Freshwater Biology

*Freshwater Biology* (2012) **57**, 2297–2305 doi:10.1111/fwb.12003

# Estimating migratory fish distribution from altitude and basin area: a case study in a large Neotropical river

JOSÉ RICARDO S. BARRADAS*, LUCAS G. SILVA*, BRET C. HARVEY† AND NELSON F. FONTOURA*

**Departamento de Biodiversidade e Ecologia, Pontifícia Universidade Católica do Rio Grande do Sul (PUCRS), Porto Alegre, RS, Brazil*
*†USDA Forest Service, Pacific Southwest Research Station, Arcata, CA, U.S.A.*

## SUMMARY

1. The objective of this study was to identify longitudinal distribution patterns of large migratory fish species in the Uruguay River basin, southern Brazil, and construct statistical distribution models for *Salminus brasiliensis*, *Prochilodus lineatus*, *Leporinus obtusidens* and *Pseudoplatystoma corruscans*.
2. The sampling programme resulted in 202 interviews with old residents and fishermen at 167 different sampling sites in the major rivers of the basin. Interviewees were asked whether these fish species were present in the nearby river segment, recently or in the past. The average age of respondents was 56 years, and the great majority had resided for more than 30 years in the area where they were interviewed.
3. Fish distribution patterns were modelled using altitude and basin area as environmental descriptors. Distributional patterns were estimated using logistic equations (LOGIT): $P = e^{(a_0+a_1\ln(Al)+a_2\ln(BA))}(1+e^{(a_0+a_1\ln(Al)+a_2\ln(BA))})^{-1}$, where $Al$ is the altitude and $BA$ is the basin area.
4. Accuracies of the distribution models were between 77 and 85%. These accuracies are similar to those of published distribution models for other fishes based on larger numbers of environmental descriptors.
5. The historical distributional ranges make clear that all operating or planned large hydropower dams in the Uruguay River basin, with one exception, limit or will limit the distribution of migratory fishes.

*Keywords*: dams, distribution, logistic regression, migratory fishes, Uruguay

## Introduction

More than 15% of the Neotropical fish fauna is composed of migratory species, and many of these share a common life history. Spawning generally occurs upstream from adult feeding areas. The prevailing current carries the eggs and larvae into the lowlands, where juveniles feed and grow until they join the adult stock (Carosfeld & Harvey, 2003; Godinho & Kynard, 2008; Barletta *et al.*, 2010).

The distribution patterns of migratory fishes depend on geomorphological characteristics. Elevation, for example, potentially affects several aspects of physical habitat in rivers, indirectly affecting parameters such as conductivity, pH, temperature, dissolved oxygen, flow velocity and drainage slope. Consequently, altitude alone is capable of producing an indirect environmental gradient that exerts a strong influence on species richness (Pouilly, Barrera & Rosales, 2006). Besides elevation, drainage area also strongly influences fish distribution (Garutti, 1988), probably most commonly through the relationship between drainage area and channel size.

Although additional environmental parameters can influence fish distributions, the combination of altitude and basin area appears to be a major determinant of species' distributions (Pouilly *et al.*, 2006; Alves & Fontoura, 2009). For example, Alves & Fontoura (2009)

Correspondence: Nelson Ferreira Fontoura, Departamento de Biodiversidade e Ecologia, Pontifícia Universidade Católica do Rio Grande do Sul (PUCRS), Av. Ipiranga, 6681, Porto Alegre, RS 90619-900, Brazil. E-mail: nfontoura@pucrs.br

© 2012 Blackwell Publishing Ltd

modelled the migratory fish distribution in the Jacuí basin (southern Brazil) using logistic regression (LOGIT) and applying altitude and basin area as environmental descriptors, yielding models with accuracy in the range of 71–84%.

The Uruguay River basin has a hydroelectric potential estimated at 16 500 MW, of which only 16% is currently in use. In the Uruguay main channel, four large hydroelectric dams are in operation and three are in different stages of implementation. In the basin as a whole, 30 large hydroelectric dams are planned or already operated (ANEEL, 2012: http://sigel.aneel.gov.br/). While Zaniboni-Filho & Schultz (2003) review available information concerning migratory fish biology in the Uruguay River basin, no detailed descriptions of the distributions of migratory fishes are available. Among the large long-range migratory fishes in the Uruguay River basin, the most emblematic species are *Salminus brasiliensis* (Cuvier, 1816), *Prochilodus lineatus* (Valenciennes, 1847), *Leporinus obtusidens* (Valenciennes, 1847) and *Pseudoplatystoma corruscans* (Spix & Agassiz, 1829).

