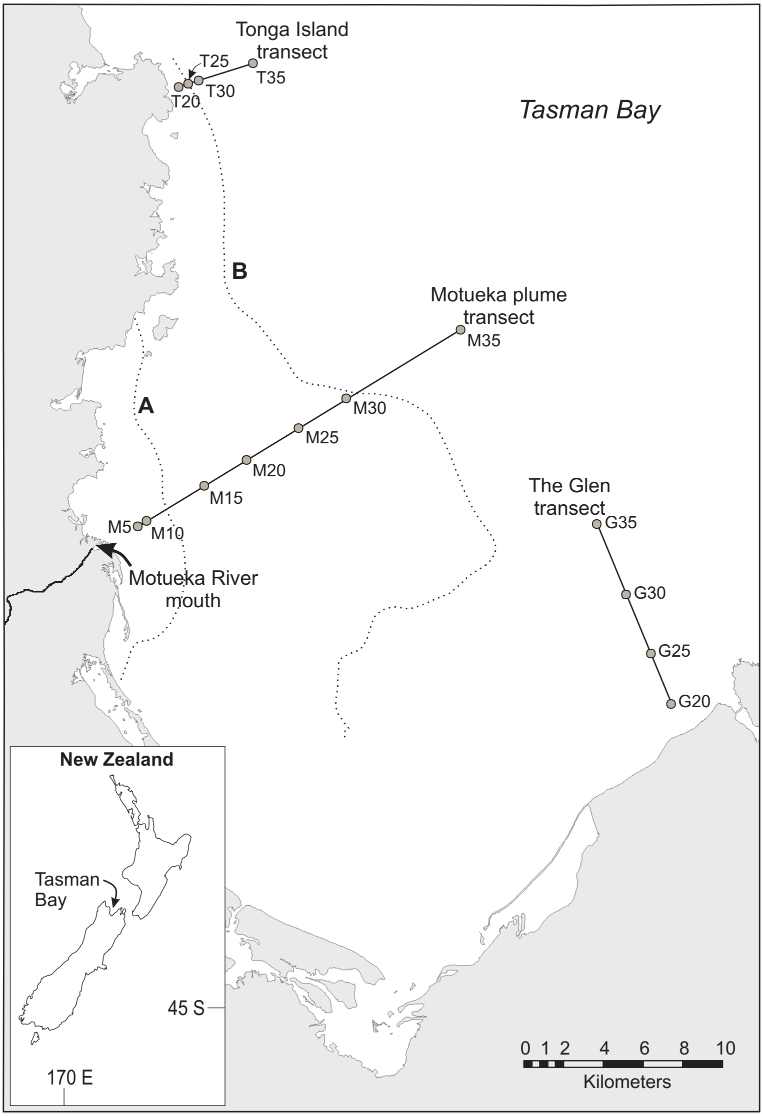

Fig. 1 Seabed transects and sites sampled in Tasman Bay, New Zealand, 20–22 April 2005. Numbers in the site codes refer to water depths from 5 m (5) to 35 m (35). Letters A and B refer to river plume boundaries (35 psu isohalines) during low flows (<18 $m^3 s^{-1}$ for 6 weeks) and moderate flood flows (210 $m^3 s^{-1}$), respectively, in the Motueka River (from Tuckey et al. 2006).

from intertidal research conducted in estuaries (e.g., Hume et al. 1991; Thrush et al. 2003). Except for a few studies of sediment transport and sedimentation effects (e.g., Lohrer et al. 2006) much less is known in New Zealand about the broader ecological influence of river outwelling plumes in situations where they impinge directly (i.e., without being buffered by an estuarine transition zone) on shallow subtidal coastal habitats. Although overseas studies reveal the potential for seabed effects across spatial scales of tens to hundreds of kilometres, they primarily reflect river systems and adjacent catchments (e.g., Mississippi River, United States; Po River, Italy) whose size is orders of magnitude larger than those in New Zealand (e.g., Danovaro et al. 2000; Justic et al. 2003; Turner et al. 2004). To understand a more typical New Zealand situation, we have initiated a programme investigating the fate of particulate organic matter and sediment-associated trace contaminants discharged into Tasman Bay, in relation to inputs from the Motueka River near Nelson (Fig. 1).

