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ENVIRONMENTAL ASSESSMENT

Spatial Modeling and Habitat Quantification for Two Diadromous Fish in New Zealand Streams: A GIS-Based Approach with Application for Conservation Management

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We developed logistic regression models from data on biotic and abiotic variables for 172 sites on Banks Peninsula, New Zealand, to predict the probability of occurrence of two diadromous fish, banded kokopu (*Galaxias fasciatus*) and koaro (*G. brevipinnis*). Banded kokopu occurrence was positively associated with small streams and low-intensity land uses (e.g., sheep grazing or forested), whereas intensive land uses (e.g., mixed sheep and cattle farming) and lack of riparian forest cover impacted negatively on occurrence at sampled sites. Also, if forests were positioned predominantly in lowland areas, banded kokopu occurrence declined with increasing distance to stream mouth. Koaro occurrence was positively influenced by catchment forest cover, high stream altitudes, and areas of no farming activity or mixed land uses. Intensive land uses, distance to stream mouth, and presence of banded kokopu negatively influenced koaro occupancy of stream reaches. Banded kokopu and koaro presence was predicted in 86.0% and 83.7% agreement, respectively, with field observations. We used the models to quantify the amount of stream reaches that would be of good, moderate, and poor quality, based on the probability of occurrences of the fish being greater than 0.75, between 0.75 and 0.5, or less than 0.5, respectively. Hindcasting using historical data on vegetation cover undertaken for one catchment, Pigeon Bay, showed they would have occupied most of the waterway before anthropogenic modification. We also modeled potential future scenarios to project potential fish distribution.

An understanding of local habitat parameters such as water depth, flow velocity, and substrate characteristics underpins models used to describe fish distribution and abundance at local scales (Gore and others 1991, McDowall 1993, Lammert and Allan 1999, Vilizzi 2002). Models for the assessment of fish communities have been developed in North America (Karr 1981), and predictive models for the presence/absence of native fish and invertebrates are in use in New Zealand (Broad and others 2001, Joy and Death 2002, 2003, 2004). For example, the Index of Biotic Integrity (IBI) assesses the biotic integrity of impacted sites based on nonimpacted reference sites nearby (Karr 1981, 1991, Fausch and others 1984, Miller and others 1988, Hoefs and Boyle 1992). The IBI metrics include species composition, species richness, fish abundance, trophic composition, fish reproductive guilds, and fish condition (Karr 1991). Assessments must be undertaken by experienced biologists who set standards based on knowledge of the regional biota (Karr 1991), a task that may require intensive monitoring over an extensive period of time (Yoder and Smith 1996). Although effective for inland streams, IBI assessments may be less useful when assessing the distribution of diadromous species, such as the predominantly diadromous fish fauna of New Zealand, where the influences of distance from the sea, altitude (McDowall 1993, 1996, 1998a, 1998b, Joy and Death 2001, 2003), and anthropogenic

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barriers to fish migration have resulted in a breakdown of the relationship between fish occurrences and proximal habitat quality (Joy and Death 2000).

Diadromous fish, by nature of their migratory behavior, exhibit continuous distributions, with species abundance tapering off with distance inland and increasing elevations (McDowall and Taylor 2000). Their spatial distributions should consequently be modeled on a species-by-species basis. We assert that rivers and streams should be regarded as continuous systems for effective research and conservation of freshwater fish because the fish are sensitive to contemporary land uses and configuration of terrestrial landscape elements throughout catchments.

Myers (1949) divided diadromy into three subcategories, each of which was progressively refined by McDowall (1997) on the basis of feeding, growing, and reproductive biomes. In anadromous fishes, the feeding and growth biomes are at sea, whereas the reproductive biome is in fresh water. Catadromous fish feed and grow in fresh water, then migrate to sea as adult fish to reproduce. Amphidromous fishes migrate to sea as larvae soon after hatching, and then migrate back to a freshwater environment as postlarval juvenile fish. With perhaps the exception of anadromous fishes that return to their natal streams, the contemporary recruitment and distribution of catadromous and amphidromous to streams is likely to reflect large-scale contemporary land uses and environmental pressures as well as local habitat features. Because the presence of amphidromous fish in a reach is related to contemporary land use, it should not be difficult to calculate the probability of encountering a diadromous fish, provided that barriers to dispersal are considered.

Both banded kokopu (*Galaxias fasciatus* Gray 1842) and koaro (*G. brevipinnis* Günther 1866) are amphidromous species (McDowall 1996, 1998a, 1998b), which potentially allows them access to a variety of habitats during migration from the marine environment back to adult freshwater habitats. Both species have the ability to form land-locked populations, but on Banks Peninsula, South Island, the adults of these species are restricted to lotic environments. Koaro and banded kokopu are exceptional climbers, with the former found at the highest elevations of any of New Zealand's native freshwater fish (McDowall 1990). Banded kokopu favors pools and backwaters in first- to third-order streams with extensive riparian vegetation (McDowall 1990). Koaro, although found in tussock streams at high altitudes, also favors cobble-boulder substrates in streams with extensive riparian vegetation. Both species are generalist predators, feeding on a variety of terrestrial and aquatic invertebrate prey (Main and Lyon 1988, McDowall 1990). Koaro and banded kokopu contribute significantly to a recreational and commercial catch of the migrating juveniles known as ''whitebait'' (McDowall 1990). Koaro and banded kokopu are still common throughout New Zealand and currently are not listed as threatened (Hitchmough 2002), but their adult habitat is thought to have been greatly reduced by changes in land use from native forest to pasture (Hanchet 1990, Rowe and others 1999).

Statistical methods not dependent upon continuous input variables, such as binary logistic regression models, can be used effectively to predict dichotomous outcomes where there is a linear relationship between independent and dependent variables (Hosmer and Lemeshow 2000), and have been used successfully to predict the presence of longfin (*Anguilla dieffenbachii* Gray, 1842) eels in a New Zealand river (Broad and others 2001). The goal of logistic regression analysis is the same as for any other model building techniques: to establish the relationship between an outcome variable (presence/absence of the focal species) and a set of independent variables (continuous or discrete) that are biologically reasonable, yet parsimonious (Hosmer and Lemeshow 2000). We apply binary logistic regression techniques with leave-one-out cross-validation procedures for modeling the spatial distribution and quantifying the amount of suitable habitat for two species of diadromous fish, koaro and banded kokopu, in streams on Banks Peninsula, New Zealand. The logistic regression approach may aid in understanding the influence that forested riparian zones, catchment vegetation, as well as specific land uses have on the distributions of diadromous fish, and may highlight the influence of habitat/catchment modification and configuration of landscape elements on migratory fish distributions. Additionally, the approach may elucidate the influences of abiotic factors such as distance from source, altitude, and potential barriers encountered in terms of steep slopes encountered. This would illustrate that the ecological dynamics of the system may respond to the configuration of patches in the landscape, even if the relative proportion of patch-types in the system remain the same (Fausch and others 2002).