*Salminus brasiliensis*, known as dourado, was important in the past for both artisanal and sport fishing, although captures are now forbidden in southern Brazil (RS) because of reduction in natural stocks. Large individuals can reach up to 1 m in length and 30 kg in mass. In the Uruguay River basin, the species distribution is known in the main river channel and major tributaries including Ibicuí, Ijuí, Canoas and Pelotas (Zaniboni-Filho & Schultz, 2003). In the Jacuí River basin, the species distribution is limited to altitudes up to 280 m and basin areas exceeding 500 km$^2$ (Alves & Fontoura, 2009). Reproductive migrations happen once a year, starting in late August (winter). Breeding occurs in the river upper reaches between December and February, during the high flood season (Carosfeld & Harvey, 2003), and the species can migrate up to 400 km upstream (Hahn, 2007).

*Prochilodus lineatus*, locally named grumatã or curimbatá, is present in almost all rivers in the Uruguay basin, supporting commercial fishing as the species with the highest biomass in the basin (Zaniboni-Filho & Schultz, 2003). In the Jacuí River basin, the species distribution is limited to the 290 m altitudinal threshold and basin areas larger than 500 km$^2$ (Alves & Fontoura, 2009). The species reproduces once a year during the spring and summer, with upstream peak migration in September and October (Capeleti & Petrere, 2006).

*Leporinus obtusidens*, known as piava, also includes long migrations in its life cycle. In the Jacuí River basin, the species presents an altitudinal limit around 300 m above sea level and requires a minimum drainage area of 200 km$^2$ (Alves & Fontoura, 2009). Removals of riparian forests and intensive farming have been listed as the main reasons for the decline of this species (Zaniboni-Filho & Schultz, 2003). In the Uruguay basin, the species spawns between October and December (Bertoletti, 1987).

*Pseudoplastistoma corruscans*, the surubim or pintado, is a large migratory species of high commercial value, exceeding 1.5 m and 50 kg (Ringuelet, Aramburu & Aramburu, 1967). The species is under strong anthropogenic pressure because of overfishing and damming, and captures in southern Brazilian (RS) are presently forbidden. In the Uruguay basin, the species is restricted to the main river channel and some of its larger tributaries (Zaniboni-Filho & Schultz, 2003). Reproduction takes place in lotic environments between November and February (Ringuelet *et al.*, 1967).

In this study, we sought to identify the longitudinal distribution patterns of long-range migratory fishes in the Uruguay River basin: *S. brasiliensis*, *P. lineatus*, *L. obtusidens* and *P. corruscans*. In addition to establishing the historical distribution of key species, we generated distribution models for each species using altitude and basin area as predictors.

## Methods

The Uruguay River basin has a total length of 2262 km, ending in the La Plata estuary, Argentina (Fig. 1). The river drains a catchment of about 385 000 km$^2$ with altitudes up to 1800 m. The climate is subtropical, with a


**Fig. 1** Uruguay River basin, Brazil.

relatively even intra-annual rainfall distribution, but with some increase from May to September (winter). Annual rainfall varies from 1800 mm in the plateau headwaters to 1300 mm around the Brazil–Uruguay border. The mean annual temperature varies between 16 and 20 °C, and the mean annual evapotranspiration is 1041 mm (Zaniboni-Filho & Schultz, 2003).

Data on migratory fish distributions were obtained from museum records (SIBIP/NEODAT III system and Fundação Zoobotânica do Rio Grande do Sul-FZB) and ten field expeditions (May 2008–July 2009). Field trips were conducted by exploiting the road network and its intersection points with stream courses. Older residents and fisherman were interviewed. Interviews involved presentation of cards with pictures and common names of the fishes of interest, asking whether these species were present in the nearby river segment, either currently or in the past. We also presented cards with pictures of well-known fishes not present in the Uruguay basin. If this step yielded false positives, more than one interview was conducted at the same site, and we used the most common responses. Sampling site coordinates were obtained with a GPS device. Field interviews ($n$ = 202 at 167 different sampling points) covered most of the drainage area within Brazil. The respondents' average age was 56 years, and the majority had resided for more than 30 years in the area where they were interviewed.

The cartographical products were prepared by means of the software Idrisi Andes 15.0 (CLARK LABS, 2006) and were generated from a digital elevation model (DEM, radar altitude records in metres, pixel of $92 \times 92$ m, LANDSAT ETM7) adapted to the Brazilian official reference system (SAD69; Weber, Hasenack & Ferreira, 2004). The basin area was obtained through three basic steps: (i) image homogenisation using a filter of minimum value in a $3 \times 3$ pixel matrix, (ii) creation of decreasing altitudinal paths using the *Pit Removal* tool and (iii) applying the *Runoff* function to estimate the upstream basin area for each pixel, correcting the number of pixels to the real area (km$^2$). The hydrographical matrix was generated by means of the *Pathway* routine for multiple paths, using the inverse of the runoff matrix as a cost matrix, resulting in a binary image (1–0) describing the predicted river network.