The Motueka River system (mean flow c. 59 $m^3 s^{-1}$) drains a catchment (2180 km^2 in area) comprising a variety of land uses, and contributes c. 62% of the total freshwater discharge to Tasman Bay (Basher

2003). Tasman Bay is considered representative of shallow coastal embayments in the Southern Hemisphere that are increasingly under pressure from direct exploitation and human modification of adjacent catchments (MacKenzie 2004). Terrestrial inputs from this catchment could conceivably influence sedimentary habitats in plume-affected areas and have important consequences for subtidal benthic consumers. The presence of a mineral belt in the upper Motueka River catchment (Basher 2003) is also of interest in this instance, because it provides an opportunity to evaluate the utility of associated trace metals in characterising the seabed footprint of sediments deposited from the river plume. There is also regional interest because natural catchment-sourced metals and their effects in Tasman Bay have never been quantified. In this paper, we therefore evaluate the utility of trace metals and other physico-chemical (grain size, organic content) and biochemical (C, N, $\delta^{13}C$, $\delta^{15}N$, fatty acids) indicators for delineating the spatial extent of river plume influence on surface sediments and associated biota (infauna, epibenthos), identifying measures that may be suitable for detailed investigations into river-plume dynamics.

MATERIALS AND METHODS

Sites

Subtidal sediments and associated biota were sampled in April 2005 at 15 sites in Tasman Bay along three transects (Fig. 1). Motueka River plume transect sites (M) were positioned in 5 m depth increments from the river mouth to just beyond the outer boundary of the plume (defined here as the 35 psu isohaline) under "moderate" flood flows (210 $m^3 s^{-1}$, Tuckey et al. 2006), as determined by water column investigations and hydrodynamic modelling (MacKenzie & Adamson 2004; Tuckey et al. 2006). Reference transects (beyond known riverine influences) near The Glen (G) in eastern Tasman Bay and in the Tonga Island (T) marine reserve to the north were included for comparison, but locations ≤15 m depth within these areas consisted of coarse sediments or rock and hence were not sampled.

Sediments

Three sediment grabs were taken from each site using a modified Van Veen sampler (0.1 m^2). Two sediment cores (100 mm deep) were extracted from each grab; a large core (130 mm diam.) for extraction and analysis of infauna, and a small core (63 mm diam.), from which the top 20 mm was retained for sediment analyses. Sediments collected at each site were composited into a single sample before analysis to provide an understanding of site-average conditions. Although understanding within-site variability for a given parameter is also important, the focus of the present study was on characterising broad spatial gradients.

Sediment size class fractions, from silt-clay through to gravel, were analysed gravimetrically after oven drying to constant weight at 105ºC. Bulk organic matter content was measured as % ash-free dry weight (DW) according to the weight loss of dried samples after ashing at 550°C for 2 h (modified after Luczak et al. 1997). Total nitrogen (N) and total phosphorous (P) concentrations of the sediment were measured according to standard methods (Total N, APHA 20th ed. 4500N C; Total P, ICP-MS, United States Environmental Protection Agency 200.2).

To evaluate terrestrial versus marine contributions to sediment organic matter, we determined Carbon(C)/N ratios and $\delta^{13}C$ and $\delta^{15}N$ isotope values of sediment samples as described in Rogers (1999) and Rogers et al. (2001). It was necessary to demineralise the sediments by overnight treatment of samples in 1 *M* HCl, hence % C and $\delta^{13}C$ values of sediments refers to the organic fraction only (TOC and $\delta^{13}C$ organic). Percentage N and $\delta^{15}N$ were determined on a non-demineralised fraction of the sample. All samples were analysed using a PDZ Europa Geo 20–20 Isotope Ratio Mass Spectrometer coupled to an ANCA elemental analyser to determine % N and % C, and $^{15}N/^{14}N$ and $^{13}C/^{12}C$ ratios. Data were converted to notation based on the ratio of heavy to light isotope in the sample (R*s*) relative to the standard atmospheric air for N and Vienna PeeDee Belemnite (VPDB) for C (R*std*): δ (‰) = (R*s* – R*std*) / R*std* × 1000. Precision was ± 0.1‰ for $\delta^{13}C$ and ± 0.3‰ for $\delta^{15}N$ based on two standard deviations of duplicate samples.

The "terrestrial" contribution to sediment organic matter was considered as a composite of non-marine sources including terrestrial vegetation and inter-tidal marsh vegetation, and may also include autochthonous river production. The contribution from these sources was estimated with a simple two-source mixing model, using a $\delta^{13}C$ value of –22‰ as a marine end-member based on typical overseas values for phytoplankton and particulate organic matter (e.g., table 1 in Maksymowska et al. 2000) that are also applicable to New Zealand (C.D. Cornelisen unpubl. data). A signature for terrestrial sources of C (–27‰) was established directly via concurrent sampling and analysis of river detritus and above-ground tissue of dominant vegetation (rushland and herb-field species) in the adjacent intertidal delta. To supplement the C/N ratio and isotopic analyses for source identification, profiles of dominant fatty acids within the sediment cores were obtained using gas chromatographic techniques (AOAC 2000, method 963.22), and the presence of those indicative of terrestrial source material evaluated (e.g., Canuel 2001; Shi et al. 2001; Cook et al. 2004).

