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Effect of damming on distribution of rainbow trout in Hokkaido, Japan

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Abstract Rainbow trout introduced into Hokkaido in 1920 have become widely distributed due to extensive release into many reservoirs and lakes for sport-fishing; their presence often results in reductions of native fish populations. We analyzed and predicted the relationship between the probability of occurrence of rainbow trout and the proximity of dams (or attributed reservoirs), using a database of the presence or absence of rainbow trout collected during 1960–2004 in Hokkaido to clarify the spread patterns of exotic species (e.g., rainbow trout) due to large-scale damming over a long period. Rainbow trout were abundant in streams within approximately 10 km of dams in recent years, regardless of whether the stream was up- or down-stream from the dam and after accounting for the effects of other environmental variables (e.g. elevation, population density, and survey year). A delayed increase in trout occurrence below dams as compared with above dams suggests that the occurrence below dams may be largely due to escapement of stocked populations and a continuously increasing abundance since 1970. The management of dams and reservoirs is necessary to prevent further spread of rainbow trout because they can threaten habitats of native Japanese salmonids through various mechanisms.

Keywords Damming · Exotic fish · Generalized additive model · Hokkaido · Rainbow trout

Introduction

Dam construction fundamentally alters river and stream ecosystems in several ways: modification of the downstream flux of water and sediment, change of water temperature, and creation of barriers (Poff and Hart 2002). These alterations induce the extirpation and loss of some freshwater fishes (Joy and Death 2001; Fukushima et al. 2007). Besides these fundamental changes, another serious impact of damming is the increased success of invasive species due to the reductions in variability of the hydrologic regime

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(Poff and Hart 2002). The expansion of invasive species also results from intentional or unintentional stocking, frequently into reservoirs. In addition, the lacustrine environment created in a reservoir supports a habitat favorable to exotic fishes, which may compete with the native fish communities (Holmquist et al. 1998; Quist et al. 2005; Marchetti et al. 2006). Although exotic fishes have been more commonly introduced and increased in reservoirs and their downstream areas, most studies have focused only on comparisons between sites with and without dams or before and after dam construction. Few studies have explicitly clarified the spread patterns of the exotic fishes due to damming at a spatial large-scale for a long period.

In Hokkaido (the northern island of Japan), 167 dams (>15 m high) have been constructed over a broad area during the past 80 years. In addition, several often predatory, exotic species have been introduced, such as rainbow trout, *Oncorhynchus mykiss*, and brown trout *Salmo trutta*. In particular, rainbow trout have almost become established in Hokkaido river basins. The rainbow trout were first introduced in Hokkaido in 1920, and their distribution has continued to expand since the 1970s for sport-fishing, mainly in lakes and reservoirs (Takami and Aoyama 1999). According to the fishery census of Japan, although a number of young rainbow trout were released in 1988, intentional stocking of them sharply decreased after 1990.[1] Introduced rainbow trout negatively impact the native white spotted charr (*Salvelinus leucomaenis*) populations by dislodging the latter's spawning redds (Taniguchi et al. 2000) and by competing for feeding habitats in Japanese streams, especially in Hokkaido (Morita et al. 2004). In this study, we examine the relationship between the occurrence of rainbow trout and various environmental variables, including the spatial relation between dams and fish survey locations in Hokkaido, by analyzing the long-term fish database compiled using a geographical information system (GIS). Our main objectives were to (1) examine whether damming affects the distributions of rainbow trout and (2) estimate rainbow trout distribution patterns and their temporal changes in relation to the up- and downstream distance from dams or reservoirs.

Methods

Study area and fish data

Hokkaido is the northernmost island of Japan (area= 78,423 km^2; 41°21′–45°33′N, 139°20′–148°53′E; Fig. 1a). Its climate is temperate to sub-arctic with average annual temperature ranging from 6–10°C and average annual precipitation in the range of 800–1,500 mm.