Materials and Methods

Study Area

Banks Peninsula is an 1102-km^2 promontory located between latitudes 43°33′S and 43°54′S on the eastern side of South Island, New Zealand (Figure 1A). The Peninsula consists of a series of volcanic cones of mid-Miocene basalt (Weaver and others 1985, Sewell 1988,

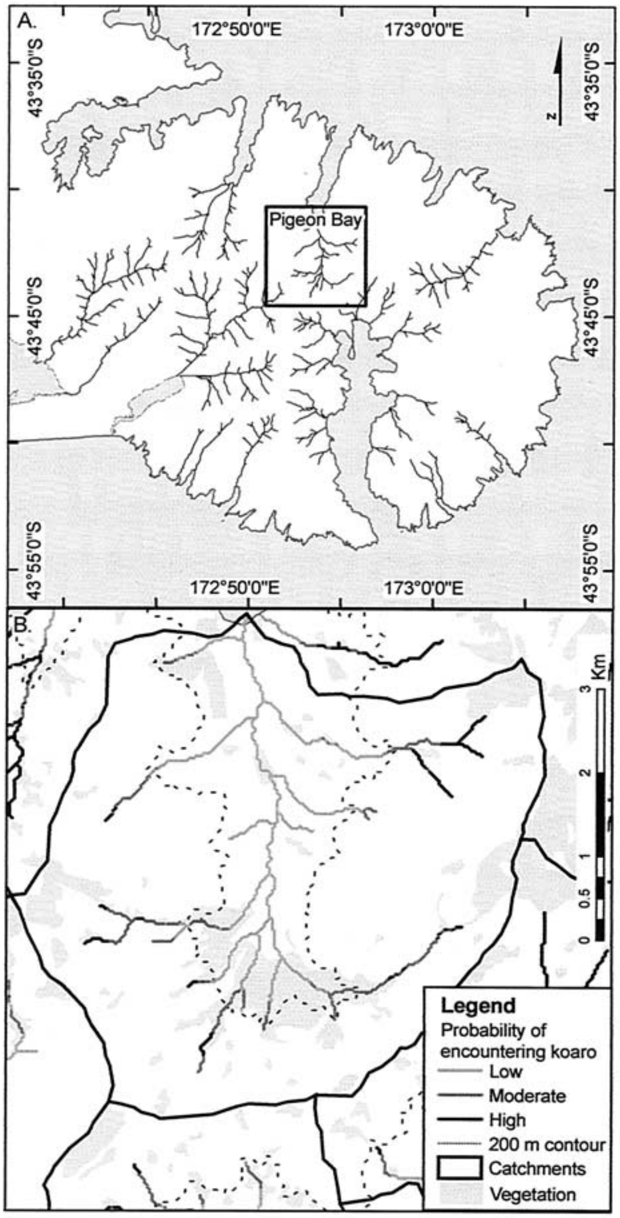

Figure 1. (**A**) Location of the 24 sampled catchments on Banks Peninsula, South Island, New Zealand, with a box (**B**) showing the Pigeon Bay catchment. The light gray patches represent vegetation (scrub and forest) cover. The dashed line is the 200-m contour line, which distinguishes upland versus lowland areas. Catchments with the majority of forest cover above the 200-m contour line are classified as being upland forested catchments. Catchments are delineated according to topographic divides, and are separated from one another on the map by thick black lines. The thinner, light gray, medium gray, and black lines represent stream reaches with a probability of encountering koaro of $p < 0.50$, $0.50 > p < 0.75$, and $p > 0.75$, respectively. These classifications were derived using backward conditional logistic regression procedures, and mapped by applying the probability equation (Eq. 1) to the database associated with the digital hydrology network to calculate a probability-of-encounter value for the species for all the individual stream segments in the stream network.

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 volcanoes have been mantled by wind-deposited loess derived from the Southern Alps, which lie some 70 km to the west, during the interglacial periods of the past two million years (Sewell and Weaver 1990). Loess represents a potential fine sedimentary input to streams, and may degrade instream habitat for fish favoring cobble-boulder substrates.

Before human arrival, Banks Peninsula was almost completely vegetated in Podocarp/hardwood forests on wetter western slopes and Southern beech (*Nothofagus* spp.) in the east (Wilson 1992). However, human activity has resulted in deforestation of much of Banks Peninsula. Most of the remaining forests were felled by Europeans within a period of 50 years after the establishment of Christchurch in 1850 (Petrie 1963). Kanuka (*Kunzea ericoides* A. Rich), tussocks (*Carex* spp.), and scrub, including the invasive weed gorse (*Ulex europaeus* L.), have spread into some of the cleared land. Isolated fragments of old growth and regenerating podocarp (*Podocarpus* spp.) forest are found in a few valleys, scenic reserves, and in the steeper headwaters of some streams (Wilson 1992).

Fish Sampling and Habitat Assessment

We used a geographical information system (GIS) to identify stream segments associated with different vegetation cover classes, and sampled stream reaches in proportion to the overall percentage forest cover in catchments. To select the stream reaches to be sampled, we randomly identified reaches with the appropriate land cover, with the restrictions that stream segments should have easy access upstream or downstream of roads, and larger catchments should have proportionally more reaches sampled. The stratified approach allowed for accurate representation of the land uses within the study area, covering a representative range of elevations, slopes, and distances from the sea for each catchment.

Records of fish occurrence for a total of 172 stream reaches in 24 catchments were included in our inventory. Of these, 37 records were sourced from the New Zealand Freshwater Fish Database (NZFFD; http://fwdb.niwa.cri.nz), whereas the rest were sampled specifically for this study. One hundred thirty-six stream reaches were sampled by single-pass qualitative electric fishing and 36 by spotlighting techniques. All newly sampled stream reaches were sampled in an upstream direction, and were 50 m in length. Electrofishing was conducted using a Kainga EFM 300 backpack electric fishing machine (NIWA Instrument Systems, N.Z.), producing 400–600 V pulsed DC (pulse width ~3 ms, 60 pulses · s^{-1}), and fish were captured in hand-held stop or dip nets. Where overhanging vegetation prevented the use of electrofishing, spotlighting was used. All available habitat types within the sampling reach (i.e., riffle, pool, backwater, and runs) were sampled at each site.