A trace metal suite comprising cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), nickel (Ni), and zinc (Zn) was analysed by ICP-OES following a moderate acid digest (HNO_3/HCl) at 95°C for 30 min (United States Environmental Protection Agency 200.2 mod.; APHA 1998). Trace metal concentrations were compared with ANZECC (2000) Interim Sediment Quality Guideline low (ISQG-low) and high (ISQG-high) values, to indicate possible and probable biological effects, respectively.

Infauna and shellfish

The three large sediment cores from each site were composited into a single sample, which was sieved through a 0.5 mm mesh. The infaunal taxa within the preserved sieve residue were later identified to the lowest practical taxonomic level with the aid of a binocular microscope, and counted. To evaluate changes in infaunal community composition along the gradient of river-plume influence, a non-metric MDS ordination procedure based on the Bray-Curtis similarity measure (Primer v5.2.2) was used to describe spatial patterns in the distribution and dominance of taxa among sites, following a square-root transformation to down-weight the influence of the most dominant (Clarke & Warwick 1994). Using group average clustering (Primer v5.2.2), site groups that formed at a 60% Bray-Curtis similarity threshold were superimposed on the nMDS ordination pattern (Clarke 1993).

The procedure BioEnv (Primer v5.2.2) was used to explore the extent to which community composition patterns were related to sediment characteristics, with the degree of concordance measured using the Spearman rank correlation coefficient, ρ (Clarke & Ainsworth 1993). Before BioEnv was performed, the full sediment data set was reduced to 17 variables by: (1) using proxy variables in instances where product-moment correlation values, r, were >0.90 for pairwise contrasts; and (2) omitting variables whose concentration was less than method detection limits at all sites. The final suite consisted of standard grain size classes (very coarse sand, coarse sand, medium sand, fine sand, very fine sand, silt-clay), ash-free DW, C, N, C/N ratio, P, Cd, Ni, Zn, polyunsaturated fatty acids (PUFA), saturated fatty acids (SFA) and the PUFA/SFA ratio. Distance from the Motueka River mouth (km) was also included as a variable for the purposes of our analysis.

Epibenthic bivalves were collected from most of the sediment sampling sites for determination of $\delta^{13}C$ and $\delta^{15}N$ isotope signatures. Bivalves were chosen on the basis that they would provide a long-term integrated measure of nutritional contributions from terrestrial versus marine sources to the nearshore food web via a suspension-feeding pathway (Jennings & Warr 2003). The species taken were determined by availability, but comprised horse mussels (*Atrina zelandica*), scallops (*Pecten novaezelandiae*), and green-lipped mussels (*Perna canaliculus*), with the exception of M5 where no specimens could be found. The main adductor mussel of each specimen (n = 1–5 per site) was excised, dried, homogenised, and analysed for $\delta^{13}C$ and $\delta^{15}N$ isotope signatures as described above.

RESULTS

Sediments

Sediments were characterised by soft muds (silt and clay) throughout the study area (Fig. 2A), with the exception of the outer Motueka transect site (M35) and inner Tonga Island reference site (T20), where sands and shell hash were prevalent. Detrital material including woody debris, leaf litter, and saltmarsh vegetation was particularly notable in sieved cores from the two nearshore sites within the Motueka River plume (M5 and M10). Total sediment organic content (% ash-free DW) did not follow any obvious spatial patterns with respect to river plume and reference transect sites, but total organic C was slightly elevated at the two nearshore plume sites (Fig. 2B).

Values of $\delta^{13}C$ (–26.8 and –26.9‰) and $\delta^{15}N$ (2.6 and 3.2‰) in sediments at M5 and M10 were within the range of signatures for river detritus and dominant salt-marsh vegetation ($\delta^{13}C$ –26.3 to –28.9‰, $\delta^{15}N$ –1.55 to 3.15‰) (Fig. 2C,D). By contrast, sites further offshore in the plume than M20 (>8 km from the river mouth) and elsewhere in Tasman Bay had $\delta^{13}C$ and $\delta^{15}N$ signatures that were comparatively enriched in both ^{13}C and ^{15}N. Mixing model calculations suggested a terrestrial contribution to sediment organic matter of >95% at

