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Whangapoua Harbour Sediment Sources

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Executive Summary

Monitoring programmes have determined that the benthic community in the Whangapoua Harbour is changing and it is suggested that the changes are associated with catchment sediment inputs. Although similar changes in other harbours have been linked to enhanced inputs of catchment soil, there was no apparent enhanced sedimentation effect and the source of the soil within the catchment is uncertain. Environment Waikato requested NIWA to undertake a study to determine the most likely sources of soil from within the catchment in the impacted harbour areas and to provide an estimate of the relative proportions of each soil source present. This report presents the results of the study and an interpretation of those results with respect to a possible mechanism contributing to the apparent impact on benthic community in Whangapoua Harbour.

This study used a recently developed technique, that can identify and apportion the contribution of soils from several different land use sources in a single catchment, at a number of locations within the harbour. This technique is based on the analysis of the stable isotopic (^{13}C) composition of specific compounds adsorbed onto the soil particles as naturally occurring markers, and their use as labels in the apportionment of the soil contribution to the harbour sediments using a matrix of results in a mixing model with post correction to soil mass. This process is called a compound specific isotope (CSI) method. The technique was applied to surface catchment soil and estuarine sediment samples (top 2 cm) which includes recent deposition and some longer-term deposition over a period of several years.

It was found that native forest and scrub contributed around 20-30% of the soil to the sediments at most sites in the harbour. The proportion was highest (~26%) in the eastern estuarine arm (Mapauriki) where native forest comprised a major proportion of the catchment land use relative to undisturbed pine forest and pasture. In the other two eastern estuarine arms (Otanguru and Owera), a substantial proportion of the sediment came from local pasture (~42% and ~25%, respectively). At all three eastern estuarine arms, there was a substantial contribution of soil from recent exotic pine forest logging, with proportions ranging from about 54% to 75% at those sites in the harbour. As only one of those estuarine arms (Owera) had active exotic pine forest logging in the catchment at the time of sampling, it was concluded that sediment from that forestry activity is dispersing as a pervasive contaminant through the eastern side of the harbour. The lack of CSI signatures associated with recent exotic pine forest logging in the western side of the harbour was consistent with post depositional resuspension by waves from the flats and lateral dispersion by tidal action including transport out of the harbour on the ebb tide and redistribution into the eastern estuarine arms on the flood tide.

The soil contribution from native forest and scrub to the western side of the harbour was relatively consistent at around 20% – 30% along a transect from the mouth of the Opitonui River to the entrance to the ocean. There was a variable overlying CSI signature of seagrass contribution to the harbour sites

along this transect line, presumably associated with sediment and detritus from the extensive seagrass beds exposed at low tide near the main channel of the harbour. The pasture land use contribution to the harbour sites along this transect were low (<10%) but there was a contribution of soil from exotic pine forest land use increasing in proportion from <10% to more than 50% along the transect line from the Opitonui River mouth. The CSI signatures of this material indicate that it was associated with the leached exotic pine forest soils in the Opitonui catchment rather than recent logging operations in the Owera catchment. This material was relatively coarse, with the characteristic red-brown soil colour from the Opitonui catchment, and existed as a thin layer overlying the characteristic fine grey-white sands of the Whangapoua Harbour.

It was concluded that this surface sediment layer in the harbour was associated with flood-event deposition as well as bed-load transport out of the Opitonui catchment with successive storm events. The lack of the fine clays, which have the greatest impact on the benthic communities, suggests sufficient wave action during periods of tidal inundation to winnow these out of the sediments so they are dispersed widely across the harbour or are ejected from the harbour with the ebb tide. Wave and tidal action would also progressively move the coarser material across the intertidal sandflats.

These conclusions are supported by historical observations of the March 1995 flood-event which deposited fine clay smothering seagrass and cockle beds before wind-wave and tidal action dispersed the deposits, and the observation of bed load sediment movement across the sandflats two months after a high intensity rainfall event across the Opitonui catchment. The reported lack of change in sediment depth despite episodic flood deposition of soil in the harbour is consistent with the deposition material being continuously winnowed by wave action and tides which disperse it across the intertidal sandflats rather than accumulating. Consequently, the apparent adverse impact on the benthic community in Whangapoua Harbour, without an apparent increase in sedimentation, may be the result of chronic and episodic exposure to mud deposition.

1. Introduction

Monitoring programmes have determined that the benthic community in the Whangapoua Harbour is changing. Although similar changes in other harbours have been linked to enhanced inputs of catchment soil, there was no apparent enhanced sedimentation effect and the source of the soil within the catchment is uncertain. Environment Waikato requested NIWA to undertake a study to determine (1) the most likely sources of soil from within the catchment in the impacted harbour areas and (2) to provide an estimate of the relative proportions of each soil source at those locations.

1.1 Background

The topography of the Coromandel Peninsula is characterised by steep mountainous bush-clad hillsides and flat fertile valley floors which, coupled with a high and often intense rainfall, indicate that the land is prone to erosion due to weathering. Over geological timescales, material washed into the Whangapoua Harbour has resulted in substantial in-filling and the development of extensive intertidal flats which now support a diverse macrobenthic community. Large cyclonic storms are uncommon with a 2-year recurrence but, because of the intensity of local rainfall, they can cause major erosion (Marden & Rowan 1995) which may result in catastrophic sedimentation on the intertidal flats and devastation of the macrobenthic community (Thrush et al. 2003a). Recovery from isolated events is possible given sufficient time (Thrush et al. 2003a) but chronic inputs of sediment can be pervasive and may delay that recovery of, or induce a change in, the benthic community of the harbour as mud replaces the sand (Thrush et al. 2003b).

In recent times, large areas of former native forest and scrub in the Whangapoua catchment have been replanted with exotic pine for production forest. This has occurred mainly on the steepland between the farmland on the valley floor and the native forest on the ridge lines. Once established, pine forests provide a similar level of protection as native forest to soil erosion by storm runoff. However, even with best management practices (Marden et al. 2006, Phillips et al. 2005), large areas of clearfell pine forest land is vulnerable to erosion for periods of up to six years following harvest. Deep disturbance associated with log hauling produces more sediment than shallow disturbance (Marden et al. 2006). Skidder pads and the roading infrastructure created to remove the logs is also a source of soil erosion and the roads can act as conduits for the sediment laiden runoff which might otherwise have been filtered by vegetation. Consequently, activities associated with production forestry are potential sources of fine sediment delivered to the harbour.

1.2 Study rationale

There are a number of soil properties that can be used to trace their transport and deposition in the environment. For example, suspended sediments transported through stream systems can be compared with catchment and stream-bank soils using a range of physical, chemical, mineralogical, and radio-isotopic (^{210}Pb, ^{37}Cs) analyses. Direct monitoring of soil loss from potential source areas is presently the most widely used approach. Alternatively, sediment sources can be identified using their chemical fingerprint which compares suspended sediment properties with those of the catchment soils and stream-bank sources.

NIWA has developed an ecological-based fingerprinting technique which has proved effective at a catchment scale (Gibbs 2005). The technique is capable of identifying and apportioning the soil sources contributing to estuarine sediments from within a single catchment. This technique uses the stable isotopic signature of carbon (^{13}C) in specific compounds adsorbed onto soil particles from plants growing in the source soils. Although all plants produce the same general range of organic compounds, by the nature of their growth habit and their symbiotic relationship with unique assemblages of mycorrhizal fungi to process soil minerals into usable plant nutrients, the isotopic signature of carbon in these specific compounds, which label the top-soil, will be different.

These compound specific isotope (CSI) differences are sufficient to distinguish between soils derived from native forest, exotic pine forest, and pasture and deposited in estuaries. With sufficient soil samples, this technique can also discriminate between local sources of the same land use type within that catchment and provide estimates of the most likely proportions of each soil source contributing to a sediment sample taken from any location in an estuary.

This report documents the analyses and results of a CSI tracer study undertaken in the Whangapoua catchment and harbour in December 2005. The aim of this study was to determine and apportion the likely sources of soil in the sediment at a number of locations in Whangapoua Harbour including those where the macrobenthic community has been impacted. The data are interpreted in the context of processes that transport and deposit catchment derived soil in the sediments of the Whangapoua Harbour. This report also presents an interpretation of the results with respect to a possible mechanism contributing to the apparent adverse impact on benthic community.

2. Methods

2.1 Site

Whangapoua Harbour on the north-eastern side of the Coromandel Peninsula (Fig. 1) is a large, shallow sand-barrier-lagoon type estuary. The harbour is substantially in-filled with extensive intertidal flats between the streams that drain the sub-catchments: the Waitekuri and Opitonui Rivers in the western side, the Owera and Otanguru Streams on the southern side and the Mapauriki Stream on the eastern side. The western arm of the harbour has extensive areas of bare sandflats with salt-marsh meadows near the shore and seagrass beds near the low water channels. The intertidal and river bed in this arm consist of a thin layer of red-brown coarse sand extending more than a kilometre from the confluence of the Waitekuri and Opitonui Rivers across the otherwise grey-white sands of the harbour. Inshore areas of the southern and eastern arms have extensive growths of grey mangroves, *Avicennia marina*, extending to the channel edges but are backed with the salt-marsh meadows which surround most of the harbour at the high water level. Sediments beneath the mangroves consist of fine silts.

The Whangapoua catchment is dominated by exotic pine production forest on the steepland with extensive areas of lowland pasture which are used for dairy farming and dry stock grazing (Table 1). Native forest and scrub land is largely confined to local remnant patches in gullies and along the ridges above the exotic pine forests.

Table 1: Land cover in the catchments draining into Whangapoua Harbour.

Land cover	**Ha**	**%**
Coastal Vegetation	392	4.0
Wetland	38	0.5
Pasture	2,283	21.0
Pine	5,481	50.0
Scrub	680	5.5
Native Forest	2,142	19.0
Total Area	10,996	100%

Eroded soils are primarily delivered to estuaries during rainstorms with erosion increasing as the rainfall intensity increases. For example, the March 1995 storm, a weather bomb, caused extensive landslides in the Owera sub-catchment, delivering large quantities of sediment into the harbour. Although not as spectacular in effect as the March 1995 storm, episodic intense rainfall events with a 2-year recurrence also cause sediment erosion from bare land exposed by tillage or clearfell forestry logging. Production forests in the Owera catchment affected by the March 1995 storm were clearfelled and replanted between 1995 and 1997. Parts of the exotic pine forests in the

Opitonui River and Awaroa tributary catchments were clearfelled and replanted between 1995 and 2003. The exotic pine forests in the eastern parts of the catchment remain largely undisturbed although logging has commenced on the eastern side of the Owera catchment.