We separately modelled the presence/absence of each species using maximum likelihood logistic regression. We evaluated the same five candidate models for each species. The five models included various combinations of natural log-transformed values of altitude and basin area: (1) altitude only, (2) basin area only, (3) altitude + basin area, (4) altitude + basin area + a multiplicative interaction term and (5) altitude + basin area + basin area/altitude. We compared models with standard model selection techniques using Akaike's Information Criterion (Burnham & Anderson, 2002).

Maps including predicted distributions were generated through the Idrisi Andes image calculator, using as independent variables the raster images corresponding to altitude (m) and basin area (km$^2$), both converted to natural logarithms and the hydrographical matrix (basin area larger than 10 km$^2$) as the calculation mask.

## Results

The field interviews added much to the available information on the historical distribution of migratory fishes in the Uruguay River basin. Museum records provided very little information: no more than seven individual records could be identified for any one species in the NEODAT database and the fish collection of FZB. Distributional information from museum collections was also concentrated in a few areas of interest, mainly near large hydropower dams in the main channel of the upper Uruguay River. In contrast, the field interviews indicated that all four migratory fishes studied had broad historical distributions in the Uruguay River basin (Figs 2 to 5).

For all four species, the model including both altitude and basin area but lacking interaction terms (Model 3) had the greatest support as measured by Akaike weight (Table 1). Models with just one predictor, altitude or basin area (Models 1 and 2) garnered little support. The two models with interaction terms (Models 4 and 5), which allowed nonlinear relationships in the combined effect of altitude and basin area on the probability of species' presence, did not significantly improve on the fit of the additive model to the data.

The accuracy of the additive model using altitude and basin area ranged 77–85% among the four species (Table 2, Fig. 6). A more detailed examination of the accuracy of the additive models reveals that across species, the models were particularly consistent in producing low rates of false positives, in the range between 16 and 20% (Table 2). Parameter values for both altitude and basin area were highly significant in the additive models for all four species, with the exception of the constant ($a_0$) in the model for *P. corruscans* (Table 3).

In addition to establishing the extensive historical distributions of four migratory species, the field interviews also identified *Brycon orbignyanus* (Valenciennes, 1850) as an extremely rare species in the Uruguay River basin. While several reports from more than 30 years ago note the commonness of this species, professional fishermen we interviewed revealed the persistence of this

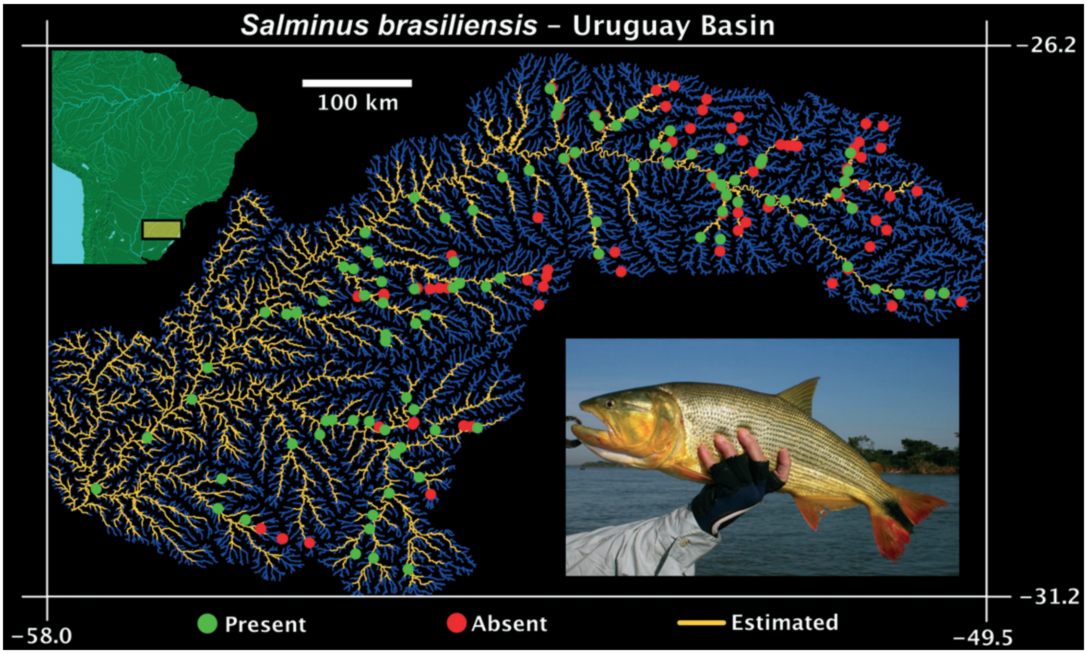


**Fig. 2** Uruguay River basin, Brazil. Historical distributional pattern of *Salminus brasiliensis*. Green spots represent species presence as informed from interviews with old residents and fishermen. Red spots represent species absence. Yellow segments represent species estimated presence according to the adjusted logistic model (LOGIT). Fish picture: Isabel Pellizzer.