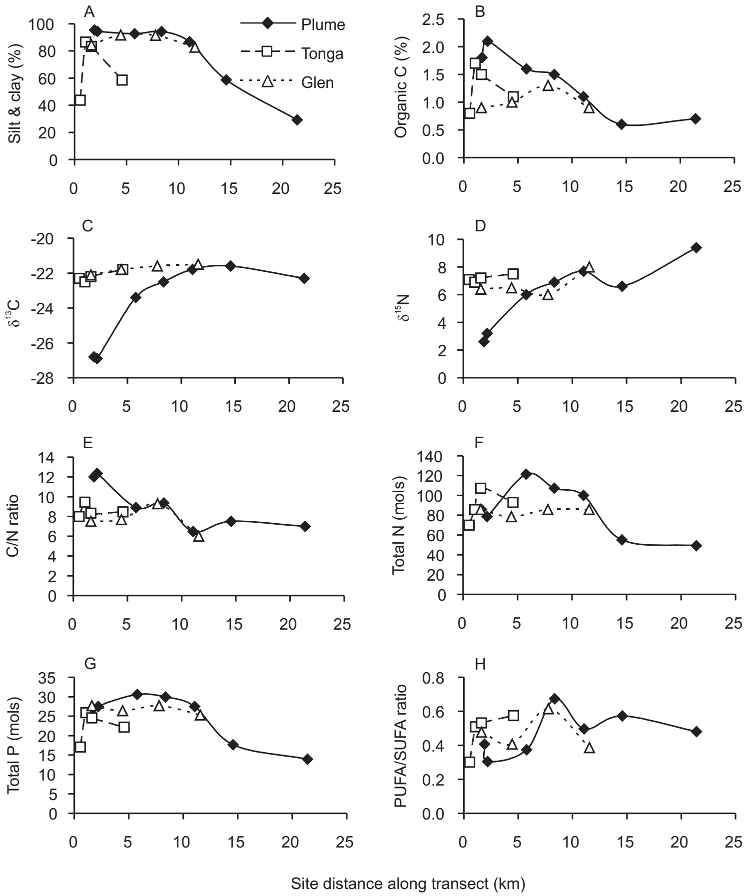

Fig. 2 Spatial patterns of physico-chemical indicators in sediments (**A**, silt-clay; **B**, organic carbon; **C**, δ^{13}C; **D**, δ^{15}N; **E**, C/N ratio; **F**, total N; **G**, total P; **H**, fatty acids—polyunsaturated fatty acids/saturated fatty acids ratio) along the three sampling transects (Motueka River plume, Tonga Island and The Glen), presented in relation to distance along each transect from the shore. Values are from three composited sediment cores.

M5 and M10, 28% at M15, and ≤10% elsewhere. The C/N ratio at M5 and M10 (c. 12.0) was elevated by comparison with all other sites (c. 6.0 to 9.4) (Fig. 2E), which is also consistent with an increasing contribution of terrestrial matter with proximity to the river mouth.

Levels of total N and to a lesser extent total P were elevated mid-way along the Motueka transect at sites M15 and M20 (c. 6 km and 8 km, respectively from the river mouth) by comparison with most other sites (Fig. 2F,G). There was no visible pattern in the distribution of total fatty acids with respect to the river plume. Polyunsaturated fatty acids (PUFA) ranged from c. 13% (at M10) to 21% (at M30) of the total, but this proportion showed no consistent pattern along the plume gradient or among plume and reference sites. Similarly, there was no clear trend in the ratio of PUFA to saturated (SFA) forms (Fig. 2H). However, when fatty acids were considered individually, it was evident that long chain (≥C20) saturated (C*n*:0) forms (notably C22:0, behenic acid; and C24:0, lignoceric acid) were more prevalent within the nearshore plume (M5–M15) than at offshore sites and reference sites.

Concentrations of Cd, Pb and Zn at all sites were low relative to ANZECC (2000) sediment quality guidelines and showed no clear spatial pattern in relation to the river mouth. By contrast, concentrations of Cu, Cr and Ni were elevated in the vicinity of the nearshore plume (Fig. 3A–C). For example, Ni levels at sites M5 and M10 were approximately 10 times higher than concentrations measured in sediments at sites along reference transects and six times greater than ANZECC (2000) ISQG-high values. Ni concentrations were also generally elevated, but to a lesser extent, across Tasman Bay, exceeding ISQG-low values at all reference sites.