Fish data were taken from the database compiled by Fukushima et al. (2007). A total of 6,634 fish surveys conducted between 1960 and 2004 were chosen from the database by selecting the sites where multiple fish species were observed. Fish were captured using either netting (e.g., cast net, gill net, fyke net) or electrofishing in habitats including pools, riffles, and reservoirs ranging from sea level to over 1,400 m a.s.l. The fish data were transformed into presence/absence observations and merged into 1625 "sub-basins," which were defined as the catchment above a river confluence less the catchment above the next upstream confluence, encompassing individual stream reaches (mean length±SD=5.21±3.77 km, range=0.123–62.76 km; Fig. 1b). In order to reduce errors associated with false absences, only the most recent survey year was used (treated as one independent record) when multiple surveys were conducted within a single sub-basin. Of the 1,625 sub-basins merged, 75.5% (1,227 sub-basins) were sampled multiple times.

Environmental data

As predictors for the occurrence of rainbow trout, we considered the following nine independent variables: drainage area (km^2), annual rainfall (mm), annual air temperature (°C), elevation (m), gradient (°), human population density (person/km^2), survey year, the location of survey sites relative to dams (hereafter referred to as the dam variable) and spatial autocorrelation. Drainage area and fish survey year were derived from GIS; elevation, gradient, rainfall, and air temperature were derived from the grid data of the Digital National Information.[2] Information on population density was based on the grid data of the

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[1] http://www.tdb.maff.go.jp/toukei/a02smenu?TokID=J126&TokKbn=C&TokIDI=J126C-006&TokKbnName=.

[2] http://nlftp.mlit.go.jp/ksj.

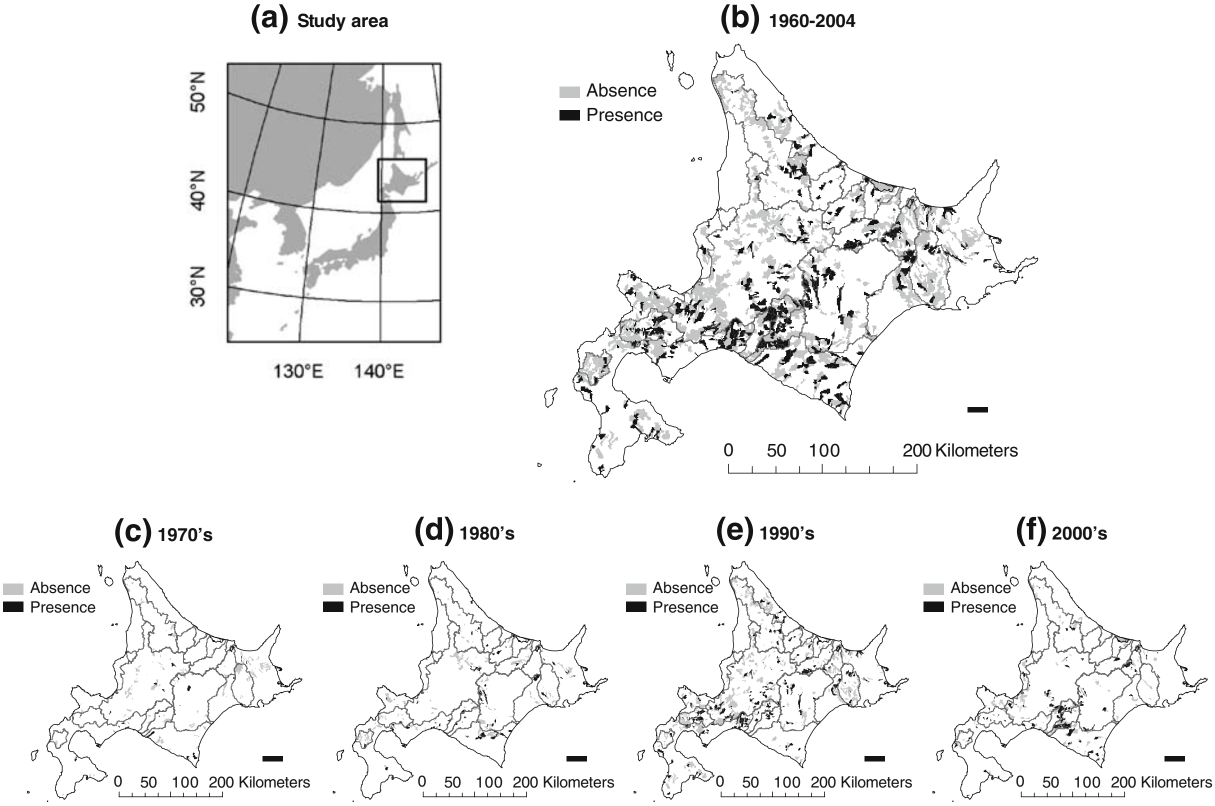

Fig. 1 **a** Geographical location of Hokkaido, Japan, and absence or presence of rainbow trout at survey sites in **b** 1960–2004, **c** 1970s, **d** 1980s, **e** 1990s, and **f** 2000s