To date, urban development within the Whangapoua Harbour catchment has been minimal and confined to isolated farm houses, although there is a small community at Te Rerenga, including a rural school and a boutique winery, near the confluence of the Waitekuri and Opitonui Rivers (Fig. 1). However, there has been rapid development of the Matarangi seaside resort of on the Omara Spit sand-barrier which forms the seawards side of the harbour (Fig. 1). Large areas of the Omara Spit were originally planted in exotic pine forest and, although some areas have been cleared, many pine trees have been retained in the development. The community waste water treatment plant is at the eastern end of the Omara Spit with overflow discharging to Whangapoua Harbour through the mangroves to the Mapauriki Stream channel in the eastern arm of the harbour.

Over the last 10 years, the largely unsealed section of state highway 25 over the steep divide between Te Rerenga and Coromandel township has been slowly upgraded to a sealed road. This process has exposed subsoils which would have been washed into the Waitekuri River and from there to the harbour in heavy rain events.

2.2 Sampling

Surface (top 2 cm) soil and sediment samples (Table 2) were collected from 22 selected locations within the Whangapoua Harbour and catchment (Fig. 1). The Whangapoua Harbour presently has relatively low sediment accumulation rates of 0.9-1.3 mm y^{-1} (Hume & Dahm 1992), based on pine pollen data from 2 cores. However, wave action reworking and mixing of surface sediments and bioturbation tend to blur the age of the surficial sediments (Mead & Moores 2004), and hence the 2 cm surficial sediment represents the most recent deposition material and may include some much older material. Top soil samples were taken from locations selected to represent the main catchment land use types — native forest (N), native scrub (NS), pasture (P), and exotic pine forest (EP) and within different sub-catchments. Additional samples of subsoil (SS) were collected from material stockpiled for road working (SS1) and from natural slip-face material (SS2). (See appendix for site photos).

Harbour samples (H) were selected adjacent to the Opitonui River channel including areas where changes in benthic biology have occurred and in the estuarine arms (HE) inshore from those sites. Site HE1 was selected to avoid contamination from the Matarangi waste-water plant by sampling ‘upstream’ of the discharge point. Site HE3 was to be the beginning of a transect line through an area of known biodiversity change but access to the harbour sites beyond the confluence of the Owera Stream mouth was denied by the land owner. Sites H1-4 comprise a transect line from H1 near the mouth of the Opitonui River [corresponding with biological monitoring site 1] along the plume of red-brown sand to the grey-white sand at site H4, where the intertidal sandflats were covered with seagrass beds. The sample from site H4 has been used as a source representing seagrass (SG). The ocean reference site sample, HO, was taken from the eastern side of the entrance to Whangapoua Harbour, on the seaward side of the Omara Spit around low tide.

2.3 Processing and analysis

The bulk samples (1-2 kg) were mixed in 5-Litre plastic buckets. An aliquot of each sample was taken and stones, leaves and debris removed before measuring moisture content, after drying at 105 ^{0}C. Organic content was determined from weight loss on ignition at 500 ^{0}C. The remainder of the sample was wet sieved (0.5 mm) to remove stones, leaves, woody debris, and any organic matter not bound to the soil particles. An aliquot of each wet sieved sample was retained for bulk ^{13}C and ^{15}N stable isotope analysis before the samples were dried (air fan oven at 60 ^{0}C). Large caked lumps of dry sample were crumbled and ground in a mechanical blender before manually grinding to a fine powder (< 100 µm) with a pestle and mortar. The fine power was stored in polycarbonate wide-mouth screw-cap jars pending analysis.

For bulk ^{13}C and ^{15}N stable isotope analysis, the aliquots of wet sample were acidified with 1N hydrochloric acid (HCl) to remove inorganic carbonate and then rinsed with deionised water (Milli RQ) before drying and grinding. The dried samples were analysed at the Waikato University Stable Isotope Unit on a Micromass isotope ratio mass spectrometer (IRMS) after combustion in an elemental analyser at 1000 ^{0}C and separation of the gasses produced by gas chromatography (GC). Results were reported in delta (δ) notation with units of per mil (‰) calculated by the formula:

$$\delta X = (R_{\mathrm{sample}} / R_{\mathrm{standard}} - 1) \times 1000 \quad ‰$$

where X is ^{13}C or ^{15}N and R is the ratio of heavy to light isotope (^{13}C:^{12}C or ^{15}N:^{14}N). Standards for carbon were a reference gas (CO_2) calibrated relative to the international standard PeeDee Belemnite. For nitrogen, the reference standard was atmospheric nitrogen.

Figure 1: Site map of sample locations in Whangapoua Harbour and catchment. The photo overlay provides detail of the harbour intertidal zones.

Table 2: Sample locations, site descriptions and soil appearance. Intertidal samples from the harbour and ocean were collected around low tide. Sample H4 was taken from within a seagrass bed and is used as a source for other harbour samples. (See Appendix for site photos).

Sample	Easting	Northing	Site Description	Appearance
HO	2745150	6493981	Ocean - eastern side of entrance on Omara Spit at low tide	Medium grey-white sand
H1	2743716	6491109	Harbour, at biological site 1 marker, near Opitonui River mouth	Coarse red-brown sand
H2	2744025	6491615	Harbour, beside Opitonui River	Coarse red-brown sand
H3	2744424	6491890	Harbour, near biological site 3, beside Opitonui River	Medium brown sand
H4 - SG	2744947	6492690	Harbour, near main channel, clear patch in extensive seagrass bed	Medium grey-white sand
HE1	2749270	6492073	Mapauriki Stream channel upstream of waste water overflow, (Mangroves)	Fine brown silt
HE2	2747821	6491196	Otanguru Stream channel, (Mangroves)	Fine brown silt
HE3	2746366	6490250	Owera Stream mouth beside channel, (Mangroves)	Fine brown silt
HL	2743645	6492684	Lagoon beside stream channel, (seagrass)	Medium grey-white sand
EP1	2741674	6487857	Silt runoff from skidder pad, well established regrowth of pines	Fine yellow silt
EP2	2743437	6485083	Silt runoff from skidder pad, well established regrowth of pines	Fine red-brown silt
EP3	2747185	6486612	Soil-mud from active skidder pad in mature pines	Fine yellow silt - clay
EP4	2749066	6490049	Surface soil beneath mature undisturbed pines beside stream bank	Organic humus with clay
N1	2737222	6490830	Surface soil from runoff beneath native forest	Fine black silty loam
N2	2739016	6487835	Surface soil from runoff beneath native forest	Yellow clay and humus
NS	2742809	6492714	Surface soil from runoff beneath native scrub, (Kauri present)	Yellow clay loam
P1	2743123	6488745	Pasture soil (low level) above flood plane of Opitonui River (dairy farm)	Black loam
P2	2746138	6487474	Pasture soil (high level) of Owera River	Black loam
P3	2742696	6491211	Pasture from western catchment	Black loam
P4	2750020	6491088	Pasture from eastern catchment	Black loam
SS1	2737112	6491492	Stock piled roading material beside Waitekuri River (SH25)	Red-purple-brown clays
SS2	2739451	6490555	Slip face material above Waitekuri River (SH 25)	Yellow clay

The CSI analyses were conducted by Isotrace (NZ) Ltd laboratories (Otago), using aliquots of the dry samples. These were extracted with dichloromethane (DCM) and the fatty and resin acids were methylated before the extract was analysed on a GC-combustion-IRMS. In this process, each organic compound separated by the GC is combusted separately and the isotopic composition of the CO_2 produced is measured on the IRMS. For each sample the results consist of the $\delta^{13}C$ values of the full suite of organic compounds present above detection limits.

Resin and fatty acids were analysed by RJ Hill Laboratories (Hamilton), using aliquots of the dry samples. These were extracted with DCM and, after derivatising, the resin and fatty acids were determined on an ICP mass spectrometer using a method developed for NIWA samples. Results were reported as mg / kg dry weight for each compound above detection level.

2.4 Source identification and apportionment

The soil-source identification technique is based on analysis of a matrix of the CSI results from all sources compared with CSI results from the harbour sample being assessed. Initially, the CSI results are inspected by eye for patterns of commonality or difference. This is followed by exploratory data analysis, which includes scatter plots of the data, to find the most likely combination of sources influencing the sample being assessed. These are the sources with CSI values that, when connected by straight lines, form the corners of a polygon that encloses the harbour sample CSI value. These sources are then used in the source partitioning model, IsoSource (Phillips & Gregg 2003), which provides an apportionment of all feasible combinations of those sources in the harbour sample. While IsoSource has been favourably evaluated for food-web studies (Benstead et al. 2006), it is not limited to food-web studies and can also be used for any mixture where isotopic signatures are available relative to potential sources. Consequently, in the soil-source identification technique, IsoSource can be used to identify and apportion catchment soil sources contributing to the harbour sediment samples.

This is a two step process. First, the feasible proportions of CSI label on the source soils are determined using IsoSource. Second, a post–model calculation is used to convert the mean label proportions from IsoSource into the proportions of source soils.

2.4.1 IsoSource operation

Standard linear isotope mixing models using *n* isotopes will allow the unique determination of at the most *n* + 1 sources in a mixture. With larger numbers of sources to assess, the source partitioning model, IsoSource, statistically constrains the relative proportions of the various sources in the mixture. To do this, IsoSource evaluates all combinations of each source (from 0-100%) in user-defined increments to identify source combinations that sum to the known isotopic signature of the mixture to within a prescribed small tolerance in ‰. These source combinations are collated into a distribution of the frequency and range of potential source contributions. Consequently, IsoSource does not offer a unique solution, but it does allow evaluation of the statistical constraints on the relative contributions of each source.