Digital Data Collection and Preparation

For all sampled stream reaches, data on riparian vegetation (within 5 m of water's edge), canopy-cover, presence of migratory barriers, and species occurrences were collected from field observations or from information contained on the NZFFD, and ground referenced in the field using a hand-held global positioning unit (GeoExplorer 3) to assess the accuracy of the digital landcover database layers. A 25-m resolution digital elevation model (DEM) of the study area was used to create a slope grid, which in turn allowed for flow direction and flow accumulation grids to be produced. In combination, these grids allowed for automated delineation of catchments in our study area according to direction and accumulation of flow, along with topographic divides. The DEM was also used to establish upland and lowland positioning of forests by plotting the cumulative percentage of cells in the DEM with increasing elevation, and establishing the breakpoint at 200 m above mean sea level, because 50% of the landmass of Bank Peninsula was accounted for when this elevation was reached. The delineated catchments were then used to intersect digital landcover maps (New Zealand Landcover Database 1 Version 2) of the study area to allow for calculation of proportion of catchment land uses within catchments. The predominant forest position within catchments was determined by draping the landcover maps over the DEM, and if more than 50% of the forest cover was in lowland areas, the catchment was categorized as a lowland forested catchment. A digital version of the hydrology network (Map sheet 262-13 1:50,000 Topographic Vector Data) was then cut according to the land uses, and further sliced into 25-m segments before rebuilding the T–F node topology (To and From node) that establishes the connectivity in the network. The underlying elevations and slopes of the hydrology network were then sampled from the DEM. Maximum downstream slopes, distances from sea, and length of streams flowing through various land use types were propagated up and down the stream network using the connectivity of stream segments established by the T–F topology. This propagation allowed values for the variables to be determined for any 25-m stream segment. Specific land uses with respect to farming practices were taken from AgriBase 2000, a national spatial farm database originally developed by MAF Quality Management Ltd., that contains information on the dominant farm types, farm sizes, and land parcels that make up a farm.

Data Analysis

Logistic regression examines the functional relationship between a categorical dependent variable and independent variables that may be either discrete or continuous in their distribution (Trexler and Travis 1993). Logistic regression works particularly well with binary data, such as presence/absence data, and can be used to generate predictive equations for the presence or absence of the focal species. In logistic regression, dichotomous and other categorical variables receive a numerical code, and in the statistical analysis one of the codings for each dichotomous variable is treated as a reference by which the regression coefficients for the rest of the categories are calculated. Subsequently, all sites included in the model are classified and cross-validated using leave-one-out cross-validation procedures (Fielding and Bell 1997). Data on catchment sizes, reach slopes, maximum downstream slopes, stream reach altitudes, distances from stream mouth (sea or lake), and proportion catchment forest cover were derived from the GIS. Proportion catchment forest cover was arcsine transformed, whereas distance measures, such as distance from source and amounts of stream reaches flowing through various land use types, were square root transformed to obtain normality. The dichotomous variables, such as dominant catchment forest position, riparian cover category, and specific land use were also determined using the GIS. These variables were then analyzed using backward conditional binary logistic regression procedures in SPSS (Version 11.0). The resulting coefficients of determination for input variables were then used in a probability calculation using the equation:

$$P = (e^{a+\beta X})/(1 + e^{a+\beta 1X1 \ldots \beta iXi}), \qquad (1)$$

where P is the calculated probability of an event, e is the base of the natural logarithm, a is a constant, and β is the correlation coefficient for variable X. Given that we have only 1 s and 0 s for presence or absence for our dependent variables, the final equation gives a probability of presence in the range of 0 to 1. The base of the natural logarithm raised to the value of the regression coefficient is the value by which the odds of the event change when the i_{th} independent variable increases by one unit. If this value is greater than 1, the odds are increased; if the value is less than 1, the odds are decreased. A value of 1 leaves the odds unchanged.

Pigeon Bay Hindcasting and Forecasting Modeling

To illustrate potential uses of the spatial prediction model, we undertook hindcasting and forecasting modeling of Pigeon Bay (Figure 1B), a 26.3-km^2 catchment on the northern part of Banks Peninsula. We digitized landcover maps for three time periods, 1860, 1880, and 1950, drafted by Petrie (1963), and projected them to New Zealand Map Grid 2000, and used them as historical input for hindcasting of koaro and banded kokopu distributions with respect to land cover changes. These digitized maps allowed for estimation of amount of forest cover and derivation of the spatial configuration of forest cover within the study catchment. For forecasting scenarios, we modeled specific land use changes based on digital land use data from AgriBase, a national spatial farm database indicating the dominant farm type classification as of February 2000. We also modeled four potential future scenarios based on potential changes in current land uses of Pigeon Bay. The hindcasting, present day, and forecasting scenarios for Pigeon Bay are outlined below.

Pigeon Bay Scenario 1860

No specific information on the amount of forest cover of Pigeon Bay for the period prior to 1860 is available. However, estimated from Petrie's (1963) forest cover map for 1860, the amount equated to 91% forest cover for this period. This amounted to 22.6 km of forested stream reaches, or approximately 83% of streams located in forested areas. For this 1860 scenario, we assumed that very little commercial farming activity was taking place and that the open land had been cleared for the purpose of obtaining building materials for nearby Lyttleton (Ogilvie 1992).

Pigeon Bay Scenario 1880

By 1880, the forest cover was reduced to 45% of the catchment area. Taking into account the spatial configuration of forest based on the digitized maps of Petrie (1963), this equated to 4.6 km of forested stream reaches. Again, for this early time period, we made no assumptions as to particular farming activities that might have been established, although there was some indication that dairy farming was taking place in the catchment (Ogilvie 1992).

Pigeon Bay Scenario 1950

In 1950, only 20% of the catchment remained forested (from Petrie 1963). Considering the spatial configuration of forest cover within the catchment, this equated to 6.8 km of forested stream reaches. For this time period, the main farming activity was intensive dairy farming, with the local cheese factory producing more than 200 tons of cheese per annum (Ogilvie 1990, 1992).

Pigeon Bay Scenario Present

This scenario gives the present-day situation of Pigeon Bay and is a part of the original distribution model developed. At present, there are 7.1 km^2 of dairy pastures, 3.3 km^2 of sheep pastures, and 12.3 km^2 of mixed sheep and dairy pastures when 3.6 km^2 of existing forested cover has been accounted for (from AgriBase 2000).

Pigeon Bay Scenario One

In this scenario, six parcels of mixed sheep and dairy pasture were converted to forest. This land conversion would result in a net forest gain of 3.7 km^2, more than doubling the present-day situation with respect to forest cover. When the spatial configuration of this gain in forested landcover is accounted for, 3.2 km of stream reaches, which at present have no forest cover along the stream margins, would have the riparian zone afforested, resulting in 11.6 km of forested stream reaches within the Pigeon Bay study catchment. What would the result of this land conversion be for koaro and banded kokopu?

Pigeon Bay Scenario Two

Fencing of waterways to prevent animals from trampling stream banks is one way in which streams and their biota can be protected from the direct negative effects of farm animals. If one were to protect streams with a 10-m fenced-off buffer on both sides of the stream that would then be allowed to afforest, what would the modeled benefit be to banded kokopu and koaro? A 10-m forested buffer around all stream reaches that at present do not have riparian forest cover would result in a net gain of 2.1% forest cover within the Pigeon Bay catchment.