Population Census of Japan (2000). Using GIS, the dam variable was made categorical, with categories corresponding to one of the following: (1) above dam: sub-basin was located in one of the inlet streams of a reservoir; (2) below dam: sub-basin was located below a dam; or (3) no dam: sub-basin had no dams downstream to the river mouth inlet stream. Neighboring points in space are more similar than would be expected by chance because species' distributions and associated environments are spatially autocorrelated (Legendre and Fortin 1989; Lichstein et al. 2002). We defined a spatial autocorrelation term for each sub-basin by estimating the presence/absence of rainbow trout in all sub-basins bordering that sub-basin. The spatial autocorrelation term took a value of 1 if at least one bordering sub-basin showed a positive observation (i.e., presence) of rainbow trout. It took a value of 0 if no bordering sub-basin had a positive observation. The absolute correlation coefficients between all pairs of all environmental variables were ranged between −0.58 and 0.61.

We examined the proximity of sub-basins to reservoirs because rainbow trout might spread into stream sites from reservoirs. The minimum distance above and below dams of model 2 and model 3 was considered as a potential predictor by replacing the dam term of model 1 to predict the probability of occurrence for rainbow trout at sub-basins above the dam and at sub-basins below the dam (Table 1). The distance above and below dams was calculated as the watercourse distance from the upstream confluence point in the sub-basin to the nearest dam for each fish survey.

Statistical analysis

We used generalized additive models (GAMs) with a binomial error distribution to model the probability of occurrence for rainbow trout and to assess the effects of damming on this probability. GAMs are nonparametric extensions of generalized linear models and allow nonlinear response surfaces to be fitted using a

Table 1 Changes in deviance when dropping a variable from the final models of occurrence of rainbow trout. Predictors denoted in by italics were selected as a nonparametric smooth function in GAMs

Variable	Total sub-basins (model 1)	Sub-basins above dams (model 2)	Sub-basins below dams (model 3)
Drainage area	**43.2**		
Annual rainfall	24.3		
Elevation	**67.1**		**24.6**
Population density	**49.7**	**27.8**	
Survey year	**46.1**	**23.6**	**29.7**
Dam	31.3	–	–
Distance above dams	–	18.7	–
Distance below dams	–	–	17.9
Spatial autocorrelation	133.7	27.7	28.1
Null deviance	1968	368	328
Residual deviance	1476	265	217
Deviance explained	0.25	0.28	0.34
Degrees of freedom	1625	270	277
AUC	0.89	0.88	0.92

range of different error structures (Hastie and Tibshirani 1990). GAMs were expressed as follows:

$$\mathrm{logit}\ \mathrm{P} = \alpha + \sum_{\mathrm{i}=1} \mathrm{f_i}(\mathrm{X_i})$$

where P is the response variable, α is the intercept, and f_i is a smooth function for the ith predictor variable X_i. To select the best set of predictor variables, we used a backward elimination procedure based on the Akaike Information Criterion (Akaike 1974). The predictor variables were considered significant if $P \leq 0.01$, based on log-likelihood ratio tests. The significance of nonparametric functions of each variable that was transformed using a smoothing spline was judged by estimating the change in deviance from the linear to non-linear term (i.e., smoothing spline) using a chi-square test (Venables and Ripley 1994). These nonparametric effects were considered to be significant only when $P \leq 0.001$.