Essentially this process works backwards from the mixture to determine all combinations of the sources that produce feasible solutions. While each feasible solution may be the correct solution, the number of times any given proportion of each source occurs is summed to produce a frequency distribution which can be evaluated statistically to give the mean % contribution. When interpreting the model output, the total number of feasible solutions found by the model is an indication of the reliability of the result with reliability increasing as the number of feasible solutions decreases towards 1, which is a unique solution.

As used in the CSI method, the CSI values do not represent the whole sample, rather they represent a label attached to the source soil. Compared with carbon content, which is measured in g/100g (i.e., 1 g/100g = 1 %), the CSIs are measured in mg/kg (i.e., 1 mg/kg = 0.0001%). IsoSource only calculates feasible solutions for each CSI, not between different CSIs, and thus the feasible solutions reflect the proportion of source soil contributions based on the labels. To obtain the proportions of each source soil contributing to the mixture being examined, the feasible solutions are post processed using an algorithm based on the %C content of the source soils and assuming conservation of mass.

The authors of IsoSource emphasise is that the range of feasible solutions generated by IsoSource should be reported rather than the statistical mean. However, in the conversion between source label proportion and source mass proportion, it is easier to use the statistical mean in the calculation. In this report, the range of feasible solutions for the source soil labels will be reported to show the reliability of the model output, and a separate table will list the % contributions of the source soils based on the mean label.

2.4.2 Assumptions

In food web studies, a fundamental and often unstated assumption of most isotopic mixing models is that the proportional contribution of a source to the mixture is similar for each element in the source (Phillips & Koch 2002). This assumption is reasonable if the elemental concentrations of each source are similar and of equal digestibility (e.g., for animals on all meat or all plant diets). Under these circumstances, there is no need to consider concentration when evaluating the mixture relative to sources and the isotopic balance will provide a range of valid feasible solutions.

If this assumption is not valid, however, a concentration dependent mixing model must be used in place of the linear mixing model in IsoSource (Phillips & Koch 2002; Newsome et al. 2004). As the concentration-dependent version of IsoSource has yet to be released, an alternative solution is to select only those elements which have similar proportions in each source for use in the model and apply post processing to convert the proportion of label to proportion of soil. This is the approach used in the present study.

A worked example (Fig. 2) demonstrates how the validity of the basic assumption of similar proportions was tested for the present study. In Figure 2, the concentrations of the selected pairs of fatty acids in each soil source are evaluated with a linear regression which gives the mean relative proportion of those fatty acids as the coefficient of “X” and the r^2 value for the relationship as an indication of how similar the proportions are of those fatty acids in each source soil.

It can be seen that there are linear relationships with high r^2 values between pairs of fatty acids in examples A and B, and relative to %C in example C (Fig. 2), which demonstrates that these fatty acids are present in similar proportions in all sources and thus meet the basic assumption of the model. This means that it is valid to use combinations of the CSI values of these fatty acids in IsoSource for source identification and apportionment. However, in example D (Fig. 2), two sources do not comply with the basic assumption, and thus the CSI values of Myristic acid cannot be used in IsoSource, unless the sources N1 and SG (Table 2) do not contribute to the mixture being assessed.

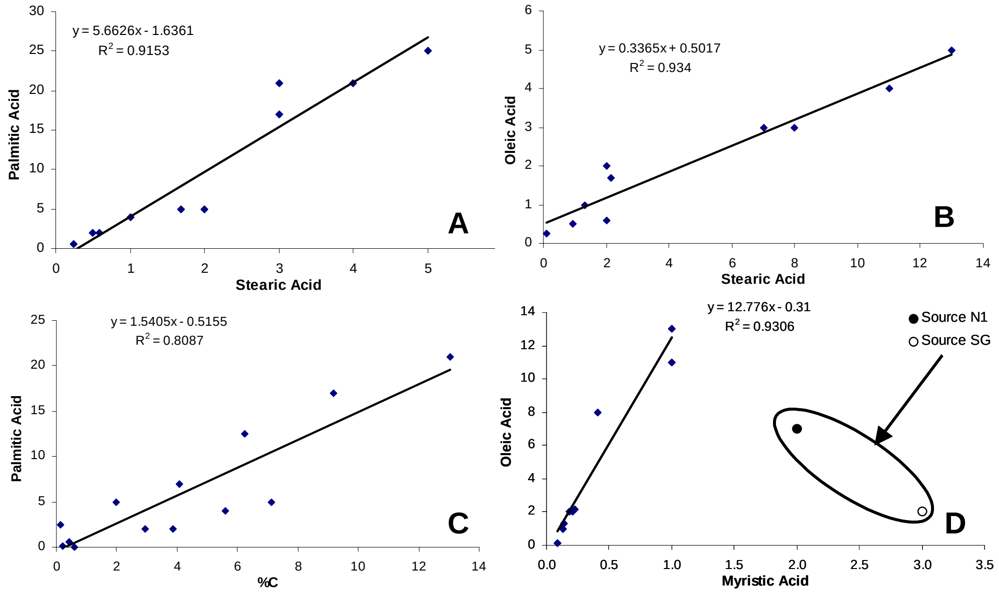

Figure 2: Relative concentrations (mg kg^{-1} dry weight) of selected compounds found in all soil sources collected for this study. In parts A and B, the fatty acid compounds selected have similar proportions in all sources. In part C, the fatty acid has similar proportions in all sources relative to %C. However, in part D, the proportions of these two compounds are very different for two sources, N1 and SG.

In the soil-source identification technique, the following assumptions have been made:

1. Representative samples from all potential sources have been collected.

2. The soil sources used in the IsoSource model are constrained by the natural linkage between each source and the sample site in the harbour (i.e., is it physically possible for that source to contribute sediment directly to that site in the harbour)[1].

3. The chemical compounds used in the modelling must be present in all sources as well as the sample being evaluated.

4. The proportional contribution of each chemical compound in each source is similar and meets the basic assumption of the IsoSource model.

[1] While it is possible for hydraulic transport of soil from one sub-catchment to the estuarine sediments adjacent to another sub-catchment depending on phases of the tide as an indirect source, initial consideration should be for the direct contribution to the site in the harbour.

5. Where chemical compounds are degraded by sunlight or microbial action, it is assumed that the degradation rates will be similar[2].

6. A polygon, drawn with straight lines joining all potential sources in a scatter plot of isotopic composition, will enclose the harbour sample[3].

7. If a potential source is not found in any harbour sample, it is assumed that that source was not contributing significantly to the sediment in the harbour within the time constraints associated with the depth of sediment collected.

8. Where the range of feasible solutions for a given source lies between finite bounds greater than zero and less than 100%, that source is definitely present and may be in the proportion of the most frequent feasible proportion. However, where the range of feasible solutions lies between zero and a finite bound less than 100%, it is possible that source is not present.

9. The usefulness of the model output is dependent on the number of feasible solutions found using any particular combination of sources. If the number of feasible solutions is low, the results are likely to be very close to the actual mixture in the sample and there is a high confidence in the result. If the number of feasible solutions is very large, the results may be of little use. However, the results may be constrained by the use of an additional isotope or CSI compound to reduce the number of feasible solutions.

In this report, the feasible solutions from a number of different compound combinations have been compared to produce the most likely apportionment of sources contributing to the sediment in each harbour sample.

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[2] For most fatty acids, which are straight chain molecules, this will be true. However, the polycyclic structure of resin acids means that some compounds (e.g., Abietic acid) breakdown faster than others (e.g., Dehydroabietic acid) (McMartin 2003) and thus resin acids may be unsuitable for use in the IsoSource modelling but do have other uses in this technique.

[3] Due to natural variability, the harbour sample CSI value may lie on the line or be within a prescribed tolerance outside the line.

3. Results

Moisture and % organic content of each sample are listed together with their bulk stable isotopic values and % carbon and % nitrogen content (Table 3). These data show strong similarities between groups of samples which are more easily seen in the C:N ratios. Open harbour samples (H) have C:N ratios around 7.5 while the estuarine arms have ratios around 11.5. The catchment soil samples show very high C:N ratios of around 24.5 for exotic pine (EP) and around 19 for native forest (N). Pasture samples (P) have C:N ratios of around 11.9 which is very similar to the C:N ratios in the estuarine arms.

The differences between combined harbour samples and combined native and exotic pine forest samples were statistically significant [$P < 0.001$]. This can be attributed to the low levels of organic carbon in the harbour sediments which is consistent with biological consumption of organic matter entering the harbour. This effect can be seen in the %Organic:%C ratios where open harbour sediments have around 10% of the organic matter as carbon compared with the terrestrial samples which have around 30% of the organic matter as carbon. Based on the % organic content at site H0 compared with sites H1 to H3 (Table 3), it is likely that about 90% of the sediment at this site is marine sand.

There were statistically significant linear relationships between %Organic and %C [$P << 0.0001$ $r^2 = 0.90$, $n = 22$), %Organic and %N [$P << 0.0001$, $r^2 = 0.80$, $n = 21$] and %C and %N [$P << 0.0001$, $r^2 = 0.86$, $n = 21$]. The relationship between the isotopic values ($\delta^{15}N$:$\delta^{13}C$) of all samples was not significant at the 95% confidence level. However, when the harbour and terrigenous samples were assessed as separate groups, there was a positive correlation for the terrigenous samples and an inverse correlation for the harbour samples, the latter being consistent with a consumption of carbon in the harbour.

Analysis of specific compounds extracted from the samples showed a range of resin and fatty acids in each sample (Table 4). While fatty acids are produced by all plants, resin acids are mostly produced by pine trees, *Pinus radiata,* but they are also produced by kauri trees, *Agathis australis*, found in some parts of the native forest around Whangapoua Harbour. These data show that the major resin acids — Abietic, Dehydroabietic, Pimaric, and Isopimaric, and Sandaracopimaric acids — were present in the pine forest samples and absent from the pasture samples, as expected, and there were traces present in the native forest samples, especially the native scrubland where there were young kauri trees present. There was an apparent absence of the resin acids from the open harbour samples but a stronger presence of these acids in the estuarine arms.