Pigeon Bay Scenario Three

Streams with protected forested margins may have indirect effects, such as farm runoff from nearby land uses, reduced. If both the direct (animals trampling

Table 1. Backward conditional binary logistic regression procedures for both discrete and continuous variables[a]

Discrete variables		Frequency of sites	Numerical code
Farming activity (Agribase 2000)	No	119	0
	Sheep	15	1
	Cattle	5	2
	Sheep and cattle	33	3
Strahler's stream order (1:50,000)	First order	29	1
	Second order	94	2
	Third order	49	0
Riparian zone	Forested	71	0
	Nonforested	101	1
Stream mouth	Lake	40	0
	Sea	132	1
Predominant forest position	Lowland (below 200 m)	58	1
	Upland (above 200 m)	114	0
Banded kokopu	Absent	117	1
		55	0

Continuous variables	Transformation
Proportion catchment forest cover	Arcsine square root
Maximum slope downstream of sampled site (deg)	None
Mean stream slope at location of sampled site (deg)	None
Length of stream downstream of sampled site (m)	Square root
Mean stream reach altitude at sampled site (m)	None
Sheep farming upstream of sampled site (m)	Square root
Sheep farming downstream of sampled site (m)	Square root
Dairy farming upstream of sampled site (m)	Square root
Dairy farming downstream of sampled site (m)	Square root
Mixed sheep and dairy upstream of sampled site (m)	Square root
Mixed sheep and dairy downstream of sampled site (m)	Square root

[a] Within categories, site records were assigned a numerical code according to the specific sub-category of the variable. Most continuous variables for all sites in our inventory were transformed to obtain normality.

stream banks) and indirect effects of land uses were eliminated, then what would the modeled benefit for the two diadromous fish species be?

Pigeon Bay Scenario Four

How could one potentially restore the streams of Pigeon Bay to a level equivalent of 1860 for both species of diadromous fish, and still leave enough room for present-day activities? Can one establish a balance of specific land uses that would allow for this?

Results

Variables included in the logistic regression analysis for the presence or absence of banded kokopu and koaro are given in Table 1. The table shows that the majority of sampled sites were in areas of no farming. However, mixed sheep and cattle grazing was the immediate land use at 33 sites, with another 15 and 5 in sheep or cattle paddocks, respectively. Most sampled sites were in second- (55%) and third-order (28%) streams, although first-order headwater streams (17%) were also represented (Table 1). Seventy-one sites had riparian forest cover (within 5 m of water's edge), whereas 101 were in open areas devoid of riparian vegetation other than grasses. Most of the streams drained directly into the ocean, although 40 sites were only accessible to migratory fish through lakes (Table 1). One third of the sampled sites were in catchments with forest predominantly in lowland areas (below 200 m), and the remaining two thirds in catchments with predominantly upland forests (above 200 m) (Table 1). Banded kokopu was present at 55 sites.

Variables retained in the models and the significance values from backward conditional binary logistic regression for presence of banded kokopu and koaro are given in Table 2. The regression coefficients of determination for the occurrences of banded kokopu and koaro at sampled sites explain 72.9% and 62.5% of the variance in site occupancy by the two species, respectively. The models performed well for both spe-

Table 2. Backward conditional binary logistic regression results for presence of banded kokopu and koaro at a site[a]

Banded kokopu	β	S.E.	Wald	*df*	*p* value	Exp(β)
Stream order (1:50,000)						
First order	2.998	1.163	6.601	1	0.010	19.837
Second order	3.191	1.091	8.553	1	0.003	24.319
Third order[b]			8.554	2	0.014	
Commercial land use activity						
None[b]			11.133	3	0.011	
Sheep farming	1.602	0.784	4.175	1	0.041	4.961
Cattle farming	−0.661	1.367	0.234	1	0.629	0.516
Sheep and cattle	−2.558	1.103	5.379	1	0.020	0.077
Riparian zone nonforested	−1.939	0.552	12.319	1	<0.001	0.144
Lowland forest position	−1.031	0.518	3.965	1	0.046	0.357
Downstream length	−0.041	0.009	23.290	1	<0.001	0.959
Koaro	**β**	**S.E.**	**Wald**	***df***	***p* value**	**Exp (β)**
Commercial land use activity						
None[b]			14.611	3	0.002	
Sheep farming	−2.568	0.839	9.359	1	0.002	0.077
Cattle farming	−3.163	2.082	2.308	1	0.129	0.042
Sheep and cattle	1.298	0.630	4.248	1	0.039	3.660
Banded kokopu present	−3.370	0.640	27.580	1	<0.001	0.030
Reach altitude	0.016	0.005	12.444	1	<0.001	1.016
Downstream length	−0.028	0.012	5.524	1	0.019	0.973
Proportion forest cover	7.096	1.641	18.704	1	<0.001	1207.358

[a] β represent the estimated regression coefficients for the predictor variables, with the standard errors (S.E.) given. The Wald statistic is the ratio of the β to S.E. of the regression coefficient squared. Reference conditions have more degrees of freedom (df) because they are used as reference for the estimation of coefficients for the non-reference conditions. The significance of each variable is given by the *p* value. The Exp(β) is the predicted change in odds for a unit increase in the predictor variable.

[b] Reference condition.

cies, with 86.0% of banded kokopu and 83.7% of koaro sites classified correctly using leave-one-out cross-validation techniques (Table 3). Banded kokopu were more likely to be absent from stream reaches flowing through areas of cattle farming, mixed sheep and cattle farming, or having no riparian forest cover along the stream margins (Table 2). Additionally, if the majority of forest cover within catchments is predominantly in the lower parts of catchments, banded kokopu are more likely to be absent. There was also a negative influence of distance from stream mouth (to sea or lake) on occurrence of banded kokopu at sites. Banded kokopu were more likely to be present in small streams flowing through sheep pastures than cattle pastures.

For koaro, there were positive influences on occurrence at sampled sites with increases in the proportion of catchment forest cover, higher stream reach altitudes, and mixed sheep and cattle farming (Table 2). Koaro site occupancy was also negatively associated with distance from source of juveniles, cattle farming, and furthermore by sheep farming. Of particular interest was a strong negative interaction between the presence of banded kokopu and presence of koaro, where koaro were more likely to be absent when banded kokopu were present.

The location of streams flowing through the four primary land uses differed both with mean distance from stream mouth and altitude above mean sea level (Figure 2). Streams with no commercial land use activity were generally located further inland and at higher altitudes than streams with commercial farming activities. Streams flowing through sheep paddocks were generally located at lower altitudes than any other commercial farming activity, and approximately equidistant from stream mouths compared to cattle paddocks (Figure 2). Mixed sheep and cattle areas were closest to stream mouths, but at higher altitudes compared to pure sheep or cattle paddocks (Figure 2). Koaro penetrated significantly further inland than banded kokopu, but no significant differences with respect to elevations or maximum slope encountered during migration were found, and both species occupied stream reaches of similar slopes (Table 4).