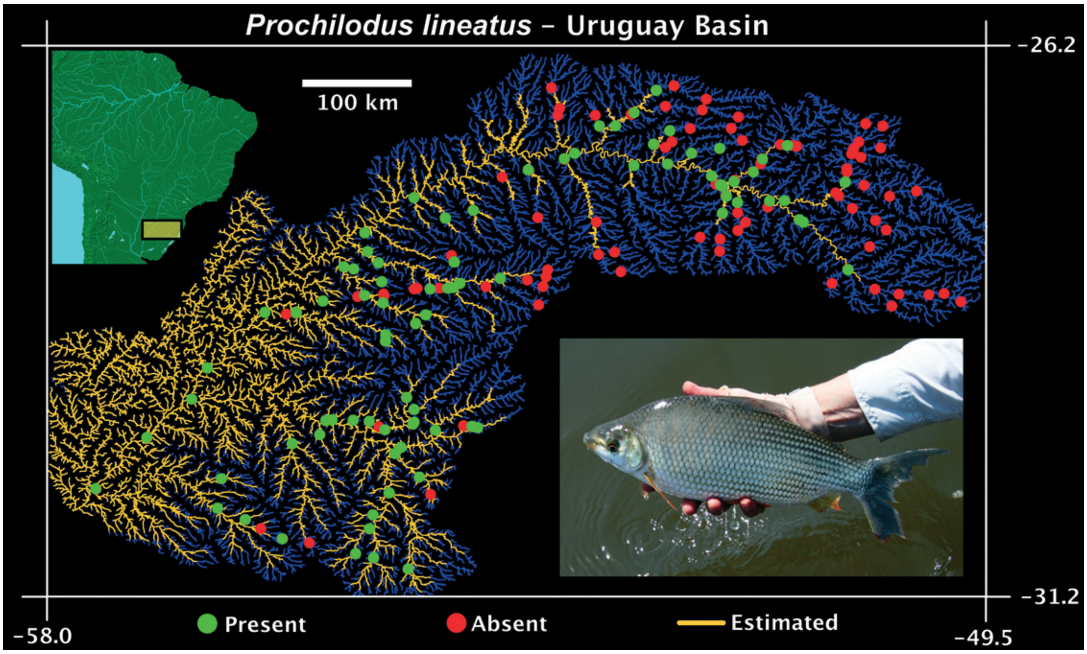


**Fig. 3** Uruguay River basin, Brazil. Historical distributional pattern of *Prochilodus lineatus*. Green spots represent species presence as informed from interviews with old residents and fishermen. Red spots represent species absence. Yellow segments represent species estimated presence according to the adjusted logistic model (LOGIT). Fish picture: Isabel Pellizzer.

species, although it is only rarely captured at present. We chose not to model the distribution of this species because its rarity created considerable uncertainty about its distribution. This study also sought to analyse the distribution of *Steindachneridion scripta* (Miranda Ribeiro, 1918). However, because interviewees had difficulty identifying the species from its image, we considered the information gathered on it unreliable.