Table 3: Bulk chemical and isotopic composition of the harbour and catchment samples. Based on the % organic content at site H0 compared with sites H1 to H3, it is likely that about 90% of the sediment at this site is marine sand.

Sample	%moisture	% Org	%N	$\delta^{15}N$ (‰)	%C	$\delta^{13}C$ (‰)	%Org:%C	C:N
HO	19.38	0.32	nd	nd	0.03	nd	10.5	nd
H1	27.78	3.54	0.04	3.52	0.26	-19.69	13.5	6.9
H2	30.91	3.89	0.05	4.14	0.37	-20.82	10.5	7.8
H3	34.15	2.69	0.03	3.70	0.19	-19.83	14.3	6.4
H4 - SG	25.70	0.32	0.02	4.49	0.15	-14.83	2.1	8.0
HE1	43.92	8.10	0.16	4.63	2.06	-25.27	3.9	12.8
HE2	27.65	2.13	0.05	3.86	0.60	-23.54	3.6	11.1
HE3	63.72	14.03	0.43	4.66	4.51	-23.90	3.1	10.4
HL	23.62	2.24	0.04	4.71	0.47	-20.65	4.7	12.2
EP1	37.18	15.15	0.17	4.11	3.87	-26.68	3.9	23.2
EP2	33.08	10.95	0.02	1.91	0.44	-26.14	24.9	28.1
EP3	32.48	5.51	0.09	-5.45	2.00	-26.40	2.8	22.6
EP4	28.18	18.49	0.25	2.86	5.94	-28.58	3.1	23.9
N1	77.30	28.74	0.70	-0.98	13.05	-28.16	2.2	18.6
N2	42.54	10.84	0.22	0.49	4.09	-28.37	2.7	18.5
NS	37.73	20.90	0.32	1.59	6.25	-27.22	3.3	19.5
P1	35.58	18.33	0.53	6.85	5.60	-23.81	3.3	10.5
P2	26.40	8.12	0.21	6.27	2.94	-23.79	2.8	14.0
P3	40.68	28.46	0.76	5.44	9.17	-24.64	3.1	12.1
P4	37.91	18.22	0.63	6.02	7.11	-23.19	2.6	11.3
SS1	39.39	6.08	0.01	1.26	0.21	-25.33	29.4	16.2
SS2	33.63	5.01	0.06	6.27	0.62	-25.24	8.1	11.0

Table 4: Resin and fatty acid content (mg kg^{-1} dry weight) in each sample. Compound abbreviations are listed in Table 5.

Sample	ABA	DHAA	PLA	IPA	PA	SCPA	7-ODHAA	MYA	PMA	STA	OLA	LLA	ARA	BHA	LGA
HO								0.10	0.69	0.30	0.12		0.02	0.08	0.30
H1								4.00	32.00	2.00	0.75	0.04	0.21	0.39	1.20
H2								1.17	10.30	1.06	0.18		0.18	0.38	1.30
H3			0.04					0.64	6.60	1.20			0.08	0.16	0.60
H4 - SG								3.00	25.00	1.12	2.00	0.19	0.16	0.39	1.60
HE1	0.21	0.02	0.10			0.24	0.05	5.00	30.00	4.00	2.00	0.23	0.85	2.00	10.00
HE2	0.06		0.05			0.14	0.02	6.00	40.00	2.00	1.66	0.16	0.42	1.17	3.00
HE3	0.08	0.03	0.16		0.15	0.17	0.05	11.00	66.00	7.00	7.00		1.47	4.00	19.00
HL						0.03		4.00	28.00	1.05	1.10	0.09	0.19	0.45	2.20
EP1	2.00	2.00	0.13	0.71	0.87	0.14	0.36	0.21	2.00	0.59	2.00	0.61	1.07	4.00	7.00
EP2	0.19	0.23	0.04	0.05	0.07		0.07	0.09	0.61	0.24	0.11		0.39	2.30	4.00
EP3	19.00	14.00	0.40	3.00	7.00	1.28	2.00	0.23	5.00	1.68	2.15	0.51	1.76	4.00	6.00
EP4	9.00	11.00	1.00	2.00	2.00	0.78	1.00	3.00	9.00	4.00	3.00	1.00	10.00	19.00	23.00
N1	0.05	0.11	0.38	0.03	0.06	0.02	0.07	2.00	21.00	3.00	7.00	2.00	3.00	15.00	62.00
N2	0.10	0.04	0.15	0.03		0.05	0.03	1.00	21.00	4.00	11.00	5.00	1.00	5.00	14.00
NS	2.00	0.24	0.42	0.10	0.49	1.00	0.59	1.00	25.00	5.00	13.00	2.00	4.00	27.00	45.00
P1			0.13					0.14	4.00	1.00	1.31	0.20	1.00	5.00	15.00
P2			0.05					0.13	2.00	0.50	0.95	0.10	0.70	3.00	10.00
P3			0.36					0.41	17.00	3.00	8.00		3.00	13.00	35.00
P4	0.03	0.04	0.19			0.04	0.02	0.18	5.00	2.00	2.00	0.54	2.00	5.00	15.00
SS1	0.05	0.10		0.14		0.02	0.02		0.13				0.11	0.35	0.70
SS2									0.05		0.12		0.02	0.15	1.20

Table 5: Codes and compound names of resin and fatty acids in Table 4.

Code	Compound
Resin acids	
ABA	Abietic acid
DHAA	Dehydroabietic acid
PLA	Palustric acid
IPA	Isopimaric acid
PA	Pimaric acid
SCPA	Sandaracopimaric acid
7-ODHAA	7-Oxodehydroabietic acid
Fatty Acids	
MYA	Myristic acid (C14:0)
PMA	Palmitic acid (C16:0)
STA	Stearic acid (C18:0)
OLA	Oleic acid (+ other C18:1 acids)
LLA	Linoleic acid (+ other C18:2 acids)
ARA	Arachidic acid (C20:0)
BHA	Behenic acid (C22:0)
LGA	Lignoceric acid (C24:0)

The presence of Abietic acid and DHAA in the estuarine arms indicates a direct and recent link with pine forest. Abietic acid is rapidly broken down in sunlight and DHAA, which lasts about 5 times longer than abietic acid, has a half life of about 190 hrs (McMartin 2003). This means that abietic acid and DHAA in the surface sediments may be completely decomposed within a few weeks to months. The absence of resin acids in the open harbour samples, however, does not imply that pine forest is not contributing to these sediments, rather it may be that the contribution was from older inputs and the resin acids have decayed or have been diluted to less than detection levels. Another consideration is the difference in observed grain size between the coarse sands in the open harbour samples and the fine silt beneath the mangroves in the estuarine arms. Adsorption of the resin acids onto soil particles may be associated with the surface area of the particles. As small particles have a larger surface area per unit mass than large particles, the expectation would be for higher concentrations of the resin acids in the fine sediments of the estuarine arms than in the coarse sediments of the open harbour, even if these sediments came from the same source at the same time.

The fatty acids present in all samples show broad patterns of concentration in the samples from different land use types. However, some compounds were not present in all samples, especially linolenic acid, and thus cannot be used in the result matrix for the IsoSource mixing model.

Table 6: Isotopic ($\delta^{13}C$) values (‰) of a range of compounds (Table 5) and the peak areas for each sample. Missing values were below detection level. (* see text about mangrove data).

Sample	MYA	area	PMA	area	STA	area	OLA	area	ARA	area	BHA	area	LGA	area
HO	-28.0	4.43	-25.9	33.24	-31.4	8.16	-30.0	13.74	-26.0	2.29				
H1	-18.7	56.24	-8.3	92.84	-17.5	12.61	-21.3	38.40	-18.5	20.43			-32.2	3.41
H2	-18.7	5.55	-17.6	56.12	-22.0	3.96	-22.3	4.54			-27.7	1.15	-26.3	1.37
H3	-22.0	4.35	-18.5	32.91	-25.4	4.95			-30.8	1.65			-27.2	2.58
H4 - SG	-12.2	12.80	-13.1	104.25	-15.7	8.57	-13.0	16.78			-30.9	1.18	-23.0	1.47
HE1	-29.3	40.59	-26.3	187.51	-28.3	17.73	-29.2	82.98	-30.8	6.80	-31.1	13.42	-36.5	5.08
HE2	-22.4	31.89	-19.5	260.06	-21.5	29.17	-25.7	49.41	-26.8	2.65	-30.4	10.23	-30.2	10.17
HE3	-24.9	39.45	-22.2	170.47	-27.7	18.66	-26.6	77.48	-30.2	5.40	-31.2	8.30	-31.2	14.53
HL	-14.9	15.27	-13.2	128.52	-17.9	10.74	-17.5	19.41	-16.5	5.34	-28.4	1.99	-23.8	2.61
EP1	-31.0	3.48	-28.8	30.21	-27.4	4.71	-30.0	25.47	-28.9	5.16	-30.6	15.89	-30.6	12.11
EP2	-27.1	6.34	-27.9	28.30	-28.2	10.07	-27.4	11.59	-29.1	4.97	-29.1	17.71	-29.8	12.82
EP3	-27.7	3.30	-28.6	22.91	-27.9	6.41	-29.5	23.58	-30.3	4.30	-30.0	7.33	-30.8	6.35
EP4	-36.9	6.61	-30.3	12.45	-29.7	4.81	-27.4	13.26	-31.7	9.16	-30.0	13.26	-31.4	9.12
N1			-34.3	118.51	-30.8	13.23	-29.0	66.13	-35.4	8.72	-33.5	26.32	-39.0	43.93
N2	-32.6	13.15	-31.8	213.20	-29.8	33.65	-30.8	172.31	-32.9	14.68	-34.0	23.83	-36.1	32.19
NS	-31.2	20.85	-27.4	167.56	-25.0	11.28	-29.0	106.70	-26.1	7.00	-29.2	25.45	-31.7	24.14
P1			-21.3	35.67	-26.5	7.56	-23.4	19.07	-27.8	5.34	-30.4	12.03	-32.0	14.80
P2	-23.5	3.20	-22.5	26.19	-26.2	7.87	-22.5	19.86	-21.3	8.12	-28.7	15.90	-29.0	20.42
P3			-27.2	147.07	-28.6	22.56	-27.6	100.31	-34.0	25.47	-32.9	34.20	-34.4	36.72
P4	-27.6	11.57	-20.9	136.72	-23.6	13.32	-23.9	46.18	-26.6	6.93	-29.1	13.82	-29.4	16.42
SS1			-30.3	12.86	-30.8	4.11	-29.6	18.65	-31.0	1.66	-31.2	4.94	-33.4	1.72
SS2	-29.4	2.62	-29.9	14.24	-30.1	4.67					-30.8	6.57	-30.7	1.13
Mangrove*	-27.3	2.56	-28.4	13.54	-30.7	2.55	-26.5	6.36	-29.2	1.53	-27.1	2.91	-30.6	4.01

The isotopic ($\delta^{13}C$) values of the most common fatty acids (Table 6) show large differences between samples for each fatty acid. Peak area data also indicates large concentration variations comparable with the measured concentrations (Table 4). In general there is a pattern of more enriched $\delta^{13}C$ values (less negative) in the harbour samples with the most enriched samples being associated with the seagrass beds at sites H4 and HL. There is a gradient across the open intertidal sandflats between site H4 and site H2 inshore which can only be explained if site H4 is regarded as a source of sediment.

