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APPLIED ISSUES

Catchment- and site-scale influences of forest cover and longitudinal forest position on the distribution of a diadromous fish

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SUMMARY

1. The hydrologic connectivity between landscape elements and streams means that fragmentation of terrestrial habitats could affect the distribution of stream faunas at multiple spatial scales. We investigated how catchment- and site-scale influences, including proportion and position of forest cover within a catchment, and presence of riparian forest cover affected the distribution of a diadromous fish.
2. The occurrence of koaro (*Galaxias brevipinnis*) in 50-m stream reaches with either forested or non-forested riparian margins at 172 sites in 24 catchments on Banks Peninsula, South Island, New Zealand was analysed. Proportions of catchments forested and the dominant position (upland or lowland) of forest within catchments were determined using geographical information system spatial analysis tools.
3. Multivariate analysis of variance indicated forest position and proportion forested at the catchment accounted for the majority of the variation in the overall proportion of sites in a catchment with koaro.
4. Where forest was predominantly in the lower part of the catchments, the presence of riparian cover was important in explaining the proportion of sites with koaro. However, where forest was predominantly in the upper part of the catchment, the effect of riparian forest was not as strong. In the absence of riparian forest cover, no patterns of koaro distribution with respect to catchment forest cover or forest position were detected.
5. These results indicate that landscape elements, such as the proportion and position of catchment forest, operating at catchment-scales, influence the distribution of diadromous fish but their influence depends on the presence of riparian vegetation, a site-scale factor.

Keywords: fish distribution, *Galaxias brevipinnis*, Galaxiidae, geographical information system, land use, New Zealand, riparian vegetation

Introduction

Biotic interactions and movement patterns such as diadromous migrations can have major influences on the spatial distribution of stream fishes (Gilliam, Fraser & Alkins-Koo, 1993; McDowall, 1996, 1998a,b), but abiotic factors operating at large spatial scales should not be ignored (Matthews, 1998). Over a quarter of a century ago, Hynes (1975) argued that, in every respect, the valley rules the stream, emphasis-

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ing the link between terrestrial and aquatic environments. Although still not completely understood, the impact of historical catchment-scale land-use practices and local modifications to the landscape on streams are becoming clearer (Hynes, 1975; Naiman, 1992; Osborne & Kovacic, 1993; Richards & Host, 1994). However, much of our current knowledge of the ecology of rivers and streams is based on studies of organisms and habitats at small spatial scales. Such small-scale investigations can limit the ecological understanding needed to underpin conservation efforts for stream fishes (Fausch *et al.*, 2002). Moreover, riverine ecosystems have frequently been degraded by ecosystem-wide activities in the terrestrial environment, and they are rarely bounded by the area selected for study (Nakano, Miyasaka & Kuhara, 1999). These activities, historical and contemporary, include road construction, forest harvesting, mining, water diversion, agricultural, industrial and municipal uses (Allan & Flecker, 1993; Kauffman *et al.*, 1997), which in turn influence the timing and quantity of flow within channels (Fahey & Watson, 1991; Richards & Host, 1994). Degradation of the stream valley ecosystems and the riparian zones that link streams with their catchments are likely to diminish a catchment's capacity to provide critical riverine functions necessary for streams and their biota (Osborne & Kovacic, 1993).

Headwater and downstream systems are linked not only by the unidirectional downstream flow of water, but also by the upstream and downstream migration of animals, notably diadromous fishes. Headwater streams are generally small and numerous, with high drainage density and numerous land use types and intensities whose roles in terms of upstream-downstream linkages are typically underestimated (Gomi, Sidle & Richardson, 2003). Therefore, to allow for effective research and conservation of fishes (Fausch *et al.*, 2002), there is a need for a continuous view of rivers and streams. This would not only recognise upstream-downstream linkages, but also incorporate the spatial heterogeneity and connectivity of habitat patches critical for completion of fish life cycles (Schlosser, 1995). Studies of fish populations in New Zealand and elsewhere have typically been undertaken at small spatial scales (but see Minns, 1990). Studies on the spatial distributions of freshwater fish that link local and landscape scales are needed. The objective of our study was to investigate catchment- and site-scale effects on of forest cover on stream-reach occupancy by a native New Zealand galaxiid, the koaro (*Galaxias brevipinnis* Günther).

New Zealand's landscape reflects the geologic history of the region as well as recent events such as floods, fires and human-induced environmental changes including deforestation, dam construction, pollution and introduction of exotic species. In New Zealand, pastoral and forestry land uses are perceived to be some of the main causes of degradation of inland waters (Scarsbrook & Halliday, 1999; Quinn & Stroud, 2002). At the catchment scale, conversion of native forest or tussock grassland to plantation forest or pasture has altered hydrologic patterns (Graynoth, 1979; Fahey & Watson, 1991), and may also have caused a loss of physical habitat and deterioration of water quality and substrate composition. Channel morphology adjustments have increased loads of fine suspended and deposited sediments (Jowett & Boustead, 2001; Quinn & Stroud, 2002).

The koaro is an amphidromous species (McDowall, 2000) whose migratory behaviour takes it through a variety of habitats during journey from the marine environment back to inland freshwater habitats where adult fish are found. Koaro are exceptional climbers and can negotiate even steep waterfalls (McDowall, 1990). While found in grassland streams at a few locations, koaro favour cobble-boulder substrata in streams with extensive riparian forest vegetation (McDowall, 1990). Koaro exhibit an open population structure because of the mixing of juveniles from different streams while they are at sea, and the species contribute significantly to a commercial and recreational catch (known as whitebait) in some areas of New Zealand (McDowall, 1990). They are generalist predators that feed on a variety of terrestrial and aquatic invertebrate prey (Main & Winterbourn, 1987; McDowall, 1990). Koaro are common throughout New Zealand and are currently not listed as threatened, although the adult habitat is thought to have been greatly reduced by changes in land use from native forest to pasture (Hanchet, 1990; Rowe *et al.*, 1999).