The validity of the GAMs was tested with the 10-fold cross-validation technique (Neter et al. 1996), in which the total sub-basins within a given model were divided into 10 groups; nine groups were used to construct a model, which was then used to predict the probabilities of occurrence for the remaining group. This was repeated by switching the group to be set aside 10 times until the probabilities of occurrence for all sub-basins had been predicted. We further repeated this whole process 10 times by randomly dividing all sub-basins. We then averaged the predicted probabilities of occurrence across all sub-basins to obtain a single set of validation data. We calculated the area under the curve (AUC) of the receiver operating characteristic (Fielding and Bell 1997) to evaluate the discrimination accuracy of each GAM between presence and absence.

Results

Fish data were collected from total 1,625 sub-basins; with 171 sub-basins in 1970s, 289 sub-basins in 1980s, 822 sub-basins in 1990s, and 343 sub-basins in 2000s. Rainbow trout was detected from 478 of 1,625 sub-basins examined (Fig. 1b); with 23 sub-basins (13.5%) in 1970s (Fig. 1c), 78 sub-basins (27.0%) in 1980s (Fig. 1d), 253 sub-basins (30.8%) in 1990s (Fig. 1e), and 124 sub-basins (36.2%) in 2000s (Fig. 1f). The proportion of sub-basins with rainbow trout increased in recent time period.

The three final models of occurrence of rainbow trout had moderate to high accuracy (AUC>0.80; Swets 1988). Among the nine variables considered, the multiple regression model for the total sub-basins identified seven variables—drainage area, survey year, elevation, population density, rainfall, spatial autocorrelation, and dam—as the best predictors for occurrence of rainbow trout (Table 1: model 1; Fig. 2a–f: spatial autocorrelation term was eliminated from the plot because it is only used to reduce spatial autocorrelation error). The five continuous predictors except rainfall were significantly nonlinear ($P<0.01$). The occurrence of rainbow trout decreased with increasing drainage area (Fig. 2a) and rainfall

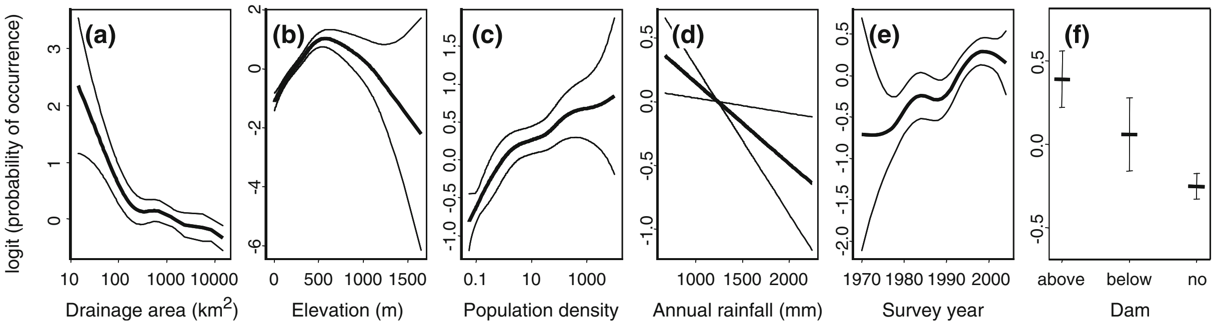

Fig. 2 The effects of the significant predictor variables on the probability of occurrence for rainbow trout, as estimated by GAMs. The thin lines indicated point-wise twice standard error bands. The *y*-axis represents the average contribution of the predictor variable in the logit scale

(Fig. 2d) and appeared to reach a maximum at the elevation of about 500 m (Fig. 2b). It increased with population density (Fig 2c) and survey year (Fig. 2e). Rainbow trout had significantly higher occurrence at sub-basins above and below dams (especially above) than at sub-basins without dams (Fig. 2f).

The GAMs to predict the occurrence of rainbow trout across the sub-basins above a dam included population density, survey year, distance above dams and spatial autocorrelation (Table 1: model 2). In the regression for the sub-basins below a dam, elevation, survey year, distance below dams, and spatial autocorrelation were selected as the significant predictors (Table 1: model 3). Although we did not illustrate the response curves for each predictor variable of these two models, the responses for the occurrence of rainbow trout were similar to each panel in Fig. 2. For different survey years, we predicted the relationships between the probabilities of occurrence and the minimum distance above and below dams using model 2 (Fig. 3a) and model 3 (Fig. 3b), respectively. Regardless of whether the sub-basins were up- or down-stream from dams, rainbow trout had the greatest occurrence at sites near dams, but the occurrence decreased dramatically away from dams (i.e., >10 km from dam). Reductions in proximity to dams obscured the direct effects of damming on rainbow trout because of inflows from tributaries. The probability of occurrence increased continuously with survey year, although it did not change significantly after 1990.