Results of backward conditional binary logistic regression analysis were applied to the digital hydrology network by inserting the probability equation (Eq.

Table 3. This classification table assessed the performance of our model by cross-tabulating the observed presence/absence of banded kokopu and koaro categories with the predicted presence/absence of the two species from logistic regression procedures[a]

		Predicted by logistic regression		
		Banded kokopu		
	Observed in the field	Absent	Present	Percentage correct
Banded kokopu	Absent	104	13	88.9
	Present	11	44	80.0
Overall percentage			86.0	86.0

		Predicted by logistic regression		
		Koaro		
	Observed in the field	Absent	Present	Percentage correct
Koaro	Absent	85	12	87.6
	Present	16	59	78.8
Overall percentage				83.7

[a] For each case, the predicted response was the category treated as 1, if that category's predicted probability was greater than specified probability cutoff of 0.5. Cells on the diagonal from top-left to right-bottom were correct predictions. Cells on the opposite diagonal, from bottom-left to top-right, were incorrect predictions.

1) into its associated database and calculating the probability of occurrences for the two species under the various case scenarios. This allowed for visualization (Figure 1B) and quantification (Figure 3) of suitable stream reaches, based on probability of occurrence in stream reaches, for the two species. The amount of stream reaches modeled as good ($p > 0.75$), moderate ($0.75 < p > 0.50$), and poor ($p < 0.50$) was predicted to be similar for each species (Figure 3), but the spatial distribution of the two species differed considerably, although there was considerable spatial overlap in the streams classified as poor for both species (Figures 3 and 4). Streams modeled as moderate and good for banded kokopu occurred further inland than streams classified similarly for koaro, whereas poor banded kokopu streams occurred closer to sea (Figure 4). Mean altitude for good koaro streams was higher than similarly modeled banded kokopu streams, but streams classified as moderate or poor for koaro were at lower altitudes than similar streams for banded kokopu (Figure 4). Mean distance from source for good, moderate, and poor stream classifications for both species occurred at 3.4, 4.2, and 3.3 km from the source of juveniles, respectively. Mean altitudes for the same overlapping stream reaches occurred at 299, 238, and 70 m above mean sea level.

Pigeon Bay Hindcasting Results

Our modeled case scenarios of koaro and banded kokopu distribution in Pigeon Bay reveal different responses, by both species, to changes in land uses of the catchment (Figure 5). In 1860, our model predicts koaro would have been present throughout the catchment, whereas banded kokopu would have occupied a few kilometers less (24.2 km). By 1880, the effects of forest removal probably reduced the amount of good habitat for koaro (18.7 km) more so than for banded kokopu (22.4 km), which is more sensitive to the removal of riparian forest cover. However, by 1950, with both forest removal and changes in specific land uses from barren land to cattle pastures affecting both species, the amount of good habitat would have been about equal for both species (4.2 km for banded kokopu and 4.5 km for koaro). The present-day distribution further reflects changes in specific land use from cattle farming to other land use types, such as sheep pastures and mixed sheep and cattle pastures, with less negative influence on the distribution of koaro. As a result of these land use changes, suitable stream reaches for koaro (16.4 km) are currently nine times that of banded kokopu (1.8 km) (Figure 5).

Forecasting Results

The model indicated that banded kokopu required forest cover along stream margins, whereas the presence of koaro was positively correlated with catchment forest cover, but not to riparian forest cover. Given the strong negative interaction between koaro and banded kokopu, and their different interaction with landscape

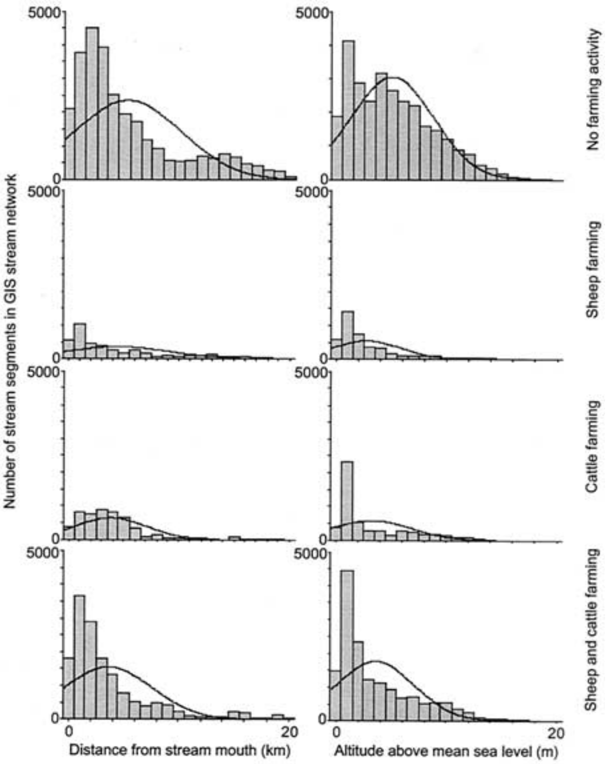

Figure 2. Location of stream segments in the GIS hydrology network for Banks Peninsula relative to stream mouth (distance to stream mouth) and elevation above mean sea level (altitude) for four categories of land uses. From top to bottom, stream reaches flowing through areas of no farming, sheep, cattle, and mixed sheep and cattle farming are given. Normal distribution curves are represented by the solid black lines.

features, land use could be selectively manipulated to benefit one or both species.

In 1984, New Zealand's Labour government took the step of ending all farm subsidies. Subsequently, marginal grazing land would be expensive to maintain, and a change in land use from mixed sheep and cattle pastures to plantation forestry would not be an unlikely scenario.

With the conversion of six parcels (3.7 km^2) of mixed sheep and cattle land uses to forests, the amount of ''good'' banded kokopu habitat is predicted to increase by 0.75 km because of the increase in stream length with the riparian forest, and by almost 2 km for koaro because of the doubling of the proportion of forest cover within the catchment (Figure 6; Scenario 1).

With riparian fencing and subsequent reestablishment of forested stream margins, the effect of removing the direct negative (trampling of stream banks) influences of specific farming activities is more pronounced. We predict banded kokopu would benefit more from this scenario, with the amount of good habitat increasing to about 8.5 km. This increase in good banded kokopu habitat would in turn influence koaro distribution negatively. Furthermore, the increase in catchment forest cover would not be sufficient to offset the negative effects of banded kokopu presence, and good koaro habitat would subsequently be reduced to 15.8 km (Figure 6; Scenario 2).