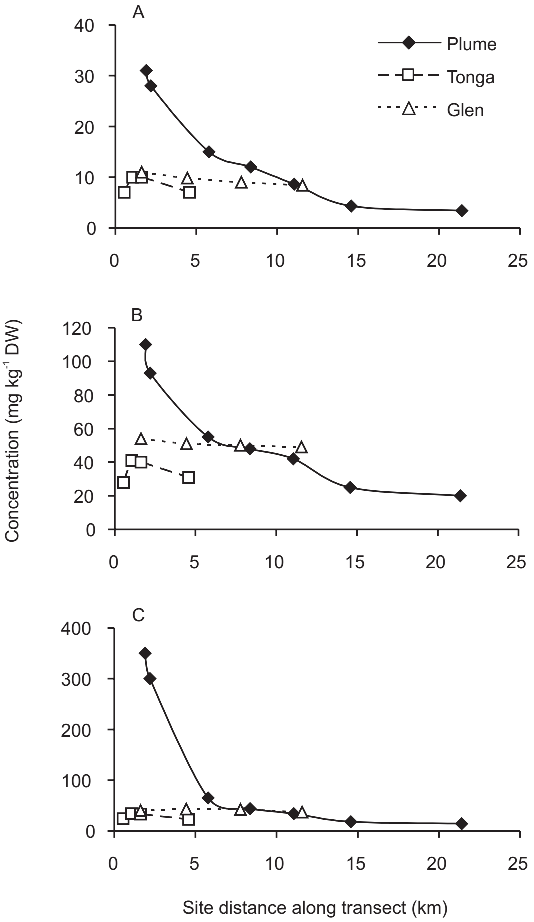

Fig. 3 Spatial patterns of: **A**, copper; **B**, chromium; and **C**, nickel in sediments along the three sampling transects (Motueka River plume, Tonga Island and The Glen), presented in relation to distance along each transect from the shore (DW, dry weight). Values are from three composited sediment cores.

Infaunal communities and shellfish

Isotopic signatures from the adductor tissue of epibenthic shellfish were comparable across all sites with values ranging from –16.6 to –19.4 for $\delta^{13}C$ and 8.1 to 11.0 for $\delta^{15}N$ (Fig. 4). Scallop tissue was slightly more depleted in ^{15}N ($\delta^{15}N$ 8.1–9.1‰) than that of the two mussel species ($\delta^{15}N$ 9.5–11.0‰). There was no evidence of any direct assimilation of terrestrially-derived organic matter, even in horse mussels at M10 where there was a strong terrestrial signal in surface sediments, although a slight nutritional shift was evident in scallops collected from M15 (Fig. 4).

Infaunal species richness ranged from 10 to 49 taxa per site, with 111 taxa recorded across the survey area. Spatial patterns in distribution (Fig. 5A,B) reveal that the most impoverished sites (in both species richness and density) were those closest to the river mouth (M5 and M10). These sites were characterised by a number of disturbance-tolerant taxa, including oligochaete worms, the polychaete *Heteromastus filiformis* and the non-indigenous bivalve *Theora lubrica*, which were either absent or at reduced densities at most other sites. By contrast, the offshore sites along the plume transect were relatively taxa-rich, having a number of common or co-dominant infaunal taxa that were absent from M5 and M10. Examples included small bivalves (*Ennucula strangei* and *Nucula* cf. *gallinacea*), species from several polychaete families (Paraonidae, Spionidae, Cirratulidae, Lumbrineridae), cumaceans, ostracods, and ophiuroids. Site T20 was anomalous in that it was reasonably taxa-rich but had relatively high densities of enrichment-tolerant capitellid worms (*Heteromastus filiformis*) and nematodes (Pearson and Rosenberg 1978), which is consistent with the observation that sediments at this site had a high organic content.

In accordance with these main biological differences, the ordination procedure and cluster analysis discriminated three clear groups of sites based on taxa composition and dominance patterns (Fig. 6A). The infaunal assemblage at M5 and M10 was approximately 75% dissimilar to the other two site groups. Bubble plots in Fig. 6B–D show the relative levels (at each site) of the variables that the BioEnv procedure identified as being the most highly correlated with the ordination pattern in Fig. 6A (e.g., the two large bubbles in Fig. 6C represent high values of Ni at sites M10 and M15 relative to the other sites). Site distance from the Motueka River mouth and "trace metal" concentrations based on Ni distribution (the distribution of Cr and Cu was highly correlated with Ni, r >0.94) were the variables most correlated (Spearman ρ values 0.60 and 0.59, respectively) with the pattern of infaunal composition and abundance among sites, with the C/N ratio being the only other variable with a correlation coefficient >0.50. Explanatory power was not appreciably increased by using more complex models based on two or more variables. However, when spatial patterns along the seven sites on the Motueka plume transect were considered in isolation (i.e., omitting the variability from the spatially disparate reference sites), the distribution of trace metals was highly correlated ($\rho = 0.94$) with the biological pattern.