Discussion

Although the occurrence of this species was not correlated to watershed area, this result does not preclude the conclusion of an unsuccessful invasion of rainbow trout in larger watersheds. Trout possibly have a non-random distribution in larger watersheds because they tend to live in the impoundments (i.e., reservoir and

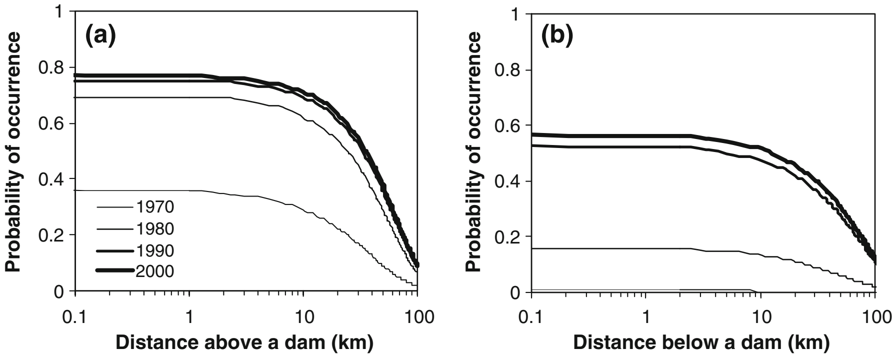

Fig. 3 Relationships between minimum distance **a** above and **b** below dams and the probability of occurrence for rainbow trout with different survey years (1970, 1980, 1990, and 2000), respectively. Each curve of plot **a** and **b** were predicted from the model 2 and model 3 shown in Table 1, respectively. In this prediction, we used the average human population density and elevation for all sub-basins in Hokkaido, and used a value of 0 for spatial autocorrelation

lake) as well as up- and down-stream of them. Human activity may help the spread of invading fishes (Padilla et al. 1996) by providing intentional or unintentional pathways (e.g., the aquaculture, bait, sport, and pet industries, the ballast water and hulls of ships) for introduction of non-native fishes and by producing an altered habitat (e.g., agriculture and landscape) commonly favored by non-native species (Kolar and Lodge 2002; Stohlgren et al. 2006). High occurrence at relatively high elevation may be related to stocking in reservoirs located at higher elevations and the suitable habitat (e.g., cold water temperature) of the upper reach of a river (Coleman and Fausch 2007).

The presence of dams was a significant predictor of occurrence of rainbow, suggesting that rainbow trout were more common in sites above and below dams than sites without dams. This result supports previous studies that suggested a positive relationship between damming and exotic species diversity (Holmquist et al. 1998). Streams regulated by damming may increase the invasive success of exotic species due to the suppression of natural disturbance regimes (Walker 1985; Raymond 1988).

Rainbow trout in Hokkaido streams showed increased relative abundance closer to the dams (i.e., associated reservoirs). Although rainbow trout may be directly stocked in unimpounded stream reaches, their movement out of reservoirs may largely control their spread in Hokkaido streams. High occurrence in sites above dams is inevitable because the fish are able to move freely upstream from a reservoir (Holmquist et al. 1998; Valdez et al. 2001). Spread into streams below dams may be attributed to various displacements, such as water releases from reservoirs and downstream fish ladders. In addition, the trout can expand further downstream by high water velocities that result from flooding (Lamberti et al. 1991). Slow and shallow reaches due to suppression of peak flow (Raymond 1988; Scheidegger and Bain 1995) and a more extensive food base (Blinn et al. 1995; Benenati et al. 1998) may also facilitate the reproduction and spread of rainbow trout in streams below dams. Although this study does not include interaction terms in the modeling process, distance below a dam generally have negative correlation with elevation. Therefore, given the negative relationship between distance below a dam and probability of occurrence, there is the possibility of overestimation of these terms because of the distance below a dam-elevation interaction.