If forested riparian corridors were to completely eliminate potential negative effects of surrounding land uses, the amount of good habitat for banded kokopu would return to levels similar to 1860 conditions, with more than 24 km of good habitat. However, with very little gain in proportion of catchment forest cover and such a dramatic increase in good banded kokopu habitat, koaro habitat would be reduced to an all-time low of 2.5 km (Figure 6; Scenario 3).

If the management goal was to achieve equal amount of habitat classified as good for both banded kokopu and koaro, having afforested the waterway margins, it could be accomplished by further planting forests within the catchment, with koaro reaching levels similar to that of banded kokopu at about 64% catchment forest cover (Figure 7).

Discussion

Modeling

Typically, studies of fish populations have been undertaken at small spatial scales (but see Minns 1990), following a logical statistical design (e.g., stratified random) that allows researchers to draw inferences from their sample to the larger population of such sites about relationships between stream fish and their habitat, in turn providing information to managers in hopes of enhancing the focal populations (Fausch and others 2002). In many cases, it is not feasible to take measurements and field samples on a case-by-case basis. Consequently, models based on sound preexisting data provide a reasonable and quick alternative for field sampling, provided that the models used accurately predict the distribution of the focal species.

Koaro and banded kokopu use the entire waterway throughout their life history, from the spawning sites in the headwaters, drifting to the sea as larvae, returning to a freshwater environment as juvenile whitebait, and eventually reaching the headwaters again as mature fish (McDowall 1990). Banded kok-

Table 4. Descriptive statistics for sites with banded kokopu (N = 55) and koaro (N = 75) sampled sites

	Banded kokopu sites				Koaro sites				T-test independent samples		
Variables	Min	Max	Mean	S.E.	Min	Max	Mean	S.E.	*t*-value	*df*	*p*-value
Reach slope at sites (deg)	0.0	59.5	9.7	1.4	0.0	59.5	9.4	1.1	−0.224	128	0.822
Slope downstream of sites (deg)	8.5	59.5	26.2	1.5	1.1	59.5	25.3	1.4	−0.428	128	0.669
Altitudes of sites (m)	102	278.5	99.9	8.1	9.2	374.6	123.0	10.4	1.647	128	0.102
Length downstream of sites (m)	103.2	6477.9	1908.0	165.0	23.9	16833.7	3313.4	448.3	2.589	128	0.011

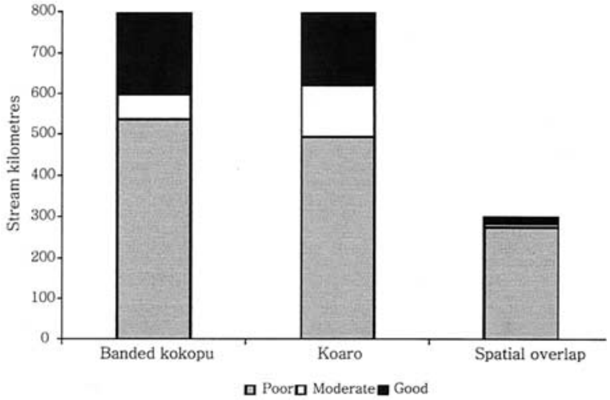

Figure 3. Stream reaches were classified as good ($p > 0.75$), moderate ($0.75 < p > 0.50$), and poor ($p < 0.50$) for banded kokopu and koaro according to the calculated probability of encountering the species from the logistic regression procedures. This figure shows the amount of stream kilometers on Banks Peninsula that comprise these categories for the two species. Also shown is the amount of spatial overlap of stream reaches for the three classification categories in kilometers for Banks Peninsula. Note that there is considerable overlap in stream reaches classified as poor for both species, whereas moderately good and good habitat have less overlap.

opu and koaro distributions on Banks Peninsula are fragmented by anthropogenic habitat degradation, and as with many other species in other parts of the world, the critical habitats required are often created through interactions with intact landscapes (Boutin and Hebert 2002).

In New Zealand, pastoral and production land uses are perceived to be the main causes of degradation of inland waters (Smith 1993, Scarsbrook and Halliday 1999), and similarly, streams on Banks Peninsula are no exception. Agriculture and deforestation alter the physical structure of small streams, either by reducing the amount of woody debris entering the streams and hence altering the depth, substrate composition, and current diversity, or by removing spatial complexity by channelization (Schlosser 1991). In our study, we found that koaro and banded kokopu responded differently to different types of land uses, resulting in distinct, yet not entirely exclusive, stream reaches classified as good, moderate, and poor for the two species based on the calculated probability of encountering the species within a given stream reach. Both species were negatively influenced by cattle farming. It may be that cattle, by trampling the stream banks and disturbing substrates, exert an intense direct negative effect on both species, as well as less intense indirect effects through contamination of streams by fecal material. Responses to sheep farming differed for the two species, with banded kokopu responding positively to sheep farming, whereas koaro was negatively influenced. It is likely that koaro, positively influenced by reach altitudes and less affected by distance from source, is absent from stream reaches with sheep farming because its migratory drive has taken it beyond the areas with this particular land use type, whereas banded kokopu still occupies these lowland reaches. Mixed sheep and cattle farming had the opposite effects of sheep farming on both species. This particular land use type on Banks Peninsula tends to occur at higher altitudes compared to either cattle or sheep farming alone. Thus, it may be that koaro is positively correlated by mixed sheep and cattle farming as a result of its spatial distribution in the landscape, rather than any direct benefit of the land use *per se*, and that banded kokopu is negatively correlated with this land use because it is generally absent from areas where banded kokopu are found.

In view of the many functions of riparian forest cover, it is not surprising that the banded kokopu is negatively influenced by the absence of forested riparian margins. It is also possible that riparian cover not only provides for better microhabitat, but also improves the connectivity between suitable upland and lowland habitats. Our observations are consistent with the findings of Hopkins (1979), Rowe (1981), and Hanchet (1990), who found banded kokopu and koaro to be common in streams flowing through indigenous forest, but often absent or rare in pasture streams (Hayes and others 1989). It is possible that riparian