We expected to find higher proportions of sites with koaro within catchments with greater proportions of their surface covered by forests and of sites with riparian forest on their banks, as the species prefers forested streams (McDowall, 1990). Because forest cover attenuates possible negative impacts of detrimental land uses, we also expected to find a higher frequency of koaro occupancy in catchments with higher overall proportions of forest cover compared with catchments with little forest cover. Finally, we anticipated finding higher site occupancy of koaro in catchments with forested upland reaches, as forested upland areas play a significant role in maintaining overall stream habitat quality even in downstream locations.

Our three main objectives were to: (i) elucidate the role of the dominant position of forests within catchments on koaro occurrence in the catchment, (ii) to determine the influence of the extent of catchment forest cover on koaro occurrence in the catchment and (iii) to investigate the effect of riparian forest at sites and its effect on the influence of catchment-scale forest cover on koaro distribution.

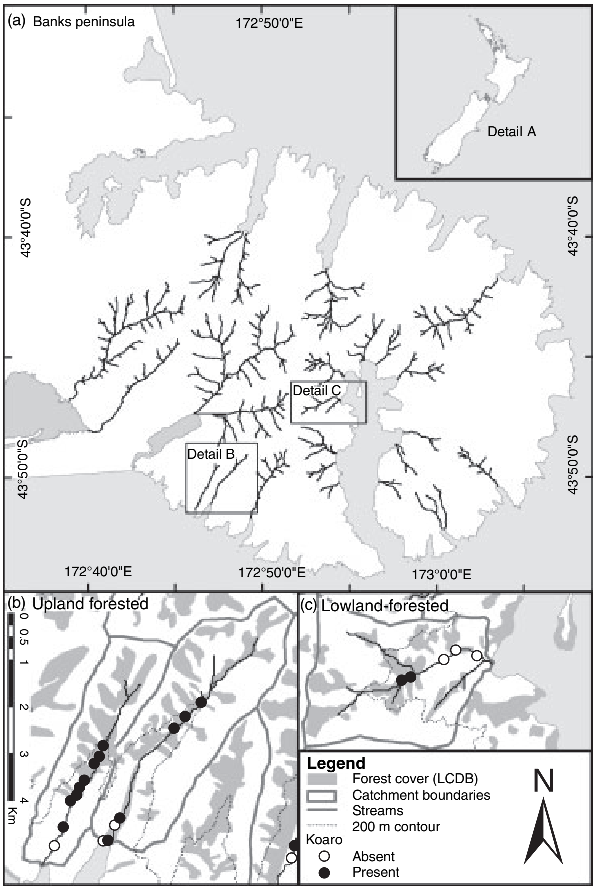

Fig. 1 (a) Location of the 24 sampled catchments on Banks Peninsula. (b) Two catchments with a greater percentage of forests in upland areas. (c) One catchment with a greater percentage of forest in lowland areas.

Methods

Study area

Banks Peninsula is an 1102-km^2 promontory feature comprising two extinct shield volcanoes located on South Island, New Zealand (Fig. 1a). As volcanic activity ceased, the central areas of the volcanoes were eroded out and then inundated to form Lyttleton and Akaroa harbours and the present day terrestrial topography (Weaver, Sewell & Dorsey, 1985; Wilson, 1992). The Peninsula rises to 919 m a.s.l., and is dissected by more than 100 isolated, short, steep catchments (Harding, 2003). The eroded slopes of the craters are mantled by wind-deposited loess derived from the Southern Alps to the west during the glacial periods of the past two million years (Sewell & Weaver, 1990). Prior to human habitation, Banks Peninsula was blanketed by forests of totara, matai and kahikatea towering over a sub-canopy of hardwood trees such as mahoe, broadleaf, fivefinger and ribbonwood (Wilson, 1992). Beech forests (*Nothofagus* spp.) dominate the eastern parts of the Peninsula.

Human-mediated deforestation on Banks Peninsula was swift. By the time the Europeans arrived, starting around 1850, Maori had already cleared about one-third of the forest cover (Petrie, 1963). Thereafter, fires and deforestation because of logging cleared another third of the forest cover on the Peninsula within a period of 50 years (Petrie, 1963). Kanuka, tussocks and scrub including the invasive weed, gorse have spread into the cleared land (Wilson, 1992, 1993, 1994); however, isolated fragments of old growth and regenerating podocarp (*Podocarpus* spp.) forest are found in a few valleys, scenic reserves and the steeper headwaters of some streams (Harding, 2003).

Banks Peninsula has a cool temperate, oceanic, subhumid climate and no part is above a potential timberline (Wilson, 1992, 1993). Mean annual rainfall ranges from about 600 mm in the north-west to about 2000 mm in the south-east (Wilson, 1992).

The study area is suitable for pursuing our study objectives because the amount of forest cover within study catchments range from almost exclusively open grassland to mostly forested. Also, within our study catchments, about half of the catchments are dominated by upland forest position, and the other half with predominantly lowland forests. Also, given the scenario above, open and forested stream reaches are abundant, and in close proximity to one another, providing for an ideal study area.

Catchment and local habitat assessment

Data on the vegetation of sampled sites, riparian vegetation (within 5 m of waters edge), canopy-cover, the presence of barriers to fish migration and other fish species present were collected from field observations and notes on the New Zealand Freshwater Fish Database (NZFFD; http://fwdb.niwa.cri.nz). Percentage of catchment land use (total forest cover, native forest cover or area of open pasture), altitude, reach slope, maximum downstream slope and distance from sea of each site were derived from digital data layers (New Zealand Landcover Database 1 Version 2 and South Island 25 m resolution Digital Elevation Model) using ArcView 3.2 (Environmental Systems Research Institute, Redlands, CA, U.S.A.). The maximum downstream slope variable was derived by propagating individual stream segment slopes of the digital hydrology network upstream, so that with increases in stream slopes traversing upstream, the steeper slope value would be retained until an even steeper value was encountered.