Furthermore, although changes of occurrence both up- and down-stream of dams immediately after 1990 were unremarkable, the occurrence of rainbow trout increased in recent years. One possible reason for these patterns is that fish sampling efficiency was improved due to the introduction of electrofishing; another reason may be the continuous stocking of rainbow trout and their reproduction. However, differences in response to survey years both above and below dams are probably caused by the latter or by other reasons (e.g., movement from another location) rather than by the former reason. Occurrences above and below dams largely increased in 1980 and in 1990. As mentioned in the introduction section, rainbow trout were broadly introduced in the 1970s for fishing in lakes and reservoirs (Takami and Aoyama 1999), thus explaining a large increase in occurrence between 1970 and 1980 at sites above dams. However, as compared with responses to survey year at the upstream of dams, rainbow trout response at the downstream of dams showed a delayed pattern, i.e., low occurrence between 1970 and 1980. The increased occurrence below dams in 1990 probably resulted from escapement of rainbow trout stocked in reservoirs and the continuously increasing abundance of these species in reservoirs since 1970 (Martinez et al. 1994).

The presence of dams has significant influences on the occurrence of introduced rainbow trout in Hokkaido. Also, their population has increased continuously since introduction. Elimination and controlled stocking of them in reservoirs are important and necessary steps to protect populations of native fishes. Although our target species was only rainbow trout, brown trout (*Salmo trutta*) on Hokkaido Island have rapidly increased since 1980 (Takami and Aoyama 1999; Kaeriyama 2002), and the establishment of a reproducing population of Brook trout (*Salvelinus fontinalis*) has been reported in Nijibetsu Creek (Hikita et al. 1959). These exotic species were commonly released into reservoirs or lakes so that they could spread into streams from impoundments, like rainbow trout. Though intended to restore native fishes, fish ladders and beach/habitat-building flows released from dams may, at times, facilitate exotic species' spread into extended areas, regardless of their original proposes. Therefore, managers should consider both positive and negative effects of the dam operation and the fish ladder.

References

Akaike H (1974) A new look at the statistical model identification. IEEE Trans Automat Contr 19:716–723 doi:10.1109/TAC.1974.1100705

Benenati PL, Shannon JP, Blinn DW (1998) Desiccation and recolonization of phytobenthos in a regulated desert river: Colorado River at Lees Ferry, Arizona, USA. Regul Rivers Res Manage 14:519–532 doi:10.1002/(SICI)1099-1646(1998110)14:6<519::AID-RRR518>3.0.CO;2-H

Blinn DW, Shannon JP, Stevens LE, Carder JP (1995) Consequences of fluctuating discharge for lotic communities. J N Am Benthol Soc 14:233–248 doi:10.2307/1467776

Coleman MA, Fausch KD (2007) Cold summer temperature regimes cause a recruitment bottleneck in age-0 Colorado River cutthroat trout reared in laboratory streams. Trans Am Fish Soc 136:639–654 doi:10.1577/T05-288.1

Fielding AH, Bell JF (1997) A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ Conserv 24:38–49 doi:10.1017/S0376892997000088

Fukushima M, Kameyama S, Kaneko M, Nakao K, Steel EA (2007) Modelling the effects of dams on freshwater fish distributions in Hokkaido, Japan. Freshw Biol 52:1511–1524 doi:10.1111/j.1365-2427.2007.01783.x

Hastie T, Tibshirani RJ (1990) Generalized additive models. Chapman & Hall, London

Hikita T, Kameyama S, Kobayashi A, Sata Y (1959) Some biological observations on the rainbow trout *Salmongairdneri irideus* in the Nishibetsu River, with special reference to the consumption of salmon eggs and fry by predaceaous fishes. Bull Natl Inst Salmon Hatch 14:91–121

Holmquist JG, Schmidt-Gengenbach JM, Yoshioka BB (1998) High dams and marine-freshwater linkages: Effects on native and introduced fauna in the Caribbean. Conserv Biol 12:621–630 doi:10.1046/j.1523-1739.1998.96427.x

Joy MK, Death RG (2001) Control of freshwater fish and crayfish community structure in Taranaki, New Zealand: dams, diadromy or habitat structure? Freshw Biol 46:417–429 doi:10.1046/j.1365-2427.2001.00681.x