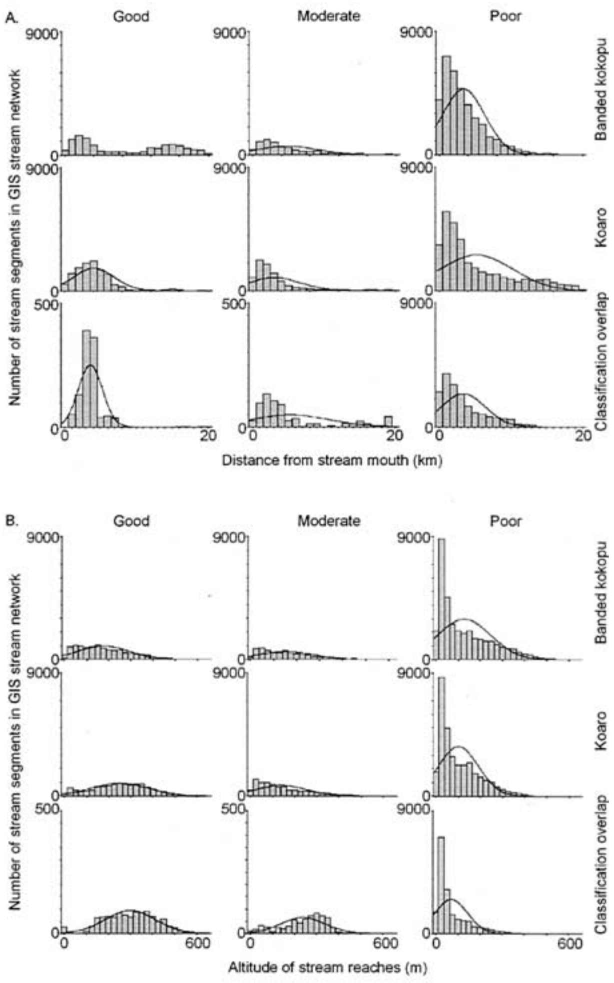

Figure 4. (**A**) The *y*-axis represents the number of stream segments in the digital hydrology network for Banks Peninsula, all of which are less than 25 m in length. The *x*-axis represents categories of distance to stream mouth, either to a lake, or to the sea, giving an indication of the spatial location and the amount of stream segments at given distances from the stream mouth. Normal curves for the distributions are given by solid black lines. From left to right, graphs represent stream reaches classified as good, moderate, and poor for the focal species. From top to bottom, the graphs represent banded kokopu (top), koaro (middle), and the degree of spatial overlap (bottom) of the stream segments for the two species and three categories. Note that there is little overlap in stream reaches classified as good for the two species, and that the overlap occurs at locations proximal to the stream mouth. The distribution of overlap of moderately good stream reaches at occur across the range of distances from the stream mouth, whereas poor stream reaches overlap occur close to stream mouths as well. (**B**) Again, the *y*-axis represents the number of stream segments in the digital hydrology network for Banks Peninsula, all of which are less than 25 m in length. This time, the *x*-axis represents categories of stream reach elevations above mean sea level. The graphs, from left to right, and top to bottom, are in the same order as in (A) above. Note that overlap of stream reaches classified as good occur at most elevations, but more so at medium elevations. Similar trends were found for reaches classified as moderately good for the two species. Overlap of poor stream reaches for the two species occurred mostly at low elevations.

cover not only provides for better microhabitat for the fish, but also improves the connectivity between suitable upland and lowland habitats.

The koaro is strongly influenced by the overall amount of forest cover within catchments, whereas the banded kokopu responded to the proximal presence of forested riparian margins. At the catchment scale, conversion of native forest to plantation forest or pasture alters hydrologic patterns, and may also cause a loss of physical habitat and deterioration of water quality and substrate composition (Smith 1993). Subsequently, channel morphology adjusts to these altered conditions, often expressed as a simplification of stream structure, and increased load of fine suspended and deposited sediments (Alabaster 1972, Kauffman and others 1997, Jowett and Boustead 2001). It may actually be that the local presence of forested riparian cover along with catchment-scale forest cover acts to provide suitable habitat for both species, because the negative influence of banded kokopu on koaro pres-

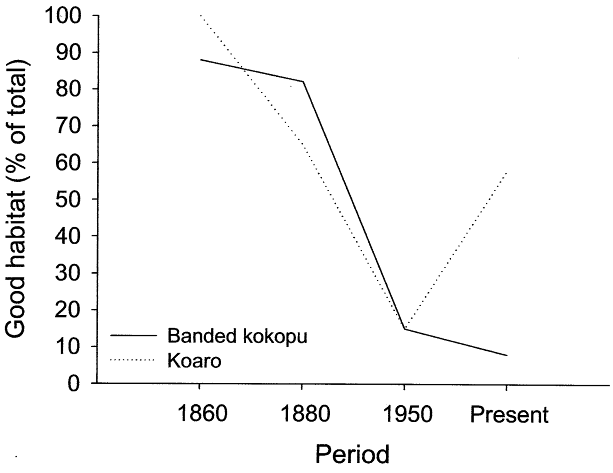

Figure 5. Hindcast modeling of banded kokopu (dashed lines) and koaro (solid line) distributions at Pigeon Bay, Banks Peninsula, over four dates from 1860 until present. The percentage of stream length in the catchment predicted, by applying probability equation (1) with the predictor variables from logistic regression procedures, to be good habitat (i.e., $p >$ 0.75 chance of banded kokopu/koaro to be present) is indicated. Figures for 1860, 1880, and 1950 were calculated using historical information on forest cover and a logistic regression model of contemporary distribution of the two species.

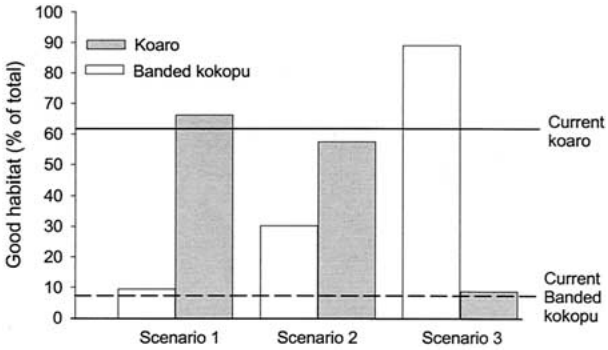

Figure 6. Forecast modeling of three scenarios of the amount of stream length at Pigeon Bay, Banks Peninsula, predicted to become good, by using a logistic regression model of contemporary distribution of banded kokopu and koaro under three possible future scenarios for the catchments: 1) conversion of six parcels of mixed sheep and cattle pastures to plantation forestry, 2) afforestation and fencing of the riparian margins with direct effects of livestock removed, and 3) both direct effects of livestock having access to the stream and indirect effects of adjacent land use types removed. Solid black line represents present-day status for koaro. Dotted line represents present-day status for banded kokopu.