Although the concentrations of the fatty acids at the ocean site HO are very low, consistent with the very low %C (Table 3), the $\delta^{13}C$ values indicate that terrestrial sediment has been reaching this site. The much higher concentrations for some compounds in the estuarine arms are consistent with these areas being sinks for catchment soils, presumably trapped by the fringing mangroves. Mangrove data from Mahurangi Harbour are given to demonstrate that mangroves trap sediment containing these compounds, rather than producing high levels of them. The mangrove data were not used in the IsoSource model runs.

4. Modelling and data interpretation

4.1 Scatter plots for IsoSource modelling

The data matrices were plotted as pairs of compounds for each source sample and then the individual harbour samples were superimposed to determine the likely sources contributing to that site. The sources selected were constrained by their ability to contribute directly to the site being tested. The combination of compounds and sources were then applied to the IsoSource mixing model and the model run to determine feasible proportions of each source in the sample being tested.

An example of the procedure is a shown in the following sequence (Figs. 3-6):

Using the $\delta^{13}C$ values of the compounds, Stearic acid and Oleic acid, a scatter plot is constructed which uses all the source samples (Fig. 3). The $\delta^{13}C$ values of the harbour sample, H1, for the same compounds, is superimposed on the plot (red open circle) and an ellipse is manually drawn enclosing those sources which, by virtue of their proximity to the harbour sample in the scatter plot, potentially contribute sediment to that site in the harbour.

The selection of sources is then constrained by the physical possibility of each source contributing sediment to that specific site in the harbour. It is assumed that the natural hydrology of tidal dispersion will carry sediment out of the harbour on the ebb tide and deposit sediment around the harbour edges on the flood tide with no deposition except from the inflow stream in the stream channel. Using these criteria, although sources P2, P3, and P4 are within the ellipse, it is unlikely that sediment from those sources could reach the site H1 in the harbour, and thus they can be eliminated. Similarly, it is unlikely the sediment from the source EP3 could reach site H1 and it can be eliminated. Sources outside the ellipse can also be eliminated, as potential but only minor contributors, and a straight line polygon can be drawn connecting the remaining sources (Fig. 4).

It can be seen (Fig. 4) that the position of the harbour sample H1 lies outside the polygon. This indicates that there may be another source which has not been sampled. In this case the missing sample may be pure seagrass which typically has a $\delta^{13}C$ value of around –8 ‰. However, it may also reflect sampling and analytical variability. The IsoSource model tolerance setting allows points outside the polygon to be included in the analysis. Beyond the tolerance range there will be no meaningful result. In this example, using the tolerance value was set to 2 and the model produced a set of feasible solutions for each source (Fig. 5).

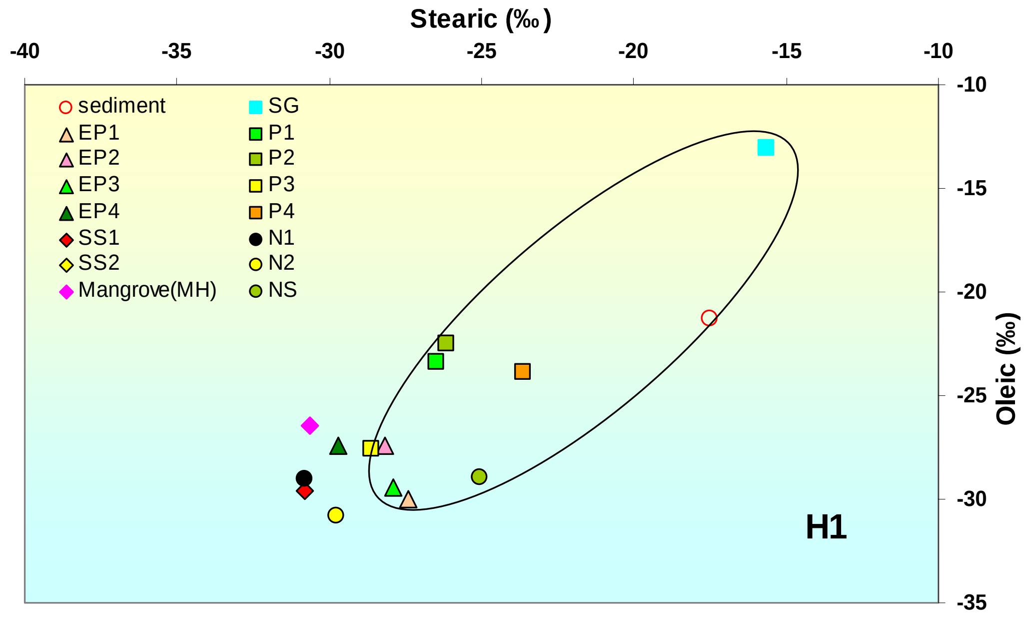

Figure 3: Scatter plot of all source samples using the compound specific isotopic values of Stearic acid and Oleic acid. The harbour sediment sample, H1, is superimposed on the scatter plot using the same compounds. The ellipse encloses potential sources contributing to the sediment at that site in the harbour.

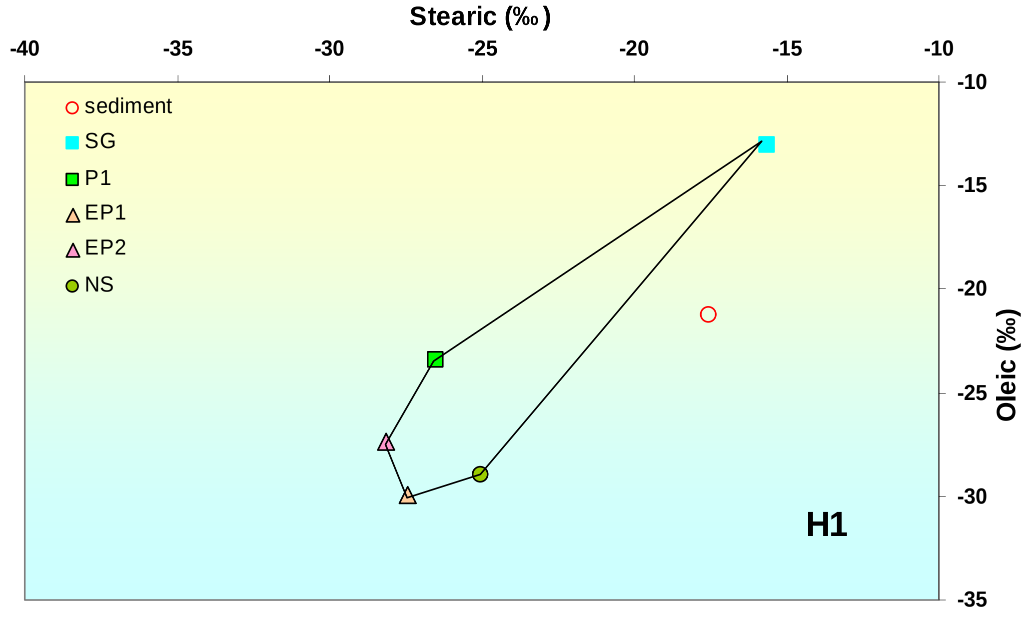

Figure 4: Selected sources plotted and connected as a straight line polygon relative to the harbour sediment sample, H1, being tested. While the sample H1 is outside the polygon, it is within the tolerance range of the IsoSource model.

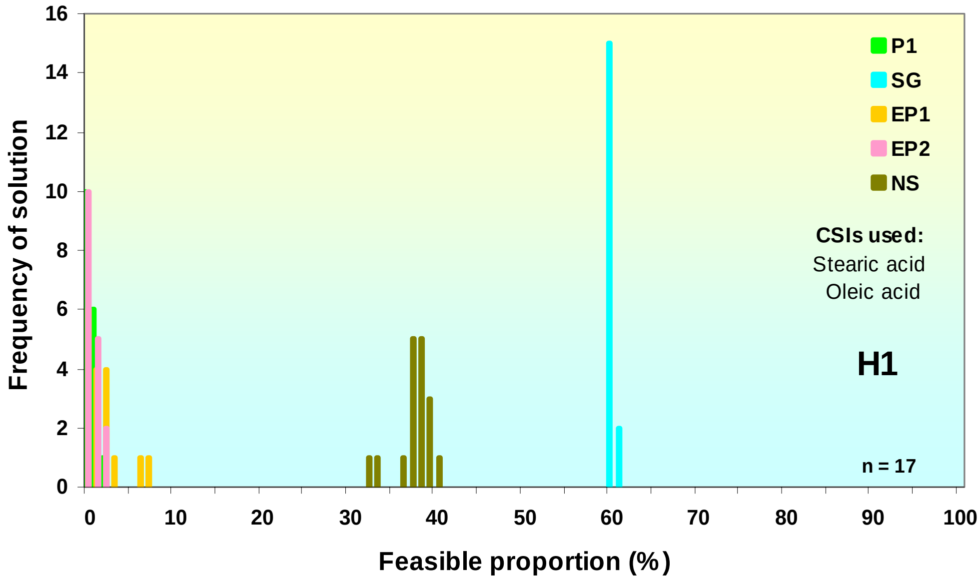

Figure 5: IsoSource model output showing the feasible proportions of the labels of each of the 4 sources at site H1 in the harbour, using the CSIs of Stearic acid and Oleic acid.