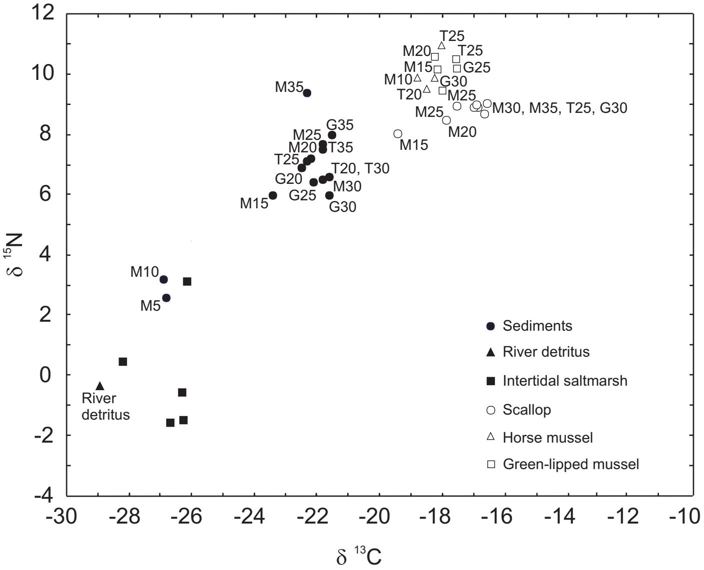

Fig. 4 Carbon and nitrogen isotope signatures in Tasman Bay sediments, shellfish (scallops, *Pecten novaezelandiae*; horse mussel, *Atrina zelandica*; green-lipped mussel, *Perna canaliculus*), river detritus, and saltmarsh vegetation.

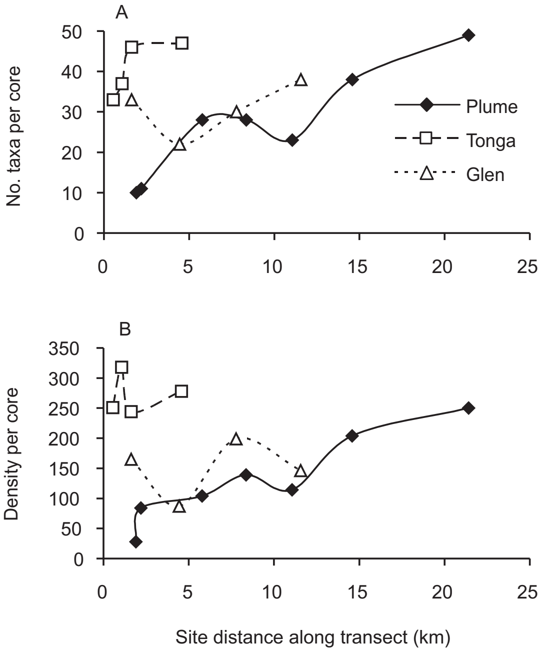

Fig. 5 Spatial patterns of: **A**, infaunal species richness; and **B**, infaunal abundance along the three sampling transects (Motueka River plume, Tonga Island and The Glen), presented in relation to distance along each transect from the shore. Values are from three composited sediment cores (each 0.013 m^2).

DISCUSSION

Tracers of river plume influence

The influence of the Motueka River plume was evident through a number of the indicators used in this study. In particular, elemental C/N ratios, stable C and N isotopes, certain lipid biomarkers and trace metals revealed a terrestrial signature within the sediments at sites up to 6 km from the river mouth. Elevated C/N values at the two nearshore sites in the river plume (M5 and M10) are consistent with those expected for sediments containing terrestrially derived organic matter (C/N ratio c. 12), whereas those offshore and along reference transects indicated greater mixing with marine-derived organic matter (C/N ratio c. 8; Maksymowska et al. 2000; Jaffé et al. 2001; Frascari et al. 2006). By comparison with overseas studies (e.g., Riera 1998; Cook et al. 2004), values of $\delta^{13}C$ and $\delta^{15}N$, and application of a simple mixing model, also suggested a distinct gradient between terrestrial/freshwater and marine organic matter along the Motueka River plume transect, with a river influence still evident at M15 approximately 6 km offshore. Although direct observations revealed terrestrial detrital material within the sediments at these sites, the inclusion of C/N ratios and isotope signatures assisted in defining the terrestrial contribution and delineating the area most influenced by the river plume.