Fish sampling and habitat assessment

A total of 172 50-m stream reaches in 24 catchments were sampled by single-pass qualitative daytime electric fishing ($n = 136$), a method that has been demonstrated to effectively detect the presence of most species of native fish (Jowett & Richardson, 1996) and night-time spotlighting ($n = 36$) techniques, a method proven especially effective for detecting nocturnal native galaxiid fish (Goodman, 2002), during the austral winter and spring of 2001 (Fig. 1a). All sites were sampled in an upstream direction, with all available habitat types within a reach (i.e. riffle, pool, backwater, run) being sampled. A Kainga EFM 300 backpack electric fishing machine (NIWA Instrument Systems, Christchurch, New Zealand) was used to produce 400–600 V pulsed DC (pulse width approximately 3 ms, 60 pulses s^{-1}); fish were captured in hand-held stop or dip nets during daytime electric fishing. Where large substratum or overhanging vegetation prevented the use of electric fishing, night-time spotlighting was used. Because of the benthic and nocturnal nature of native galaxiid fish, spotlighting is very effective where water clarity enables all habitats to be observed (Joy, Henderson & Death, 2000). Thirty-three pre-existing sampling records available on NZFFD forms were also included in our inventory. Any presence of koaro was converted to binary presence/absence format to avoid bias from different sampling techniques and/or operators.

Because we wanted to assess the influence of factors operating at the scale of whole catchments, a stratified random sampling design was used for sample site selection based on access from roads, land use within a catchment and catchment area. To stratify the sampled sites we used a geographical information system (GIS) to identify stream segments associated with different vegetation cover classes. Stream sites associated with different vegetation cover classes were then sampled in proportion to the overall percentage cover of that type in the catchment. Actual sampling sites were selected randomly from all sites with the appropriate land cover identified by GIS, with the restrictions that stream segments should have easy access upstream or downstream of roads, and larger catchments should have proportionately more sites. No roads or culverts in the study area were of a nature that would have precluded upstream migration of fish, nor was vegetation cover different near roads compared with far away from roads. The stratified approach allowed for accurate representation of the land uses within the study area, and a representative range of altitudes, slopes, and distances from the sea for each catchment.

Data analysis

Presence/absence of koaro at the 172 sampled sites in 24 catchments on Banks Peninsula was tabulated. Sampled sites were coded according to which catchments they were in (1–24) and whether the riparian margins were forested (1) or not (0). The proportions (0.0–1.0) of forest cover within the catchments was also calculated after clipping digital land cover data (Map sheet: NZ 262 13) according to topographically delineated catchments.

To differentiate between lowland and upland areas, a histogram analysis of grid cell counts (25 × 25 m) and their respective altitudes was performed using grid analysis in the Spatial Analyst extension of ArcView. The convenient break at 200 m a.s.l. was chosen because approximately half (52%) of the landmass on Banks Peninsula is below 200 m a.s.l., and allows a comparison amongst catchments to be made unbiased by catchment size and amount of forest cover. To determine whether a catchment was categorised as upland or lowland forest-dominated, we converted the forest polygon cover to a grid of the same extent and resolution as the altitude grid, and plotted cumulative percentage forest cover against the average altitude of forest and recorded the overall position of forest cover as either predominantly in the lower (<200 m a.s.l.) or upper (>200 m a.s.l.) parts of the catchments (Fig. 1b,c). The influences of proportion of forest cover in catchments, and position of forest cover in the catchments on arcsine square root-transformed proportion of sites with koaro was tested using ANCOVA in SPSS 11.0 Standard Version. We treated the position of forest in a catchment (upland or lowland) as a fixed main effect, the proportion of total catchment forest cover as a covariate and position, and also tested the interaction of forest position and total cover on koaro site occupancy. To distinguish between the effects of total forest cover, exotic forest cover (mainly pine plantations), scrub (regenerating native forest) and native forest, we ran the ANCOVA with total forest cover, exotic forest cover removed and with exotic and scrub removed. We also performed a multivariate analysis of variance (MANOVA) followed by univariate analyses to determine if the effect of dominant forest position, total forest cover and their interaction on the proportion of sites with koaro was the same for sites with and without riparian forest. In all tests, significance was judged at alpha = 0.05.

Results

Sampled catchments ranged in size from 2.8 to 56.7 km^2, with total forest cover within catchments ranging from 7.8 to 58.3% (Tables 1 and 2). Total stream length within catchments ranged from 2.8 to 54.6 km, and stream orders of 1–4 as shown on 1 : 50 000 topographic maps based on Strahler's (1957) method of stream order determination. No sample sites were located in fourth order streams. Altitudes of the highest headwater streams within catchments ranged from 266 to 560 m a.s.l. (Table 1). Of the 24 sampled catchments, 13 were dominated by forest situated predominantly high in the catchments (>200 m a.s.l.), and 11 by forest situated predominantly low in the catchment (<200 m a.s.l.). Koaro were found at 75 of 172 sites. The steepest downstream slope gradient known to be ascended by koaro in the study streams was 60 degrees (based on 25 m resolution digital elevation model) (Table 3), which was also the steepest slope within the sampled catchments (Table 1). The highest altitude at which koaro were found was 375 m a.s.l., 16.8 km from the sea (Table 3). Forest cover comprised over 1800 patches, with average patch size ranging from 12.4 ha for exotic forests to 8.0 ha for native forests (Table 3).

Table 1 Physical characteristics of catchments sampled on Banks Peninsula, South Island, New Zealand. Highest stream altitude taken from Land Information New Zealand 260 Map Series (1 : 50 000 scale).

Catchment characteristics	Minimum	Maximum	Mean	±SD
Area (km^2)	2.8	56.7	13.7	13.2
Forest cover (%)	7.8	66.3	26.7	14.7
Highest stream altitude (m a.s.l.)	266	560	428	14
Total stream lengths (km)	2.8	54.6	13.6	13.3
Maximum stream slope (deg)	0	60	24.1	12.6
Stream order (Strahler)	1	4		

Predominant position of forest within a catchment had a significant effect on the distribution of koaro. Catchments with forest positioned high in the catchment had a significantly higher proportion of sites with koaro (Fig. 2a). Similarly, at the site-scale, streams with riparian cover were more likely to contain koaro than streams lacking riparian cover (Fig. 2b).