The number of feasible solutions is an indication of the reliability of the result with reliability increasing as the number of feasible solutions decreases towards 1, which is a unique solution. The model output (Fig.5) shows that there are a total of 17 feasible solutions for the source labels using this combination of sources and the CSIs of Stearic acid and Oleic acid. The native scrub source, NS, contributes between 33-41% of the label to site H1 in the harbour while the seagrass source, SG, contributes 60-61% with 16 of the 17 solutions favouring 60%. Of the other three potential sources, feasible solutions indicate that while the exotic pine source, EP1, may contribute up to 7%, the other exotic pine source, EP2, and the pasture source, P1, probably contribute less than 2% of the label to the harbour sediment at this location and at this time. However, because EP1, EP2, and P1 include a high number of solutions at 0%, it is also feasible that these sources contribute nothing to the site H1 in the harbour, although this is unlikely.

The procedure used in the example is repeated for a number of different CSIs and adding or subtracting different CSIs and sources. For example adding a third isotope, bulk $\delta^{13}C$, did not alter the feasible proportions of the sources selected, which gives confidence in the result. However, while changing the minor sources EP1 or EP2 for native forest source, N1, did not substantially alter the result, changing the native scrub source to native forest significantly increased the number of feasible solutions from 17 to 414,733, meaning that there is low reliability in any one solution. The broad ranges of feasible solutions produced spread from 0% to >40% for all but seagrass which spread from 39-80% (Fig. 6). The shift from finite ranges of feasible solutions to broad ranges indicates that at least one of the sources is wrong or that a source is missing. To cause this response by changing native scrub to native forest is compelling evidence that native scrub is a major contributor of sediment to the site H1 in the harbour.

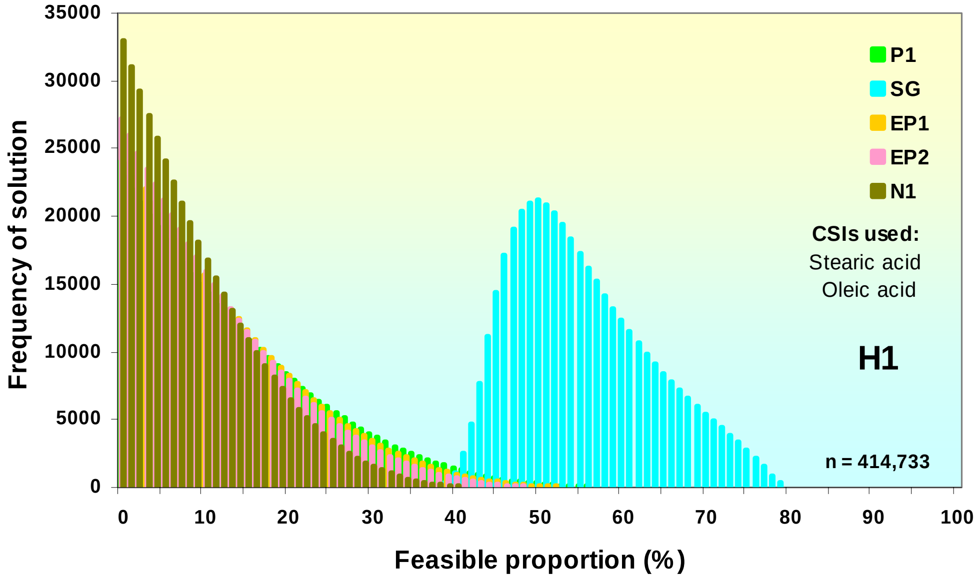

Figure 6: IsoSource model output showing the effect of changing the native scrub source, NS, to native forest, N1. The large number of feasible solutions indicates low reliability in the result. The broad pattern to the feasible proportions of each source indicates that at least one of the sources is wrong or that there is a missing source.

After a number of model runs, a range of feasible results is built from which there is confidence that the same pattern is being seen and that the range of results produced is a reasonable apportionment of the labels of the sources contributing sediment to that site in the harbour.

4.2 Model output

The results of repeated modelling runs provided a set of feasible proportions of the labels of individual source contribution to the sediment at each of the sites sampled in the harbour and estuarine arms (Table 7). These results are presented as best estimates. They do not imply that other sources of sediment do not contribute, rather that the soil sources identified are the major contributors with other sources possible in small proportions. These results are also tempered with the assumption that all possible source types were represented in the terrigenous samples collected and it is possible that a source may have been missed.

Table 7: Summary of source label apportionments as percent contribution of each source at the specified site in the harbour. Values given as a finite range indicate that source label is present within the limits of that range at that site in the harbour**.** Values with a range from zero indicate that the source is minor or may not be present. Blank cells indicate that those sources were most likely not present due to geographic constraints or their inability to contribute to a meaningful result. Solutions is the number of feasible solutions found using the major source components listed. The reliability of the major component result increases as the number of solutions decreases towards 1, a unique solution. (Values for site H0 are for the ~10% terrigenous component, ~90% = marine sand.) [EP = exotic pine forest; N = native forest; NS = native scrub; P = pasture; SG = sea grass; SS = sub-soils; H = harbour flats; HE = harbour estuarine arms].

Site	**Solutions**					**Sources**									
	(number)	**EP1**	**EP2**	**EP3**	**EP4**	**N1**	**N2**	**NS**	**P1**	**P2**	**P3**	**P4**	**SG**	**SS1**	**SS2**
H0	28			24-28				38-42	0-2	24-27		6-11			
H1	6	0-7	0-2			0-2	0-7	32-40	0-7				60-61		
H2	5	39-42				0-5		10-13	0-6				47-48		
H3	7	45-48				0-4		30-34	0-12				21-22		
HE1	3			30-31		69-70						0-2			
HE2	18			24-29			0-3	0-7			6-11	63-67			
HE3	22			52-55					37-45	2-8					

Table 8: Summary of source apportionments as percent contribution of each soil source at the specified site in the harbour. Values are calculated from the means of the source label apportionments (Table 7) corrected for mass using %C values for each source. These estimates are rounded to the nearest whole number as a decimal place would imply greater accuracy than is possible. [EP = exotic pine forest; N = native forest; NS = native scrub; P = pasture; SG = sea grass; SS = sub-soils; H = harbour flats; HE = harbour estuarine arms]. (Values for site H0 are for the ~10% terrigenous component, ~90% = marine sand.)

Site	**Solutions**	**Sources**													
	(number)	**EP1**	**EP2**	**EP3**	**EP4**	**N1**	**N2**	**NS**	**P1**	**P2**	**P3**	**P4**	**SG**	**SS1**	**SS2**
H0	28			44				22	1	29		4			
H1	6	4	1			0	4	26	3				62		
H2	5	44				1		8	2				45		
H3	7	52				1		22	5				21		
HE1	3			74		26						1			
HE2	18			54			1	2			6	36			
HE3	22			75					20	5					

The model output (Table 7) gives the feasible proportions of the source labels at each site. Using a post processing algorithm, these feasible proportions are converted to the mean proportions of soil sources as % contribution to the sediments in the harbour at the time of sampling (Table 8). A comparison of the source contributions at each site (Fig. 7) uses the sum of the main land use types (i.e., native forest including scrub, exotic pine forest, and pasture) plus seagrass for clarity.

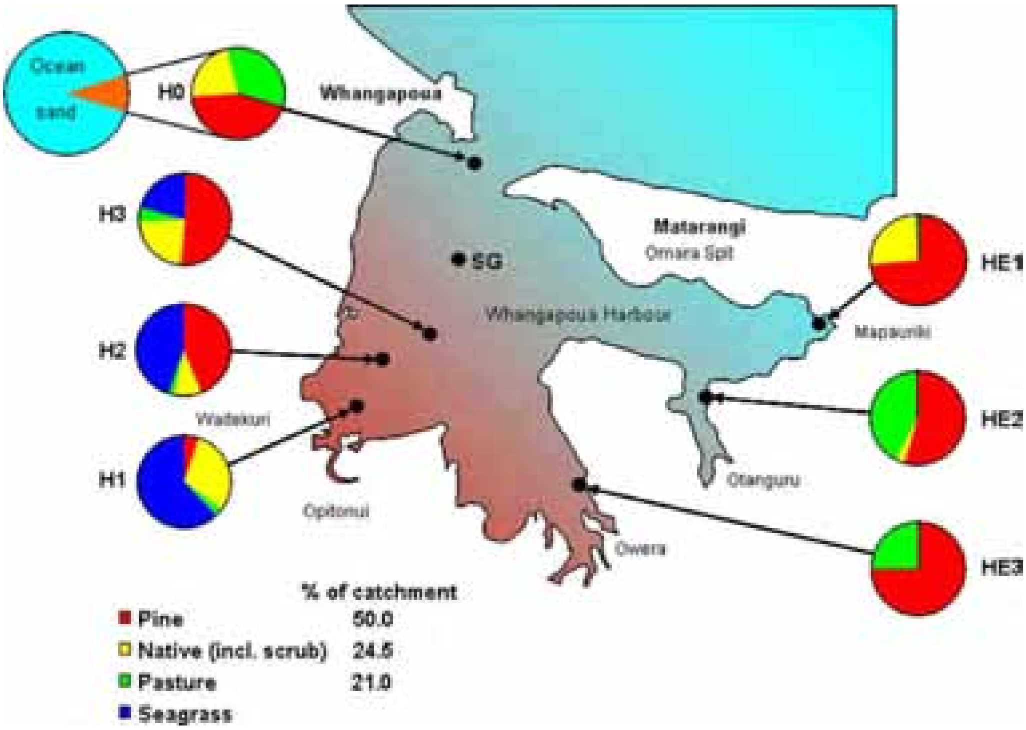

Figure 7: Comparative source contributions at the sites sampled in the Whangapoua Harbour. At site H0, about 90% of the sand is of marine origin and the proportions of terrigenous soil contributions are estimated for the non-marine component. SG = seagrass beds.