Kaeriyama H (2002) Salmo trutta. In: The Ecological Society of Japan (ed) Handbook of alien species in Japan. Chijinshokan Press, Tokyo

Kolar CS, Lodge DM (2002) Ecological predictions and risk assessment for alien fishes in North America. Science 298:1233–1236 doi:10.1126/science.1075753

Lamberti G, Gregory S, Aahkenas L, Wildman R, Moore K (1991) Stream ecosystem recovery following a catastrophic debris flow. Can J Fish Aquat Sci 48:196–208 doi:10.1139/f91-027

Legendre P, Fortin MJ (1989) Spatial pattern and ecological analysis. Vegetatio 80:107–138 doi:10.1007/BF00048036

Lichstein JW, Simons TR, Shriner SA, Franzreb KE (2002) Spatial autocorrelation and autoregressive models in ecology. Ecol Monogr 72:445–463

Marchetti MP, Lockwood JL, Light T (2006) Effects of urbanization on California's fish diversity: differentiation, homogenization and the influence of spatial scale. Biol Conserv 127:310–318 doi:10.1016/j.biocon.2005.04.025

Martinez PJ, Chart TE, Trammell MA, Wullschleger JG, Bergersen EP (1994) Fish species composition before and after construction of a main stem reservoirs on the White River, Colorado. Environ Biol Fishes 40:227–239 doi:10.1007/BF00002509

Morita K, Tsuboi J, Hiroyuki M (2004) The impact of exotic trout on native charr in a Japanese stream. J Appl Ecol 41:962–972 doi:10.1111/j.0021-8901.2004.00927.x

Neter J, Kutner MH, Nachtsheim CJ, Wasserman W (1996) Applied linear regression models, 3rd edn. Times Mirror Higher Education Group, Inc., Chicago

Padilla DK, Chotkowski MA, Buchan LAJ (1996) Predicting the spread of zebra mussels (*Dreissena polymorpha*) to inland waters using boater movement patterns. Glob Ecol Biogeogr 5:353–359 doi:10.2307/2997590

Poff NL, Hart DD (2002) How dams vary and why it matters for the emerging science of dam removal. Bioscience 52:659–668 doi:10.1641/0006-3568(2002)052[0659:HDVAWI]2.0.CO;2

Quist MC, Hubert WA, Rahel FJ (2005) Fish assemblage structure following impoundment of a Great Plains River. West N Am Nat 65:53–63

Raymond HL (1988) Effects of hydroelectric development and fisheries enhancement on spring and summer Chinook salmon and steelhead in the Columbia Basin. N Am J Fish Manage 8:1–24 doi:10.1577/1548-8675(1988)008<0001:EOHDAF>2.3.CO;2

Scheidegger KJ, Bain MB (1995) Larval fish distribution and microhabitat use in free-flowing and regulated rivers. Copeia 1:125–135 doi:10.2307/1446807

Stohlgren TJ, Barnett D, Flather C, Fuller P, Peterjohn B, Kartesz J et al (2006) Species richness and patterns of invasion in plants, birds, and fishes in the United States. Biological Invasions 8:427–447 doi:10.1007/s10530-005-6422-0

Swets JA (1988) Measuring the accuracy of diagnostic systems. Science 240:1285–1293 doi:10.1126/science.3287615

Takami T, Aoyama T (1999) Distributions of rainbow trout and brown trout in Hokkaido, northern Japan. Wildl Conserv Jpn 4:41–48

Taniguchi Y, Fausch KD, Saito H (2000) Redd superimposition by introduced rainbow trout on native charrs in a Japanese stream. Ichthyol Res 47:149–156 doi:10.1007/BF02684235

Venables WN, Ripley BD (1994) Modern applied statistics with S-plus. Springer, New York

Valdez RA, Hoffnagle TL, McIvor CC, McKinney T, Leibfried WC (2001) Effects of a test flood on fishes of the Colorado River in Grand Canyon, Arizona. Ecol Appl 11:686–700 doi:10.1890/1051-0761(2001)011[0686:EOATFO]2.0.CO;2

Walker KF (1985) A review of the ecological effects of river regulation in Australia. Hydrobiologia 125:111–129 doi:10.1007/BF00045929