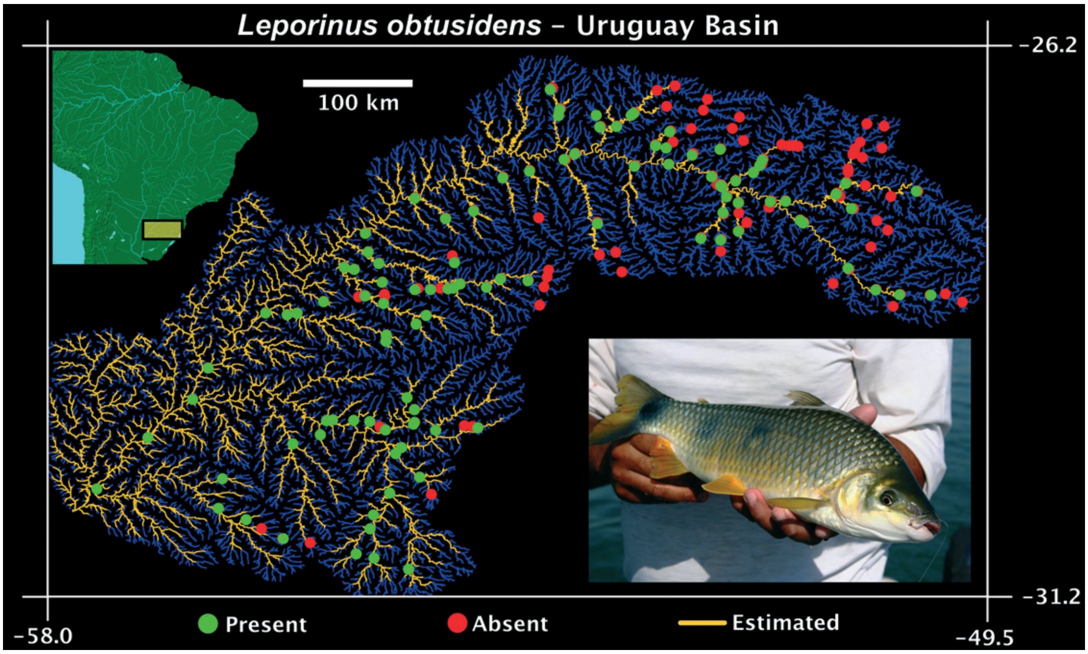


**Fig. 4** Uruguay River basin, Brazil. Historical distributional pattern of *Leporinus obtusidens*. Green spots represent species presence as informed from interviews with old residents and fishermen. Red spots represent species absence. Yellow segments represent species estimated presence according to the adjusted logistic model (LOGIT). Fish picture: Isabel Pellizzer.

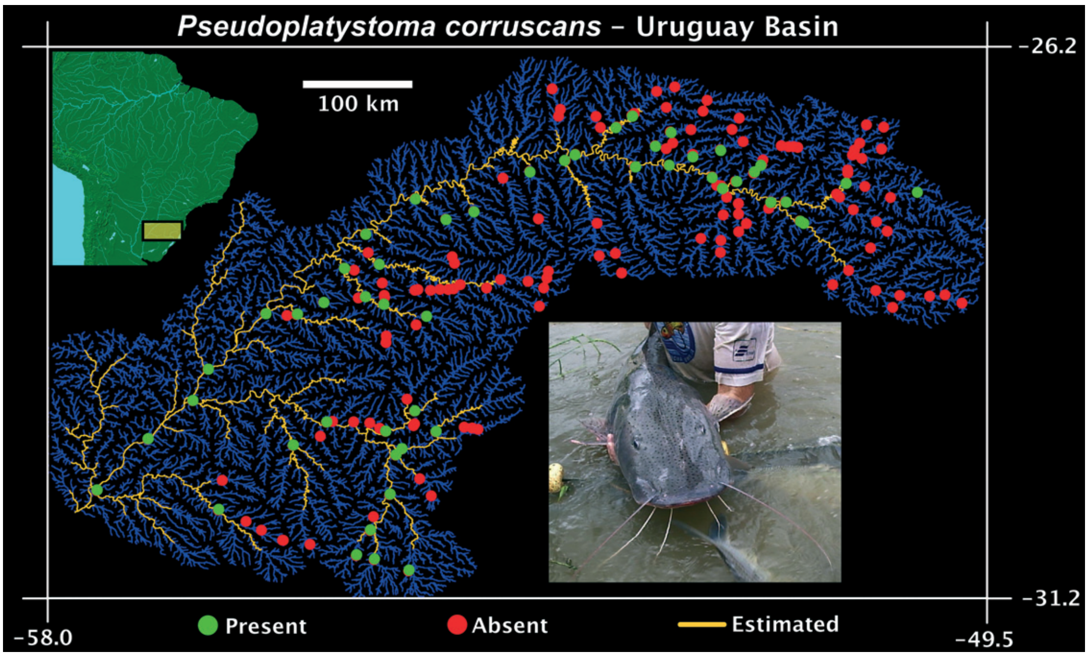


**Fig. 5** Uruguay River basin, Brazil. Historical distributional pattern of *Pseudoplatystoma corruscans*. Green spots represent species presence as informed from interviews with old residents and fishermen. Red spots represent species absence. Yellow segments represent species estimated presence according to the adjusted logistic model (LOGIT). Fish picture: Aparicio Streit.

## Discussion

The quality of distribution models, measured as the agreement between the predicted and verified distributions, can be affected by the accuracy of the presence/absence data set, the selected statistical model and the methodological approach, including the nature and number of environmental descriptors.