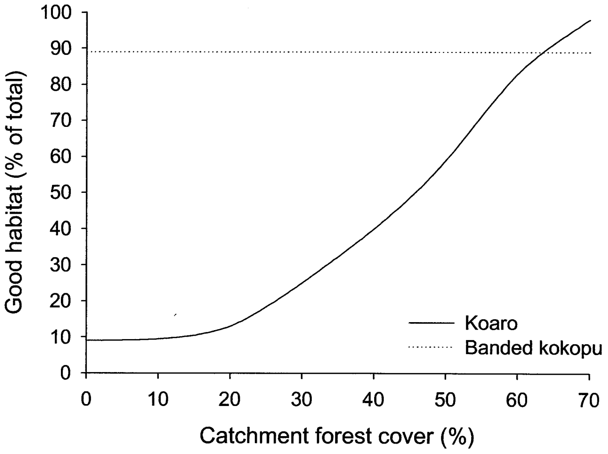

Figure 7. If all stream reaches were fenced off and afforested, with no direct effects of land use immediately beyond the riparian corridor, the distribution of banded kokopu is predicted by the logistic regression model to remain constant at around 90% of the available watercourse of Pigeon Bay (Scenario 3). Koaro, however, responds strongly to the overall amount of forested cover within the catchment as a whole. This graph illustrates how much of the catchment would have to be afforested to offset the negative influence of the presence of banded kokopu on koaro distribution. The solid line shows the projected response of koaro to increased catchment forest cover, whereas the dotted line shows the projected response of banded kokopu.

ence in stream reaches is balanced by high proportions of forest cover within catchments. This further emphasizes the need for more landscape-oriented research with respect to migratory fish distributions.

Hindcasting Results

The spatial distribution and amount of good-quality stream habitat (classified as having a greater than 0.75 probability of encountering the focal species) for both koaro and banded kokopu in Pigeon Bay were predicted to be quite different in 1860 compared to the present day. Our model predicted both species to have been present throughout most of the Pigeon Bay catchment in 1860. However, possible interactions with closely related species no longer present on Banks Peninsula, such as the giant kokopu (*G. argenteus* Gmelin, 1789), which was reported to be present on Banks Peninsula in the past (Stokell 1949), and shortjaw kokopu (*G. postvectis* Clarke, 1899) cannot be discounted. Giant kokopu and shortjaw kokopu are the two largest galaxiid fish species in New Zealand, and it is likely that these species would have competed or preyed on koaro, and perhaps also on banded kokopu. The immediate effects of forest removal between 1860 and 1880 on koaro and banded kokopu distributions are likely to have been dramatic, more so for koaro than for banded kokopu. In our models, koaro distribution was more closely related to proportion of forest cover at the catchment scale, whereas banded kokopu distribution was related to proximate forest cover at reach scale. Riparian forest cover in Pigeon Bay was still relatively intact between 1860 and 1880, so banded kokopu were still likely to have been widespread, whereas koaro would have likely been restricted to areas without banded kokopu. By 1950, with further deforestation and land use change to more intensive cattle farming, both koaro and banded kokopu would likely have had severely restricted distributions, with the majority of the stream reaches within the catchment offering poor quality habitat for both species. The present-day distribution of koaro in Pigeon Bay reflects a diversification of land use types from cattle farming, to less intensive mixed sheep and cattle and pure sheep farming, with some increase in the overall proportion of forest cover within the catchment. This diversification and conversion of land use has increased the amount of good quality habitat for koaro compared to 1950. However, the situation for banded kokopu is likely to have worsened because of further removal of riparian forest cover, but also because of the different response of banded kokopu to mixed sheep and cattle farming, a land use that affects the species more negatively than cattle farming.

Forecasting Results

The outcome of our conversion of six parcels of mixed sheep and cattle land use in the upper reaches of Pigeon Bay would benefit both koaro and banded kokopu. The immediate afforestation of the streams flowing through this new land use type would produce good quality habitat for banded kokopu, but with the doubling of the amount of forest cover within Pigeon Bay catchment, the benefits for koaro would be even more so than for banded kokopu. This scenario illustrates the interactions between catchment-scale and reach-scale variables, because banded kokopu responds to the reach scale presence of riparian forest cover, and koaro responds to the catchment scale proportion forest cover increase. There are encouraging signs that some New Zealand farmers are conscious of the negative influences that farming activities have on unprotected streams and their biota, and many are taking measures to prevent these negative effects (Graeme 2002). A first measure in stream protection is to fence the stream edges to prevent stock from entering the stream, thus removing the direct negative influences of the specific land use type. To assess possible outcomes of farmers' decisions to protect streams on their lands, we modeled two possible scenarios where the stream margins were protected and allowed to afforest with little gain in proportion catchment forest cover: one with the direct negative effects of stock access to the stream eliminated by fencing off streams as well as stream-side afforestation, and another with both the direct and indirect effects of adjacent land uses removed. Our results indicate that in removing both direct and indirect effects of adjacent land uses, banded kokopu stands to gain the most, with good quality stream habitat increasing from less than 10% at present to more than 30% with direct effects removed, and good stream habitat similar to 1860 conditions if both direct and indirect effects were removed. With very little gain in overall proportion catchment forest cover for these two scenarios, and given the negative interactions between the presence of banded kokopu and koaro, the amount of suitable koaro habitat would be greatly reduced in both cases.

Goals for environmental management are often multifaceted, and a management outcome that only benefits one out of two species of significance rarely comprises a warranted management output. The two scenarios above beg the question: How can acceptable management levels be achieved for both species? Clearly, by protecting stream margins from the direct negative effects of production farm types by planting along riparian margins, banded kokopu would benefit greatly. To achieve the same level of benefit for koaro would require afforestation in the catchment to approximately 62% to achieve the same level of distribution as banded kokopu. This would offset the direct negative effects of banded kokopu presence on koaro, because the strong positive effect of forest cover on koaro distribution would prevail over the negative influence of the presence of banded kokopu.

Restoration of stream ecosystems is ultimately complicated by the fact that the status quo is often far removed from prior scenarios, and a return to any state resembling past species distributions is difficult, or perhaps impossible, especially given the reservations as to what species were actually present within the system in the past. In our case, it may be that other species, such as shortjaw kokopu and giant kokopu, with similar habitat requirements compared to our focal species, might have been present within the study area, and the potential effects of their presence can only be guessed at. If interactions with other species of similar habitat requirements were negligible for banded kokopu and koaro, we could accurately model the extent of the distribution of both species. Additionally, not all types of stream habitat degradation may be reversible (e.g., fine sediments may stay in the stream for a long time).

Implications for Management

The combination of site-scale and landscape-scale approaches could be particularly important for the management of the large-bodied diadromous galaxiids because human alteration of the landscape occurs at multiple scales, and accordingly the ecological consequences must also be identified and managed at multiple scales. Diadromous fish, such as koaro and banded kokopu, are good habitat quality indicators because their distributions are clearly linked to contemporary land uses. By using GIS models, which allow for continuous update to account for modifications of the landscape, and having the data output in a convenient map format that the public at large can easily comprehend, a more effective management can be achieved. Fausch and others (2002) emphasized that a continuous view of rivers is essential for effective research and conservation of fish and other aquatic biota in Montana, U.S.A., allowing for a view of the entire heterogeneous scene of the river environment unfolding through time. Also, a multiscale GIS-assisted approach to riverine fisheries management may greatly improve current conservation efforts, and may encourage managers to expand the scale at which solutions are sought (Boutin and Hebert 2002).

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