Many combinations of sources and CSIs produced apportionments with high numbers of solutions (i.e., low reliability). However, applying the constraint of geographic proximity (i.e., the possibility for the source to contribute sediment to the site in the harbour being tested) reduced the number of feasible solutions and, consequently, increased the reliability of the results to a range of best estimates (Table 7).

It was apparent during modelling that some soil types were more site specific within the catchment than others, such as the native soil types, which appear to be generic and occur at many locations around the harbour. Sources SS1 and SS2 were more localised and, although they had the potential to contribute to the sites at H1-3 and HO, no meaningful results (number of solutions very large) were obtained while using either of these sources.

5. Discussion

Whangapoua Harbour receives freshwater inputs from 5 major rivers or streams which drain land that is covered with native forest or scrub, exotic pine forest, and pasture. The results of modelling and apportionment of potential sediment sources at the 7 sites in the harbour (Table 7) show that, while the majority of these sources contribute little, there are sources which have recently contributed substantial amounts of sediment to these sites. The results show that, within the constraints of geographic possibility, there are highly reliable feasible solutions that describe and apportion the contribution of possible upstream sources at most sites in the harbour.

The results, converted to % soil contribution (Table 8, Fig. 7), demonstrate that soil from pasture generally contributes a minor amount to the harbour sediments at most sites, but there is a substantial soil contribution from native scrub or forest at many sites. This is consistent with minimal erosion of lowland farm land and the presence of native forest and scrub in the steep-sided gullies where erosion is more likely to occur. High country slippage during severe storm events, such as occurred in March 1995, is the most likely cause of the large native soil component in the harbour (Marden & Rowan 1995).

The results also show that, at almost all sites, there is a substantial soil component from exotic pine forestry. Erosion from undisturbed pine forest is unlikely to be very different to that occurring in stable native forest and none of the model results (Table 8) show any significant contribution of soil from undisturbed pine forest (EP4). However, when the pine-forest soil becomes exposed during logging operations, it is likely to remain a source of terrigenous soil for up to 2 years (Marden et al. 2006) until weed cover and subsequent planting stabilises the surface soil against erosion. While in this vulnerable state even light rainfall can induce sediment mobilisation (Photo 1). Skidder pads and cuts made for roading are also potential sources of sediment (Photo 2). Deep disturbance due to log hauling produces more sediment than shallow disturbance (Marden et al. 2006).

When interpreting the results (Table 8) it is important to appreciate that the sediment contributions from various sources estimated from the modelling includes recent deposition and some longer-term deposition over a period of several years. Since 2000 there have been at least eight high intensity rainfall events which have produced flood flows of >150 $m^3 s^{-1}$ in the Opitonui River. Harvested pine forest is more vulnerable to these rainfall events because the vegetative cover has been removed as part of normal best practice management of clearfelling. Once vegetative cover is re-established the erosion risk is reduced to that of native forest. The amount of clearfelled land and roading within the forest and the land slope determine the amount of soil eroded during an intense rainfall event, rather than the area of the catchment in pine forest (Phillips et al. 2005).

Photo 1: Bare soil exposed by clearfell logging and replanted showing vulnerability to erosion even during light rain.

Photo 2: Access roads to extract the logs, are also vulnerable to sediment erosion and may act as conduits for sediment laden runoff directly to streams.

5.1 Transport mechanisms

Comparison of the CSI method results (Table 8) and the resin acid composition data (Table 4) at each site in the harbour suggests that the forestry soil component in the estuarine arms may be recent (Abietic acid present) while the forestry component in the open harbour sandflats is from past activity and highly leached (i.e., almost no measurable resin acids present). Also, the presence of soil from recent forestry logging activity at sites HE1 and HE2, when there is no forestry logging activity in their catchments, indicates that there has been a pervasive dispersal of that soil from another catchment where there is active logging. These observations indicate that there are likely to be two different sediment transport mechanisms for dispersing the soil eroded from exotic pine forest and other catchment sources: (1) dispersion by the freshwater layer over the estuarine salt wedge and (2) delayed bed-load transport from the rivers and streams.

5.1.1 Freshwater dispersion over the estuarine salt wedge

Catchment soil is sequentially eroded by rainfall by particle size with the smallest and lightest particles usually being mobilised first. Consequently, even light rain will cause a stream to “colour”. These fine particles are typically silts and clays which remain in suspension in the freshwater layer as it flows out into the harbour as a surface buoyant layer. Subsequently, wind and wave action cause the freshwater layer to mix with seawater which induces flocculation and sedimentation out of the water column.

On the ebb tide, this turbid water mixture is drawn out of the harbour and sedimentation occurs in the coastal waters. Traces of most sources were detected in the sediment at site HO confirming transport out of the harbour. On the flood tide, however, the incoming salt wedge intrusion lifts the freshwater into a surface layer (Photo 3) and pushes it back against the river flow so that it is dispersed laterally into the fringing mangroves. There the terrigenous soils are trapped as they flocculate and sediment out of the water column. River water that has reached the main harbour channel will be carried eastwards by the inflowing tide.

This transport mechanism means that the fine clays eroded from exotic forestry land exposed during logging operations in one catchment may be carried into adjacent estuarine arms as a pervasive contaminant. This mode of sediment transport is consistent with finding deposition of recently eroded (within months) exotic pine forest soil in the eastern estuarine arms of Whangapoua Harbour, at sites HE1 and HE2, even though there was no active logging in those sub-catchments. Note that soil from the sub-catchment will be found in the main channel of the estuarine arm, whereas transported sediment will not, as it will be deposited along the shoreline at high tide.

Photo 3: Clay trapped in the freshwater layer on the surface of the harbour can be transported laterally into adjacent estuarine arms on the rising tide.

At site HE1, the dominant source of sediment was exotic pine forest (~74%) while native scrub, which is a major land-use type in that sub-catchment and surrounds that estuarine arm, contributed substantially less (~26%). Local pasture was only a minor contributor of sediment to the site sampled. At site HE2, the dominant source of sediment was also exotic pine forest (~54%) although local pasture contributed almost the same (~42%) which is consistent with that small estuarine arm being surrounded by farmland. Native forest or scrub contributed little to the site sampled. In contrast to the expected sediment sources, the high contribution of soil from recently logged exotic pine forest (EP3) has no local source in either sub-catchment and thus it must have been carried to these sites from another sub-catchment, on the rising tide.

At site HE3, the dominant source of sediment was from exotic pine forest (EP3) (75%), which is consistent with the recent logging activity in that sub-catchment. Lowland pasture contributed most of the rest of the soil at that site (20%) with additional pasture soil (~5%) coming from higher in the catchment.

At sites H1, the main terrigenous sediment source was native scrub (NS) (~26%) and, although there were low levels of sediment derived from lowland pasture (P1) and exotic pine forest soils (EP1), the CSI isotopic signatures were dominated by a strong seagrass influence of around 60%. The presence of the seagrass (SG) signature well inshore of the main seagrass beds on the open sandflats, suggests transport inshore of seagrass detritus on the flood tide. Subsequent burial and breakdown of this detritus would be a reasonable explanation for the observed CSI isotopic signatures. Seagrass detritus was found on the sands at site HO (Appendix Site Photo HO) although substantial burial and decomposition of that debris at that site was not evident from the CSI results.

At sites H2 and H3, the seagrass influence was reduced and the proportional contributions of soil from exotic pine forest (EP1) and native scrub (NS) became dominant (Table 8). This is consistent with the large area of land under young pine cultivation and native scrub in this sub-catchment. The low percentage of pasture soils (P1) at these sites is also consistent with the proportion of lowland pasture in this sub-catchment.

While there was a large proportion of soil contribution from exotic pine forest in the harbour sediments at sites H2 and H3, the lack of the signature of recently logged pine forest (EP3) indicates that this soil has been in the system for sufficient time to allow degradation of the major resin acids by sunlight or the resin acids have been leached. This indicates that that sediment may be associated with the delayed bed-load transport mechanism.

5.1.2 Delayed bed-load transport from the rivers and streams

While light to moderate rainfall will mobilise the smallest and lightest particles first, high intensity rainfall and "weather bombs" cause the larger particles, including sand, gravels, rocks, and fallen trees etc., to be washed down the rivers in flood flows. The fine particles will remain in suspension in the freshwater much longer than the larger particles as the flood water flows out into the harbour.

However, in large flood events such as March 1995, the quantity of fines is likely to exceed the capacity of the tide to transport it out of the harbour and the harbour sediments will be covered with mud. Such events are rare but have a catastrophic effect on benthic communities. The mud smothers plants and animals living in and on the intertidal zones (Photo 4). Wave action on subsequent tidal cycles will gradually erode the mud layer, winnowing it out of the courser material where it will be dispersed elsewhere in the harbour or transported out of the harbour on the ebb tides.

However, material that did not reach the harbour during the period of the flood can be washed out of the rivers and streams by bed load transport during lesser rainstorms subsequent to the main flood event. Again, winnowing will tend to transport the finer material first leaving the coarser material to be flushed out much later on.