**Table 1** Comparison of five logistic regression models of the presence/absence of large migratory fishes in the Uruguay basin. *Al* represents altitude (m) and *BA* the basin area ($km^2$). Akaike weights provide the relative weight of evidence for each model. Total accuracy indicates the overall percentage of correct classifications

| Species | Model: $\mathrm{LOGIT}(p)\ln\left(\frac{p}{1-p}\right) =$ | Akaike weight | Total accuracy |
|---|---|---|---|
| *Salminus brasiliensis* | $a_0 + a_1 \ln(Al) + a_2 \ln(BA)$ | 0.489 | 80.8 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(Al) \times \ln(BA)$ | 0.337 | 80.2 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(BA)/\ln(Al)$ | 0.174 | 80.8 |
| | $a_0 + a_1 \ln(BA)$ | 0.000 | 73.2 |
| | $a_0 + a_1 \ln(Al)$ | 0.000 | 70.7 |
| *Prochilodus lineatus* | $a_0 + a_1 \ln(Al) + a_2 \ln(BA)$ | 0.548 | 81.9 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(Al) \times \ln(BA)$ | 0.240 | 81.3 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(BA)/\ln(Al)$ | 0.211 | 83.1 |
| | $a_0 + a_1 \ln(Al)$ | 0.000 | 72.9 |
| | $a_0 + a_1 \ln(BA)$ | 0.000 | 66.9 |
| *Leporinus obtusidens* | $a_0 + a_1 \ln(Al) + a_2 \ln(BA)$ | 0.438 | 76.7 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(BA)/\ln(Al)$ | 0.409 | 77.3 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(Al) \times \ln(BA)$ | 0.153 | 76.1 |
| | $a_0 + a_1 \ln(Al)$ | 0.000 | 73.7 |
| | $a_0 + a_1 \ln(BA)$ | 0.000 | 71.9 |
| *Pseudoplatystoma corruscans* | $a_0 + a_1 \ln(Al) + a_2 \ln(BA)$ | 0.410 | 85.0 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(Al) \times \ln(BA)$ | 0.357 | 83.2 |
| | $a_0 + a_1 \ln(Al) + a_2 \ln(BA) + a_3 \ln(BA)/\ln(Al)$ | 0.233 | 85.0 |
| | $a_0 + a_1 \ln(BA)$ | 0.000 | 82.0 |
| | $a_0 + a_1 \ln(Al)$ | 0.000 | 71.3 |

**Table 2** Information on the accuracy of logistic models of the distribution of migratory fishes in the Uruguay River basin. Models for all four species have two independent variables: altitude and basin area

| | Accuracy (%) | | | | |
|---|---|---|---|---|---|
| Species | Total | Sensitivity | Specificity | False positives | False negatives |
| *Salminus brasiliensis* | 80.8 | 84.2 | 75.8 | 15.8 | 24.2 |
| *Prochilodus lineatus* | 81.9 | 80.9 | 83.1 | 15.3 | 21.0 |
| *Leporinus obtusidens* | 76.7 | 84.6 | 66.7 | 19.6 | 30.0 |
| *Pseudoplatystoma corruscans* | 85.0 | 65.4 | 94.8 | 17.1 | 14.3 |

Methodological approaches other than the LOGIT equation have been applied to model species distributions from presence/absence data. Joy & Death (2004) applied an Artificial Neural Network (ANN) to model the distributional pattern of 14 fish and crustacean species in New Zealand. Even though they used a complex set of environmental descriptors, the adherence between the estimated and observed distributions ranged from 69 to 95%, averaging 84%. The multivariate adaptive regression splines technique (MARS) was applied by Leathwick *et al.* (2005) to study the distribution of 15 diadromous fish species, also in New Zealand. Using a complex set of descriptors, model adherence ranged from 71 to 94%, again averaging 84%.

Logistic regression is perhaps the most widely used approach to describe species distributions as a function of environmental factors (Guisan & Zimmermann, 2000; Pearce & Ferrier, 2000; Turner *et al.*, 2003; Syartinilia & Tsuyuki, 2008; Franklin, 2009). Porter, Rosenfeld & Parkinson (2000) applied logistic functions to model the distribution of 14 fish species in British Columbia. Using an original set of 14 environmental descriptors, which was reduced to six after analysis of multicollinearity, Porter *et al.* (2000) were able to predict species distributions with accuracy rates from 69 to 94%, averaging, again, 84%.