Dominant forest position and total catchment forest cover affected the proportion of sites with koaro as indicated by the significant *P*-values in the ANCOVA with total forest cover included (Table 4a). There were no significant two-way interactions of dominant forest position and total catchment forest cover (Table 4a). Similar results were obtained when the effects of exotic forest cover was removed, with a slightly weaker relationship than with total forest cover (Table 4b). When the effects of both exotic forest cover and scrub were removed, only dominant forest position was related to koaro presence (Table 4c). No significant two-way interactions were obtained when testing exotic or bush cover alone (ANCOVA, $P > 0.05$).

Table 2 Location of catchments sampled on Banks Peninsula. Northings and eastings (New Zealand Map Grid 2000) for catchment outflows given to 100-m accuracy. Forest position was designated upland (above 200 m a.s.l.) or lowland (below 200 m a.s.l.) based on the location of the majority of forest within the catchment.

Catchment	Northing	Easting	Area (km^2)	% Forest	Position	Number of sites
Anchorage Bay	57095	25023	4.7	24.3	Lowland	5
Armstrong	57044	25106	4.5	45.2	Upland	5
Aylmer	57109	25068	4.4	24.2	Lowland	5
Barrys Bay	57162	25028	10.6	11.0	Upland	9
Flea Bay	57044	25104	4.3	52.1	Upland	6
French Farm	57143	25026	7.9	22.1	Lowland	5
Kaituna	57146	24822	46.0	24.4	Upland	10
Little River	57142	24924	57.7	23.1	Upland	9
Ohinepaka	57079	25025	2.8	31.8	Lowland	5
Okuti	57132	24931	26.2	27.1	Upland	9
Opara Stream	57238	25145	27.2	7.8	Lowland	6
Otanerito Bay	57076	25146	10.6	66.3	Upland	7
Owhetoro Stream	57272	24955	12.5	10.2	Upland	6
Pawsons	57174	25045	9.2	14.0	Lowland	5
Peraki Bay	57052	24957	16.8	47.2	Lowland	12
Pigeon Bay	57245	25016	26.3	13.9	Upland	15
Pipers Valley	57171	25053	7.0	7.8	Lowland	5
Port Levy tributary	57273	24948	3.8	16.3	Lowland	5
Prices Valley	57126	24846	16.3	25.9	Lowland	6
Robinsons Bay	57159	25070	12.0	11.5	Lowland	7
Te Kawa Stream	57272	24951	14.8	44.1	Upland	5
Te Oka Bay	57064	24927	7.8	24.9	Upland	7
Tumbledown Bay	57060	24913	4.6	22.7	Upland	9
Wainui	57102	25023	9.8	26.6	Upland	9

Table 3 Summary characteristics of GIS derived variables for sites with koaro on Banks Peninsula. The number of sites classified by stream order is also given. The forest patches, with frequency and average size, for the entire Banks Peninsula are given as per New Zealand Landcover Database Version 2.

	Minimum	Maximum	Mean	±SD
Slope below site (deg.)	0	60	24.9	13.0
Site slope (deg.)	0	60	9.2	9.8
Site altitude (m a.s.l.)	5	375	121	91
Distance from sea (km)	0.1	16.8	3.3	3.9

Number of sites in streams (as indicated by 1 : 50 000 scale maps) of

First order	18
Second order	44
Third order	13

Forest fragments of three sub-categories	Total number	Area average (ha ± SE)
Exotic	256	11.9 ± 2.4
Scrub	1096	9.8 ± 0.7
Native	868	8.1 ± 0.5

Multivariate analysis of variance to test the effects of forest position, total catchment forest cover and their interaction for sites with and without riparian cover showed that all factors were significant (Table 5). Separate univariate ANOVAS showed that in sites with riparian cover, the coefficients of determination explained 65.7% of the variance in koaro site occupancy. However, in the absence of forest cover, no catchment-scale factors were significant and only 39.4% of the variance in koaro site occupancy was explained.

Thus, the percentage of sites with koaro was positively correlated with amount of catchment forest cover (Table 5); however, the strength of the relationship depended on the influence of riparian forest cover (Fig. 3). Sites with riparian cover showed a positive relationship between percent catchment forest cover and presence of koaro (Fig. 3a,b). At sites without riparian cover, no relationship was found between the proportion of sites with koaro and catchment forest cover (Fig. 3c,d). There was a significant interaction between forest position and total forest cover for sites with riparian cover (Table 5). This occurred because total catchment cover had a stronger positive influence on koaro occupancy when the majority of the forest was positioned in the lowland (Fig. 3a,b).

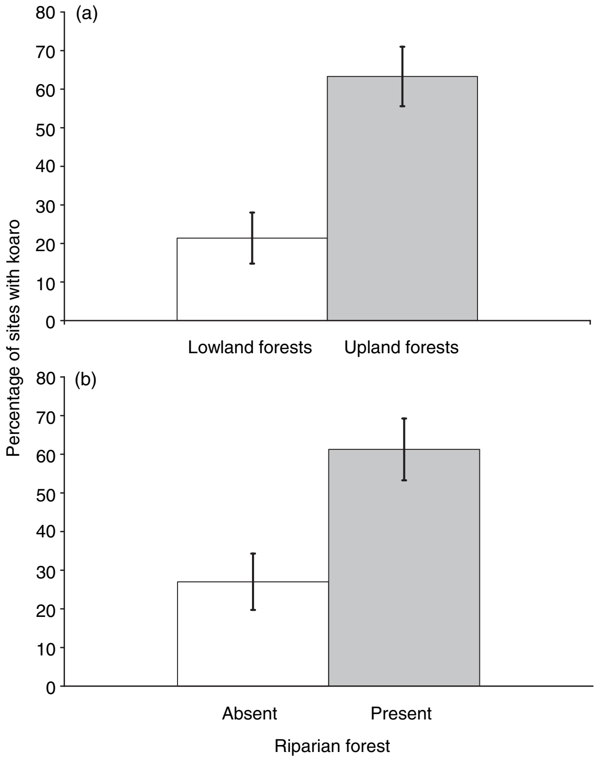

Fig. 2 (a) Percentage of sites (±SE) with koaro in catchments with upland- and lowland-positioned forests (independent samples *t*-test: $t_{(2),22} = -4.066$, $P = 0.001$). (b) Percentage of sites (±SE) with koaro in stream with riparian zones forested and non-forested (paired sample *t*-test: $t_{(2),23} = -4.508$, $P < 0.001$).