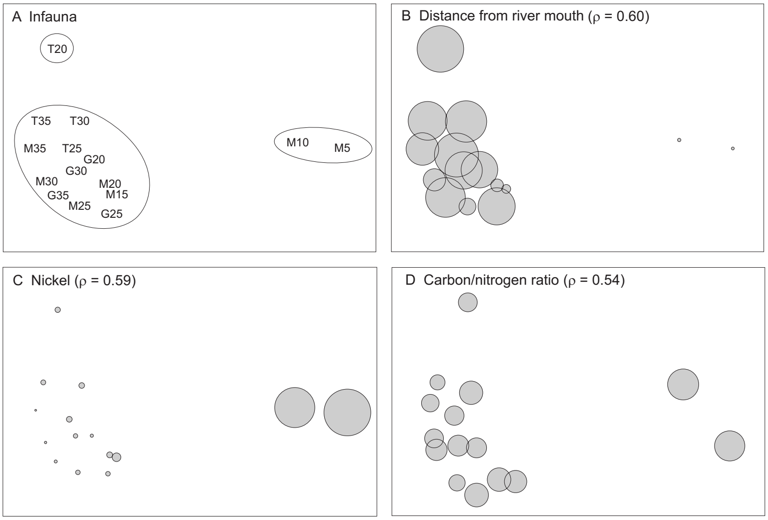

Fig. 6 MDS ordination showing: **A**, similarity of all 15 Tasman Bay sites based on their infaunal taxa composition (2D stress = 0.07, sites circled ≥60% similar); **B–D**, bubble plots indicating relative values for the most correlated (Spearman ρ values) explanatory variables.

The apparent peak in nutrient (N and P) concentrations mid-way along the Motueka plume transect is unusual. Overseas studies have described elevated N and P in seabed sediments of frontal areas, for example where nutrient-rich river plumes mix with waters of marine origin leading to elevated primary production and hence a localised increase in sedimentation (e.g., Josefson & Conley 1997; Frascari et al. 2006). Although we did not consider primary production in this study, previous work has at times revealed elevated levels of dissolved nutrients (MacKenzie 2004), and enhanced phytoplanktonic and microphytobenthic biomass (Gillespie 2003), in the general vicinity of mid-plume sites. Without a measure of variability around our sediment nutrient estimates, and in the absence of concurrent information on primary production, these observations should be interpreted with caution, but they do point to a worthwhile area for further investigation.

Long-chain saturated fatty acids regarded from overseas studies as indicative of terrestrial source material (e.g., Shi et al. 2001; Cook et al. 2004) were more prevalent within the nearshore plume (sites M5 and M10) than at offshore sites, corroborating the findings from the C/N ratio and isotopic analyses. However, for reasons unknown there was no corresponding overall pattern in the spatial distribution of total saturated versus polyunsaturated fatty acids, as might be expected with a change from refractory (saturated) terrestrially-derived organic matter within a river plume to more bioavailable (polyunsaturated) material of marine origin with distance (Canuel 2001; Loh et al. 2006). Hence, some of the findings from overseas studies may not apply to the Tasman Bay situation, although a more thorough evaluation would be required before any firm conclusions are made.

The dramatically elevated concentration of Ni and to a lesser extent Cr and Cu at the two nearshore plume sites was an unexpected finding, and is of particular interest considering that the source relates to the geology of the upper catchment (P.A. Gillespie unpubl. data). Trace metal contamination from river plumes across similar spatial scales has been described in studies overseas, but typically reflects anthropogenic sources that grade to background concentrations with distance (Brady et al. 1994; Jaffé et al. 1995; Tankere & Statham 1996). Tasman Bay is therefore unusual in that, by comparison with other New Zealand coastal sediments, Ni, Cr and Cu concentrations are generally elevated across the region (Smith 1986 and references therein) presumably reflecting ongoing catchment inputs (from the Motueka River as well as other rivers) that become widely dispersed over long time scales.

Benthic influence of the river plume

In terms of the ecological effects of the river plume, it is of particular interest that Ni concentrations exceeded, by at least six-fold, ANZECC (2000) ISQG-high trigger level guidelines for probable biological effects at sites M5 and M10. Although these guidelines are conservative, our previous experience with other trace metal and organic contaminants in the region has revealed marked ecological degradation in sediments when ISQG-high values are reached (e.g., Forrest et al. 1997). In this context, it is notable that the two contaminated river plume sites were the least species-rich, with trace metal (Ni, Cr, Cu) concentrations explaining most of the variability in the distribution of infauna along the plume transect. A possible interpretation is that the apparent nearshore biological effect of the plume is to some extent attributable to metal toxicity, although a number of caveats in this regard need to be recognised. In the first instance, the correlation between biological patterns and trace metal distribution may not be causal, since other unmeasured influences (e.g., physical disturbance, gradients of salinity, terrestrial debris) could conceivably be the primary drivers. Furthermore, the routine analysis applied to the metals involved a moderate hot acid-extractable digestion procedure that is likely to overestimate the bio-available proportion (Loring & Rantala 1992), and hence potential biological effects.