Alves & Fontoura (2009) used logistic regression to study the distribution of migratory fishes in the Jacuí basin, in the southeastern limits of the Uruguay River basin. These authors also used altitude and basin area as environmental descriptors, but applied a different methodological approach. The sampling programme was concentrated in the upper segments of the basin, in an attempt to identify the limits of occurrence of each species. From this data matrix, the authors assumed that each species was present in all segments downstream from the farthest upstream record. This procedure has the advantage of greatly increasing the data matrix. In the Jacuí River basin, a set of 40 000 information pixels was obtained. However, this approach

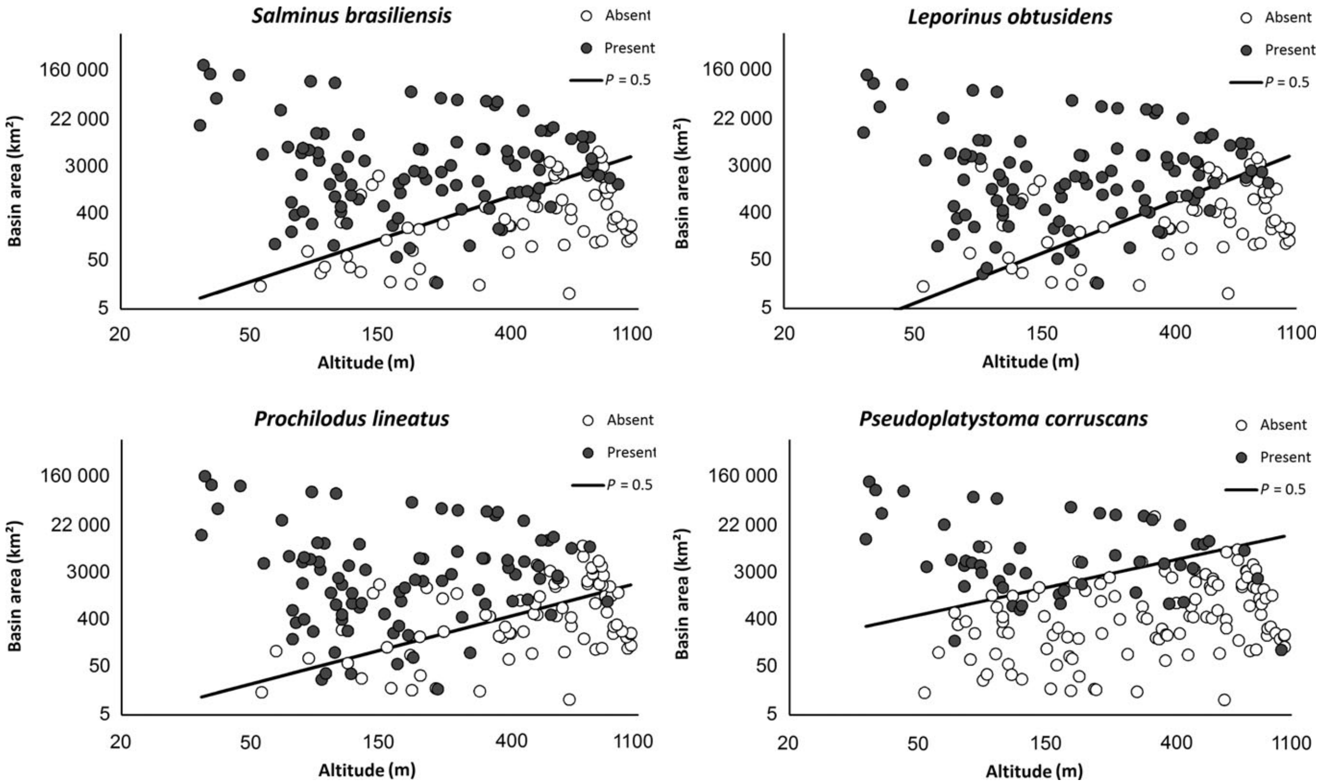


**Fig. 6** Uruguay River basin, Brazil. Plots of historical distributional pattern (presence/absence) for migratory fish species as a function of altitude (ln) and basin area (ln). The contour lines represent presence probability of 0.5 according to adjusted LOGIT models for each species.

**Table 3** Estimated parameters for presence probability ($P$) in the Uruguay River basin as estimated by the logistic equation: $P = e^{(a_0+a_1\ln(Al)+a_2\ln(BA))}(1+e^{(a_0+a_1\ln(Al)+a_2\ln(BA))})^{-1}$, where $Al$ is the altitude in metres, $BA$ is the basin area in km$^2$, $a_0$ represents the fraction of the probability of occurrence that is not explained by any environmental descriptors, and $a_1$ and $a_2$ are the rates of increase in the probability of occurrence according to altitude and basin area, respectively