Table 4 Results of ANCOVA testing the relationship between proportion of sites with koaro, position of forest in catchment (upland or lowland) and total catchment forest cover for (a) total forest cover, (b) with exotic forest removed and (c) with exotic and scrub cover removed. The coefficients of determination for the models were 0.669, 0.600 and 0.570, respectively.

	d.f.	MS	*F*-ratio	*P*-value
(a) Source				
Position	1	0.003	7.295	0.014
Catchment forest cover	1	0.005	14.430	0.001
Position × catchment forest cover	1	<0.001	2.667	0.118
Error	20	<0.001		
Total	24			
(b) Source				
Position	1	0.003	7.284	0.014
Native + scrub cover	1	0.003	8.401	0.009
Position × (native and scrub cover)	1	<0.001	2.220	0.152
Error	20	<0.001		
Total	24			
(c) Source				
Position	1	0.005	10.565	0.004
Native cover	1	0.002	3.373	0.081
Position × native cover	1	0.002	3.327	0.083
Error	20	<0.001		
Total	24			

Discussion

The aim of this study was to determine how landscape features influenced the distribution of koaro in Banks Peninsula streams, and at what scales these factors operated. Our results indicate the presence of riparian forest cover, the position of forest within catchments and the total amount of catchment forest cover, regardless of forest type, influence the overall distribution of koaro. However, the catchment-scale variables were most influential when local riparian cover was present.

Table 5 Multivariate analysis of variance (MANOVA) and univariate analyses using dominant forest position (upland/lowland) as fixed effect, total catchment forest cover as covariate and their interaction for the total proportion of sites with riparian forest and no riparian forest streams with koaro for 24 catchment

Response variable	Source	d.f.	MS	*F*-value	*P*-value
MANOVA	Constant	2,19	0.967*	0.324	0.727
	Position	2,19	0.643*	5.263	0.015
	Total forest cover	2,19	0.519*	8.820	0.002
	Position × total forest cover	2,19	0.696*	4.157	0.032
Riparian cover	Constant	1	0.059	0.408	0.530
	Position	1	1.371	9.478	0.006
	Total forest cover	1	2.672	18.471	<0.001
	Position × total forest cover	1	0.745	5.149	0.034
	Error	20	0.145		
No riparian cover	Constant	1	0.024	0.113	0.740
	Position	1	0.035	0.167	0.687
	Total forest cover	1	0.147	0.693	0.415
	Position × total forest cover	1	0.321	1.519	0.232
	Error	20	0.212		

*Wilks' Lambda.