Based on the sediment and infaunal patterns, it is also useful to consider contaminant burdens in shellfish, given the importance of Tasman Bay for recreational and commercial resources (MacKenzie 2004). Analysis of archived samples from the present study revealed Ni in adductor tissue of horse mussels and scallops from sites M10 and M15 at concentrations (1.0–1.5 mg kg^{-1}) 3 to 5 times greater than at reference sites (B. M. Forrest unpubl. data). These results suggest some degree of bioaccumulation, although arguably of little significance on the basis that concentrations were low relative to guidelines on maximum limits for human consumption (USFDA 2001). These findings are consistent with the projected diet of suspension feeders sampled in this study. Assuming a trophic shift of 1.3‰ for C and 2.2‰ for N for suspension feeders (McCutchan et al. 2003), a diet with a large terrestrial/riverine contribution to nutrition would have resulted in considerably lighter isotopic signatures than we found for the three bivalve species (on the order of –26‰ for $\delta^{13}C$ and 3–4‰ for $\delta^{15}N$; Cook et al. 2004). Rather, the $\delta^{13}C$ and $\delta^{15}N$ values from this study are consistent with a diet of marine phytoplankton (Maksymowska et al. 2000) and suggest that suspension feeders within the river plume may have limited capacity to derive direct nutrition from land-based detrital inputs or to accumulate significant levels of contaminants. However, our findings should be interpreted with caution given that few shellfish were sampled overall and none from the site closest to the river mouth.

Implications for understanding spatial scales of river plume influence

This study has provided knowledge of the spatial influence of the Motueka River discharge on adjacent subtidal soft sediments, indicating a direct terrestrial signature that extends at least 6 km offshore (to site M15) in the direction of the plume, but with a notable ecological effect limited to c. 2 km (sites M5 and M10). Our findings are consistent with other studies (e.g., Frascari et al. 2006) in demonstrating a gradient of direct terrestrial organic matter input from the river mouth. Furthermore, elevated mid-transect nutrient concentrations are consistent with a more dispersed seabed effect from increased water column primary production towards the frontal boundary of the plume. The spatial scale of obvious terrestrial influence (i.e., to at least site M10) is comparable to the river plume boundary under low river flows of <18 m^3 s^{-1} (see Fig. 1), and is consistent with observations that river flows were 14–25 m^3 s^{-1} in the 2 weeks preceding our study (Tasman District Council unpubl. data).

During flood flows the Motueka River plume can extend several tens of kilometres offshore and in a northerly direction, with an associated depositional footprint of fine (2–20 μm particle size) river-derived sediment predicted to largely follow the plume boundaries under these conditions (Fig. 1; MacKenzie & Adamson 2004; Tuckey et al. 2006). Such predictions are consistent with overseas work that reveals a coupling between river plume distribution and seabed effects (e.g., Danovaro et al. 2000; Le Pape et al. 2003; Frascari et al. 2006), suggesting that the Motueka River outwelling plume has the potential to affect benthic habitats across greater spatial scales than described by the present study. It is of interest, therefore, that a significant flood (peak flow 904 m^3 s^{-1}) occurred 1 month before our field work (Tasman District Council unpubl. data). We expected the water column influence of this event to extend across most of our survey area, yet there was no evidence of an effect on seabed sediments or biota at this scale. In terms of the physico-chemical measures we used, any broad scale event-related effects could conceivably have been mitigated over time-scales of weeks by physical (e.g., sediment resuspension and dispersion) and biological (e.g., bioturbation, assimilation) processes, hence not be evident at the time of the survey. On the other hand, any significant flood effects resulting in changes to infaunal communities should still have been evident, on the basis that time scales of infaunal "recovery" are more likely to be many months rather than a few weeks (e.g., Roberts & Forrest 1999; Dernie et al. 2003).

There is clearly a need to concurrently investigate spatio-temporal variability in the benthic versus water column influence of the Motueka River plume in Tasman Bay in relation to river outflow and mass loads of input materials. This study highlights a number of physico-chemical and biological indicators that would be useful for this purpose, which could be supplemented by measures that also aim to characterise the bioavailability and functional role of sedimentary organic matter from terrestrial versus marine sources (e.g., Dell'Anno et al. 2000; Canuel 2001; Pusceddu et al. 2003). In relation to trace metal contaminants in this particular situation, it is important to further consider bio-availability (e.g., to infaunal species), and whether the nearshore concentrations are maintained by chronic inputs or are a function of pulse events whose persistence is mitigated by mechanisms that disperse and dilute sediments, as described for other parts of Tasman Bay (Roberts & Forrest 1999). Acquisition of more detailed knowledge will allow qualitative comparisons of the Motueka catchment and river plume with other systems where similar work has been undertaken. Nonetheless, the results of previous New Zealand studies (e.g., Foster & Carter 1997; Lohrer et al. 2006) indicate that the spatial scale and magnitude of catchment effects will invariably be site-specific, as they are a function of variation in factors such as river flow and the nature and mass load of inputs in relation to the sensitivity and hydrological characteristics of the receiving environment.

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