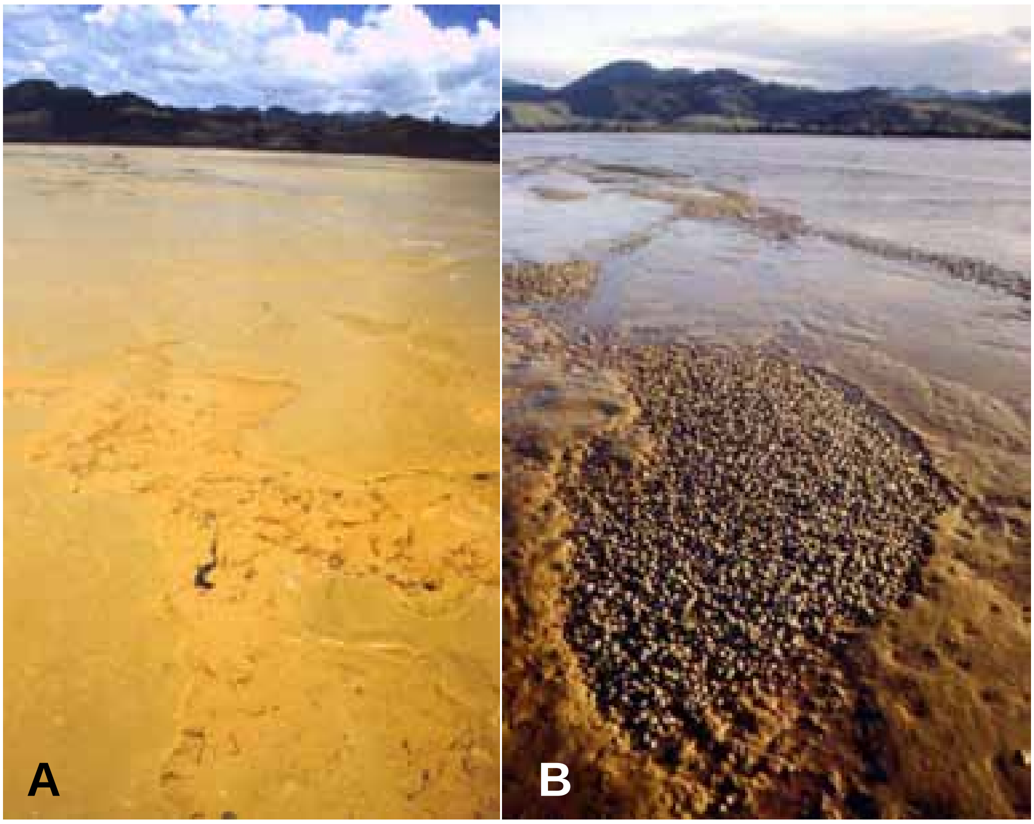

Photo 4: The March 1995 weather bomb delivered very large amounts of fine sediment to Whangapoua Harbour. The deposition of the mud was catastrophic, smothering the benthic communities throughout the harbour including the seagrass beds (A) and cockle beds B. (Photos by Ron Ovenden).

The suspension of the larger material is dependent on flow velocity and these particles will rapidly drop out of the water column as the flow velocity slows. Consequently, the river bed may store a proportion of the coarser soils and gravels for some time after the flood flow has passed. This bed-load material is gradually washed out of the river into the harbour with successive rain events and may build up around the river mouth as a delta, if the harbour is deep. Otherwise the bed-load material will roll across the shallows until it reaches deep water or wave action and tidal currents causes it to disperse across the intertidal zone during periods of immersion.

An example of this transport mechanism was observed in Whangapoua Harbour in February 1999 (Photo 5) following a major storm event in December 1998. Bed-load material slowly moved down the Opitonui River channel as a well defined layer that was about 20 cm thick at the leading edge.

Photo 5: Leading edge of coarse bed-load material slowly moving down the Opitonui River channel in Whangapoua Harbour, 5 February 1999. [Photo by Ron Ovenden].

Photo 6: Closer detail of the leading edge showing the accumulation of forest litter including sticks, bark and pine cones. This woody debris has been in the water for a considerable time to become water-logged and settle rather than floating away on the tide. 5 February 1999. [Photo by Ron Ovenden].

The inclusion of pine debris along the leading edge (Photo 6) is confirmation that at least part of this material was derived from pine forest. In December 1998, there was about 55 km^2 of clearfell forest in the Opitonui River and Awaroa tributary catchment (Quinn & Wright-Stow 2005). While the bed-load material from that storm event would eventually be flushed from the river channel, the succession of storm events means that this a chronic condition with catchment soil continuously replacing the surface layers of the intertidal sandflats. First the flood event covers the harbour sediments with mud which is then winnowed to leave coarser material which may never be completely dispersed out of the harbour and thus contributes to the in-filling.

During the sampling for this study, a cut down through the harbour sediment at sites H1-H3 showed that there was a red-brown layer several centimetres thick (Photo 7) on top of the grey-white sediment that characterises the sediments along the main channels at low tide. This confirms the presence of the bed-load layer on the intertidal sandflats.

Photo 7: A section cut down through the intertidal sandflats at site H3 showing the layer of red-brown bed-load material covering the grey-white sands of the natural sandflats. Shell fragments have been entrained into the bed-load material.

The pattern of exotic pine forest sediment contribution along the transect line from site H1 to H4 (SG Fig. 7) is consistent with the bed-load transport mechanism and tidal dispersion. At site H1, the proportion of exotic pine forest soil contribution was low at less than 5% which probably means most of the recent bed load material has been moved past that point in the harbour. The proportion of exotic pine forest soil contribution progressively increased to ~44% at site H2 and to ~52% at site H3 which is consistent it moving across the intertidal sandflats as bed load material. At site H4, beyond the ‘plume’ of red-brown catchment sediment on the intertidal sandflats, there was no measurable proportion of exotic pine forest soil contribution and that site was dominated by the seagrass isotopic signature.

In contrast to the changing levels of exotic pine forest soil contribution across the intertidal sandflats, the proportion of soil contribution from native scrub land was around 22-26% at sites H1, H3 and HO suggesting that this may be the normal level of soil runoff without the exotic pine forest contribution. This implies that, prior to the introduction of pine forestry, the natural sediment loads into the Whangapoua Harbour may have been considerably lower than at present. However, this speculation is tempered with the observation that the land presently used for exotic pine forestry would have been native forest and scrub land contributing sediment at a similar rate as at present.

A consequence of the winnowing of the fine sediment/mud and bed load transport is that sediment levels may change little across the inner intertidal zone and may be eroded away from the outer edges of the sandflats by wave action, giving the impression that the physical proportions of the intertidal sandflats are unaffected by the terrigenous sediment input.

From the perspective of the macrobenthic community living on and in these intertidal sandflats, the coarse material in the catchment soil deposits is likely to have minimal effects compared with the chronic and episodic exposure to high suspended solids and mud deposition at the time of a storm event.

6. Summary and Conclusions

Whangapoua Harbour is a complex system with five river and stream inflows and a single narrow entrance to the sea. The CSI technique has identified and apportioned the contribution of terrigenous soils from several different land use type sources in the catchment in recent sediments at a number of locations within the harbour:

- Native forest and scrub contribute around 22-26% of the soil in the sediment at most sites in the harbour.
- Pasture soil contributions were generally less than 10% at most sites in the harbour. The exceptions were at the Otanguru (HE2) and Owera (HE3) sites where local pasture contributed ~42% and ~25%, respectively.
- Recently logged exotic pine forest (EP3) contributed ~54-75% of the soil to the Mapauriki, Otanguru and Owera estuarine arm sites.
- Soil from young pine forest planted in the Opitonui catchment (EP1, EP2) contributed soil to the open sandflats on the western side of the harbour with proportions increasing from <10% at the mouth of the Opitonui River to about 52% towards the main channel of the harbour about 1.5 km downstream (Sites H1-H3).
- Seagrass beds near the main channel (SG) are exposed at low tide and thus vulnerable to wave action. CSI signatures of seagrass were found across the intertidal sandflats and indicate that seagrass debris and sediment is being transported inshore on the rising tide.
- Interpretation of the results attributes the dispersion of recently logged exotic pine forest soil to the freshwater layer carrying this material being forced inshore on the rising tide.
- Interpretation of the results also attributes the dispersion of the soils from young pine plantings to bed load transport from the Opitonui River after intense rainfall events.
- Evidence from historic photos demonstrates that flood events can cover the intertidal sediments with mud which has the potential to smother the benthic community. However, winnowing by wave and tidal action can remove the mud over time.
- Interpretation of these transport mechanisms and processes suggest that, while coarse catchment derived material may cover the intertidal sandflats and contribute

to harbour in-filling, this material is likely to have less effect on the benthic community than their chronic and episodic exposure to high suspended solids and mud deposition during storm events.

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9. Appendix - Site photos.

Site photos were taken whenever possible and are presented to show key features.

Site H1: Red-brown sediment at the Ecological site 1 marker peg beside the Opitonui River.

Site H3: Red-brown sediment 1.5 km downstream from H1 beside the Opitonui River.

Site HO: Grey-white sands at the harbour entrance. Note the seagrass debris on the sand.

Site HE2: Fine silt around mangroves in the estuarine arm from Otanguru catchment.

Site HE3: Fine silt trapped in the mangrove roots beside the Owera Stream.

Site EP1: Skidder pad silt runoff in young pine in the Opitonui catchment. The soil has a characteristic orange-brown colour and is relatively coarse grained indicating loss of fine material when the area was clearfelled during harvest.

Site EP2: Skidder pad in the Awaroa tributary of the Opitonui catchment showing the large area of young pine forest.

Site EP2: Close up view of the silt runoff from this skidder pad. The soil has a characteristic red colour and is coarse grained indicating loss of fine material when the area was clearfelled during harvest.

Site EP3: Skidder pad in active logging area in Owera catchment.

Site EP3: Close up of the soil showing the orange-yellow soil which has a mixture of coarse and fine particles intermixed with pine debris.

Site EP4: Undisturbed mature pine in the Otanguru catchment showing the dense native undergrowth which stabilises the soil against erosion.

Site EP4: Close up of the soil and pine needle litter in the forest understorey.

Site N1: Native forest dominated by Nikau palms and a dense canopy of broad leaf trees on the Coromandel Hill. This is a generic soil type.

Site N1: Close up of the black silty soil and leaf-mould beneath the native forest at N1.

Site N2: Native forest at the top of the ridge on Castle Rock road. This is a generic soil type.

Site NS Native scrub on clay slopes above the lagoon. This is a generic soil type.

Site P1: Lowland pasture on farm land above the Opitonui River flood plane.

Site P2: Highland pasture on farmland in the Owera Stream catchment.

Site P3: Hill country pasture on the western side of the catchment beside the Waitekuri River.

Site P4: Lowland pasture on the eastern side of the catchment beside the Mapauriki Stream.

In most sub-catchments of the Whangapoua catchment there are multiple sources which may include pasture, native forest, native scrub, mature undisturbed exotic pine forest, clearfelled exotic pine forest, and young exotic pine forest plantings.