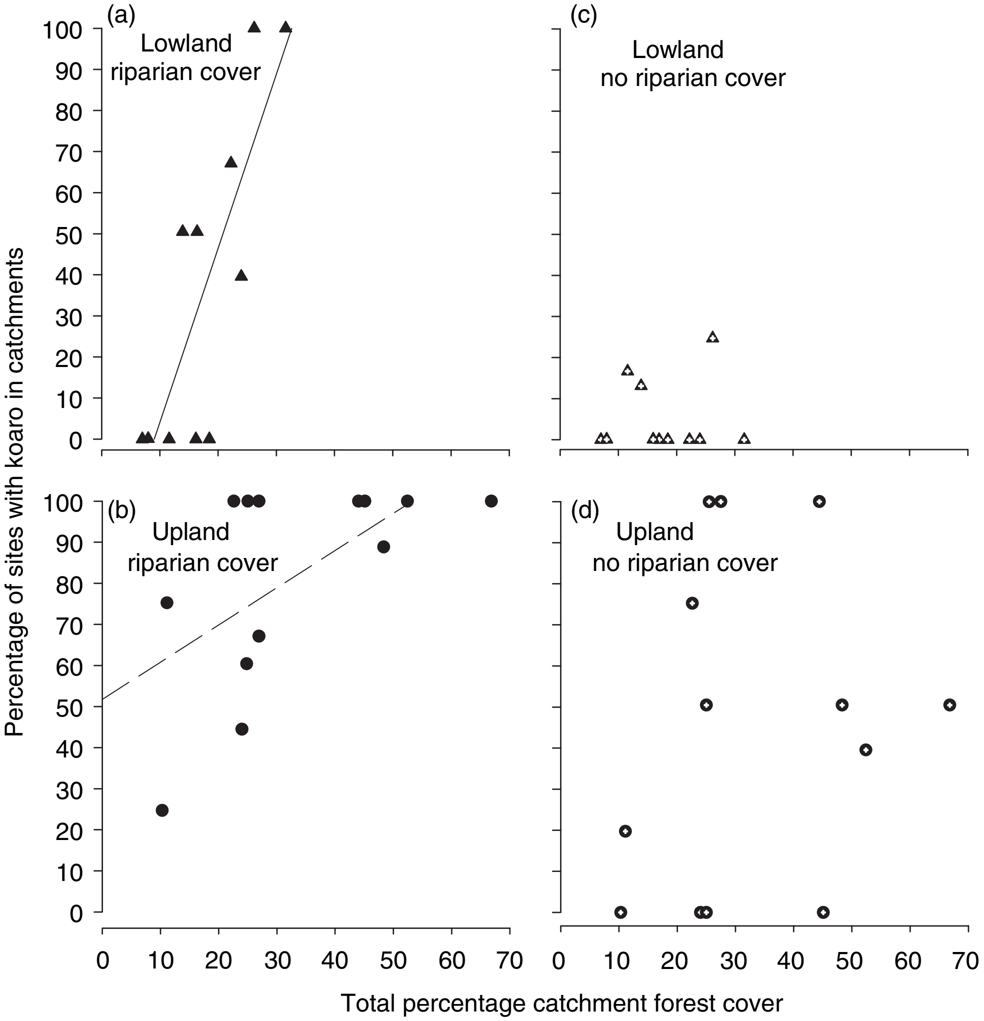

Fig. 3 Relationship between percentage of sites with koaro and total percentage forest cover in four subgroups of catchments varying in the position of forest and two riparian cover categories: (a) lowland with riparian cover, (b) upland with riparian cover, (c) lowland without riparian cover and (d) upland without riparian cover. The equations for the regression lines are (a) $y = -1.53 + 4.92x$ ($r^2 = 0.646$, $P = 0.002$) and (b) $y = 0.49 + 1.28x$ ($r^2 = 0.381$, $P = 0.02$). No significant relationships were found between catchment forest cover in lowland (c) and upland forest (d) dominated catchments and percentage of sites with koaro in the absence of riparian cover. Each point in the graphs represents a catchment. Overlapping points have been dithered for visual clarity.

Wilson (1994) reported indigenous vegetation once covered 98% of Banks Peninsula, but most of the land above 300 m a.s.l. is now dominated by tussock, whereas ryegrass and cocksfoot grazed by sheep and beef cattle is the dominant vegetation on many of the valley floors (Harding, 2003). In our study catchments, forest cover ranged from 7.8 to 58.3%, and the decrease in forest cover was paralleled by an increase in fragmentation of the forests. Agricultural land use practices and deforestation have been identified as major sources of sediment and nutrient input to streams in New Zealand and elsewhere, and are considered to be important factors limiting usable fish habitat (Russell *et al.*, 1998; Huryn *et al.*, 2002; Quinn & Stroud, 2002; Sutherland, Meyer & Gardiner, 2002), although riparian buffer strips can reduce the inputs and help retain substrate integrity in streams (Ryan, 1991). On Banks Peninsula, wind-blown loess may be a huge potential source of fine sediment input. Thus, it is not surprising that koaro, a fish commonly associated with high habitat quality, occurred more frequently in catchments with higher proportions of forest cover and riparian forest cover.

In the absence of riparian forest cover, catchment forest cover had little effect. When riparian forest cover was present, two patterns emerged, depending on the predominant location of forest within a catchment. In catchments with predominantly lowland forest there was a strong positive relationship between koaro occupancy and the total percentage of catchment forest cover. The positive response to the presence of lowland forest may be because it improves the quality of the most accessible habitat for koaro on Banks Peninsula. In catchments with predominantly upland forests, the slope of the relationships between koaro site occupancy and percentage forest cover and the proportion of variance explained by the regression were low. However, when the presence or absence of riparian cover was not included, we found that streams draining catchments with forests situated in upland areas had higher proportions of sites with koaro, and all catchments with forest predominantly in upland areas contained koaro. Thus, our results indicate that koaro are sensitive to the overall location of forest within catchments, but the strength of their response depends on the presence of forested riparian vegetation.

The presence of riparian forest cover may be important to koaro because they feed on a variety of terrestrial invertebrate prey, in addition to aquatic species (Main & Winterbourn, 1987; McDowall, 1990; Hayes, 1996; McDowall, 2000). A loss of, or change in, riparian cover can reduce the abundance and diversity of terrestrial invertebrates both in and outside the stream, thereby reducing food availability to fish (Cadwallader, Eden & Hook, 1980; Edwards & Huryn, 1995, 1996). Riparian forest cover may also be important for creating fish habitat. In New Zealand, removal of riparian vegetation has been associated with declines in woody debris, and has influenced the pool-riffle formation of some streams draining native forests (Baillie & Davies, 2002). Not only do fallen riparian trees provide in-stream refugia, but they also ameliorate stream morphology by creating pool and riffle habitats for fish. Likewise, in-stream woody debris is likely utilised by koaro as daytime refugia (McDowall, 1990). Therefore, koaro may be less likely to occupy sites without riparian cover because of a reduction in in-stream habitat.

It has been argued that upland areas often contain the last vestiges of intact stream habitats because of their poor agricultural potential, but they may become progressively isolated from their lower reaches by development lower in the catchment (Pringle, 2001; March *et al.*, 2002). Using this reasoning, if lowland areas were modified such that most forest was in upland areas, one might have expected a diadromous fish like koaro to have difficulty accessing upland streams because of the modified lowland reaches they must negotiate during their migration. This was not the case in our study because koaro occurred more frequently in catchments with most forest in upland areas. The relatively low altitudes, gradients, short distances from the sea and the absence of dams and weirs in our study catchments, mean that migratory barriers were unlikely to influence the koaro distribution patterns observed. However, it is still difficult to determine why catchments with forested upland areas had higher proportions of sites with koaro than catchments with forested lowlands. It may be that streams in forested upland areas are important to koaro because they provide suitable spawning habitat. However, this cannot be the whole explanation because koaro were present in lowland forested streams and less common in non-forested upland streams.

One likely explanation for the high occurrence rate of koaro in catchments with upland forest is the influence of upland forest on habitat quality throughout the catchment. Because of their steep slopes, upland streams are sensitive to land use changes (Gomi *et al.*, 2003) and fine sediments from surface runoff are frequently transported to headwater streams and subsequently down the catchment. Sediment originating from these headwater streams may later degrade in-stream habitat throughout the catchment (Berkman & Rabeni, 1987; Gregory *et al.*, 1991; Montgomery & Buffington, 1998). Fine sediment is likely to influence koaro by impacting aquatic invertebrates that provide food, hindering feeding (particularly of the whitebait stage) through increased turbidity and clogging of substratum interstices that provide cover for koaro (Boubee *et al.*, 1997). Having forested upland areas may protect sensitive headwater streams from these impacts, thereby reducing habitat degradation throughout the catchment, resulting in higher site occupancy as we have observed, regardless of whether riparian vegetation is present. It may also be that woody debris from upland forests is transported downstream, in turn creating aquatic habitat favourable for koaro.

Although we were able to describe the distribution patterns of koaro on Banks Peninsula in detail using our methodology, the underlying mechanisms resulting in the observed distribution are still unclear. While the presence and distribution of vegetation are implicated, other factors may also be important. For example, banded kokopu (*Galaxias fasciatus* Gray), a closely related amphidromous fish, are also known to have a negative influence on the distribution of koaro (Eikaas, Kliskey & McIntosh, in press), and may displace it from otherwise suitable habitats in lowland reaches. However, while there is a need to understand the specific mechanisms contributing to koaro distribution patterns, such observed distribution patterns can still be used to guide management.

In the present study we assessed variables that can be quantified rapidly using a GIS without the need for extensive field sampling to evaluate the influence of land use on the distribution of a diadromous fish. Our results suggest the need for stream fish management that better integrates both landscape and local processes. Without immediate protection of stream margins by riparian vegetation, larger-scale effects of catchment forest cover, such as lowland versus upland forest position and amount of catchment forest cover, had no impact at local scales. Hence, based on our observations, the aim for koaro management should be not only to increase the overall forest cover of catchments, but also to afforest the riparian zone to increase the overall proportion of sites that potentially will support koaro. In catchments with lowland forests the primary aim should be to afforest the riparian zone, whereas in catchments with upland forests the aim should be to increase the overall proportion of catchment forest cover.

The results of our study indicate that catchment scale processes have relevance for processes at local scales, but processes at the two scales interact to affect koaro distribution. Similarly, catchment scale features interact with reach scale features including riparian vegetation to determine the distribution of non-migratory fishes, such as cyprinids, campostomids, centrarchids and percids in the Northern Lakes and Forest Ecoregion in the north-central United States (Wang *et al.*, 2003). Together, these studies reinforce the need for more landscape oriented research to better understand the distributional patterns of fishes.

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References

Allan J.D. & Flecker A.S. (1993) Biodiversity conservation in running waters: identifying the major factors that threaten destruction of riverine species and ecosystems. *Bioscience*, **43**, 32–43.

Baillie B.R. & Davies T.R. (2002) Influence of large woody debris on channel morphology in native forest and pine plantation streams in the Nelson region, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **36**, 763–774.

Berkman H.E. & Rabeni C.F. (1987) Effects of siltation on stream fish communities. *Environmental Biology of Fishes*, **18**, 285–294.

Boubee J.A.T., Dean T.L., West D.W. & Barrier R.F.G. (1997) Avoidance of suspended sediment by the juvenile migratory stage of six New Zealand native fish species. *New Zealand Journal of Marine and Freshwater Research*, **31**, 61–69.

Cadwallader P.L., Eden A.K. & Hook R.A. (1980) Role of streamside vegetation as a food source for *Galaxias olidus* Gunther (Pisces: Galaxiidae). *Australian Journal of Marine and Freshwater Research*, **31**, 257–262.

Edwards E.D. & Huryn A.D. (1995) Annual contribution of terrestrial invertebrates to a New Zealand trout stream. *New Zealand Journal of Marine and Freshwater Research*, **29**, 467–477.

Edwards E.D. & Huryn A.D. (1996) Effect of riparian land use on contributions of terrestrial invertebrates to streams. *Hydrobiologia*, **337**, 151–159.

Eikaas H.S., Kliskey A.D. & McIntosh A.D. (in press) Spatial modelling and habitat quantification for two diadromous fish in New Zealand streams: a GIS based approach with application for conservation management. *Environmental Management*.

Fahey B.D. & Watson A.J. (1991) Hydrological impacts of converting tussock grassland to pine plantation, Otago, New Zealand. *New Zealand Journal of Hydrology*, **30**, 1–15.

Fausch K.D., Torgersen C.E., Baxter C.V. & Li H.W. (2002) Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *BioScience*, **52**, 483–498.

Gilliam J.F., Fraser D.G. & Alkins-Koo M. (1993) Structure of a tropical stream fish community: a role for biotic interactions. *Ecology*, **74**, 1856–1870.

Gomi T., Sidle R.C. & Richardson J.S. (2003) Understanding processes and downstream linkages of headwater systems. *BioScience*, **52**, 905–916.

Goodman J.M. (2002) *The Ecology and Conservation of Shortjaw Kokopu* (Galaxias postvectis) *in Nelson and Marlborough*. MSc thesis, University of Canterbury, Christchurch. 109 pp.

Graynoth E. (1979) Effects of logging on stream environments and faunas in Nelson. *New Zealand Journal of Marine and Freshwater Research*, **13**, 79–109.

Gregory S.V., Swanson F.J., McKee W.A. & Cummins K.W. (1991) An ecosystem perspective of riparian zones: focus on links between land and water. *BioScience*, **41**, 540–551.

Hanchet S.M. (1990) Effect of land use on the distribution and abundance of native fish in tributaries of the Waikato River in the Hakarimata Range, North Island. *New Zealand Journal of Marine and Freshwater Research*, **24**, 159–171.

Harding J.S. (2003) Historic deforestation and the fate of endemic invertebrate species in streams. *New Zealand Journal of Marine and Freshwater Research*, **37**, 333–345.

Hayes J.W. (1996) Observations of surface feeding behaviour in pools by koaro, *Galaxias brevipinnis*. *Journal of the Royal Society of New Zealand*, **26**, 139–141.

Huryn A.D., Huryn V.M.B., Arbuckle C.J. & Tsomides L. (2002) Catchment land-use, macroinvertebrates and detritus processing in headwater streams: taxonomic richness versus function. *Freshwater Biology*, **47**, 401–415.

Hynes H.B.N. (1975) Edgardo Baldi Memorial Lecture: the stream and its valley. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie*, **19**, 1–15.

Jowett I.G. & Boustead N.C. (2001) Effects of substrate and sedimentation on the abundance of upland bullies (*Gobiomorphus breviceps*). *New Zealand Journal of Marine and Freshwater Research*, **35**, 605–613.

Jowett I.G. & Richardson J. (1996) Distribution and abundance of freshwater fish in New Zealand rivers. *New Zealand Journal of Marine and Freshwater Research*, **30**, 239–255.

Joy M.K., Henderson I.M. & Death R.G. (2000) Diadromy and longitudinal patterns of upstream penetration of freshwater fish in Taranaki, New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **34**, 531–543.

Kauffman J.B., Beschta L.R., Otting N. & Lytjen D. (1997) An ecological perspective of riparian and stream restoration in the Western United States. *Fisheries*, **22**, 12–24.

Main M.R. & Winterbourn M.J. (1987) Diet and feeding of koaro (*Galaxias brevipinnis*) in forested, South Westland streams. *Mauri Ora*, **14**, 77–86.

March J.G., Pringle C.M., Townsend M.J. & Wilson A.I. (2002) Effects of freshwater shrimp assemblages on benthic communities along an altitudinal gradient of a tropical island stream. *Freshwater Biology*, **47**, 377–390.

Matthews W.J. (1998) *Patterns in Freshwater Fish Ecology*. Chapman & Hall, New York, 756 pp.

McDowall R.M. (1990) *New Zealand Freshwater Fishes: a Natural History and Guide*. Heinemann Reed and MAF Publishing Group, Auckland, 553 pp.

McDowall R.M. (1996) Diadromy and the assembly and restoration of riverine fish communities: a downstream view. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**, 219–236.

McDowall R.M. (1998a) Driven by diadromy: its role in the historical and ecological biogeography of the New Zealand freshwater fish fauna. *Italian Journal of Zoology*, **65**, 73–85.

McDowall R.M. (1998b) Fighting the flow: downstream-upstream linkages in the ecology of diadromous fish faunas in West Coast New Zealand rivers. *Freshwater Biology*, **40**, 111–122.

McDowall R.M. (2000) *The Reed Field Guide to New Zealand Freshwater Fishes*. Reed, Auckland, New Zealand, 224 pp.

Minns C.K. (1990) Patterns of distribution and association of freshwater fish in New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **24**, 31–44.

Montgomery D.R. & Buffington J.M. (1998) Channel processes, classification, and response. In: *River Ecology and Management: Lessons from the Pacific Coastal Ecoregion* (Eds R.J. Naiman & R.E. Bilby), pp. 13–42. Springer-Verlag, New York.

Naiman R.J. (1992) New perspectives for watershed management: balancing long-term sustainability with cumulative environmental change. In: *Watershed Management: Balancing Sustainability and Environmental Change* (Ed. R.J. Naiman), pp. 3–11. Springer-Verlag, New York.

Nakano S., Miyasaka H. & Kuhara N. (1999) Terrestrial-aquatic linkages: Riparian arthropod inputs alter trophic cascades in a stream food web. *Ecology*, **80**, 2435–2441.

Osborne L.L. & Kovacic L.D. (1993) Riparian vegetated buffer strips in water-quality restoration and stream management. *Freshwater Biology*, **29**, 243–258.

Petrie L.M. (1963) *From Bush to Cocksfoot: an Essay on the Destruction of Banks Peninsula's Forests*. PhD Thesis, University of Canterbury, Christchurch.

Pringle C.M. (2001) Hydrologic connectivity and the management of biological reserves: a global perspective. *Ecological Applications*, **11**, 981–998.

Quinn J.M. & Stroud M.J. (2002) Water quality and sediment and nutrient export from New Zealand hill-land catchments of contrasting land use. *New Zealand Journal of Marine and Freshwater Research*, **36**, 409–429.

Richards C. & Host G. (1994) Examining land use influences on stream habitats and macroinvertebrates: a GIS approach. *Water Resources Bulletin*, **30**, 729–738.

Rowe D.K., Chisnall B.L., Dean T.L. & Richardson J. (1999) Effects of land use on native fish communities in east coast streams of the North Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research*, **33**, 141–151.

Russell M.A., Walling D.E., Webb B.W. & Bearne R. (1998) The composition of nutrient fluxes from contrasting U.K. river basins. *Hydrological Processes*, **12**, 1461–1482.

Ryan P.A. (1991) Environmental effects of sediment on New Zealand streams: a review. *New Zealand Journal of Marine and Freshwater Research*, **25**, 207–221.

Scarsbrook M.R. & Halliday J. (1999) Transition from pasture to native forest land-use along stream continua: effects of stream ecosystems and implications for restoration. *New Zealand Journal of Marine and Freshwater Research*, **33**, 293–310.

Schlosser I.J. (1995) Critical landscape attributes that influence fish population dynamics in headwater streams. *Hydrobiologia*, **303**, 71–81.

Sewell R.J. & Weaver S.D. (1990) Geology of the Akaroa West area. In: *New Zealand Geological Survey* (Ed. M.B. Reay), pp. 1–31. Department of Scientific and Industrial Research, Christchurch.

Strahler A.N. (1957) Quantitative analyses of watershed geomorphology. *Transactions of the American Geophysical Union*, **38**, 913–920.

Sutherland A.B., Meyer J.L. & Gardiner E.P. (2002) Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. *Freshwater Biology*, **47**, 1791–1805.

Wang L., Lyons J., Rasmussen P., Seelbach P., Simon T., Wiley M., Kanehl P., Baker E., Niemela S. & Stewart P.M. (2003) Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion, U.S.A. *Canadian Journal of Fisheries and Aquatic Sciences*, **60**, 491–505.

Weaver S.D., Sewell R. & Dorsey C. (1985) Extinct volcanoes: a guide to the geology of Banks Peninsula. In: *Geological Society of New Zealand Guidebook No. 7*. pp. 1–48. Geological Society of New Zealand, Petone, New Zealand.

Wilson H.D. (1992) Banks Ecological Region: Port Hills, Herbert and Akaroa ecological districts. In: *Protected Natural Areas Programme Survey* Report No 21. Department of Conservation, Christchurch.

Wilson H.D. (1993) Bioclimatic zones and Banks Peninsula. *Canterbury Botanical Society Journal*, **27**, 22–29.

Wilson H.D. (1994) Regeneration of native forest on Hinewai Reserve, Banks Peninsula. *New Zealand Journal of Botany*, **32**, 373–383.

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