| Species | Variable | Estimate | SE | Wald | *P* |
|---|---|---|---|---|---|
| *Salminus brasiliensis* | $a_0$ | 4.2030 | 1.6759 | 6.2893 | 0.0121 |
| | $a_1$ | −1.8816 | 0.3608 | 27.1899 | <0.0001 |
| | $a_2$ | 1.0537 | 0.1774 | 35.2860 | <0.0001 |
| *Prochilodus lineatus* | $a_0$ | 7.9909 | 1.8104 | 19.4822 | <0.0001 |
| | $a_1$ | −2.4331 | 0.3974 | 37.4812 | <0.0001 |
| | $a_2$ | 0.8843 | 0.1660 | 28.3905 | <0.0001 |
| *Leporinus obtusidens* | $a_0$ | 5.6590 | 1.6775 | 11.3796 | 0.0007 |
| | $a_1$ | −1.8875 | 0.3476 | 29.4859 | <0.0001 |
| | $a_2$ | 0.8568 | 0.1565 | 29.9839 | <0.0001 |
| *Pseudoplatystoma corruncans* | $a_0$ | −1.7195 | 1.8485 | 0.8652 | 0.3523 |
| | $a_1$ | −1.3034 | 0.3210 | 16.4842 | <0.0001 |
| | $a_2$ | 1.0920 | 0.1926 | 32.1529 | <0.0001 |

can multiply errors if the record from the uppermost segment is erroneous. For the Jacuí basin, the accuracy of the distribution models ranged from 71 to 84%.

In the present study, we chose to examine only the original data set, without assuming any occurrences unsupported by interviews. In this case, rather than thousands of information pixels, we used only the 167 data points actually obtained. Also, rather than prioritising the upstream segments of major rivers, the present study was distributed widely throughout the basin, seeking to cover the ranges of the explanatory variables. We considered this approach appropriate in this case because of the large extent of the basin, coupled with the poor condition of the road network, which prevented access to lengthy continuous segments of river. It is noteworthy, however, that this different methodological approach yielded model accuracy very similar to the results from previous studies.

Parallel to Porter *et al.* (2000) and Alves & Fontoura (2009), our data suggest that even a relatively small set of geomorphological descriptors can provide significant predictive power, perhaps because of links between both altitude and basin area and a variety of environmental factors likely to directly affect fish distribution, including water temperature, conductivity, pH, current speed, slope, and the presence of pools and waterfalls (Alves & Fontoura, 2009). Although model accuracy might be

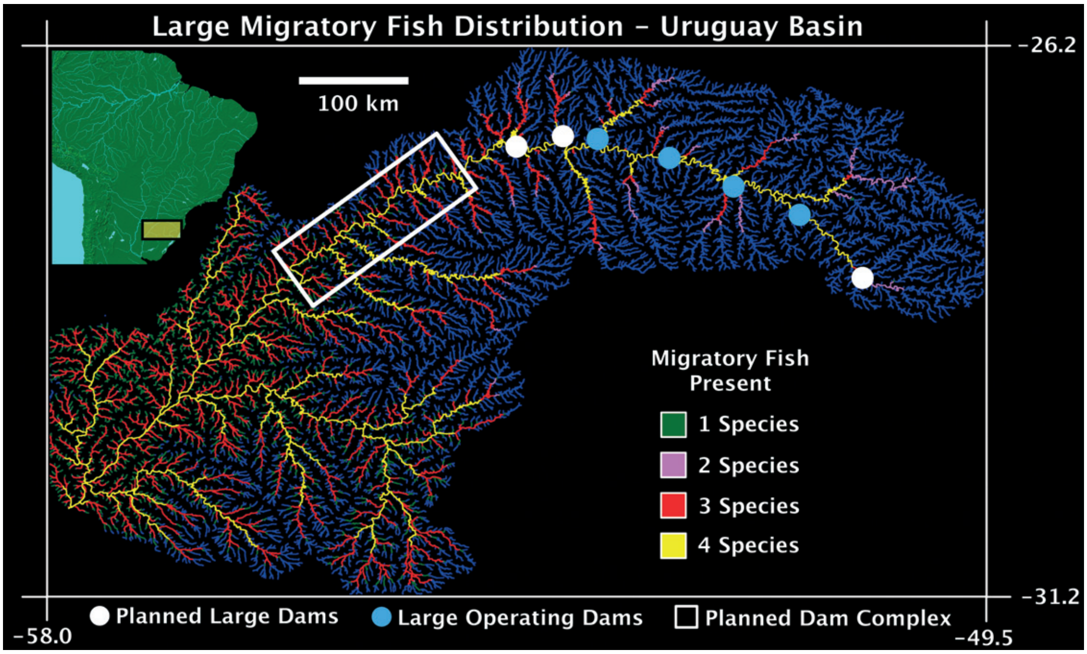


**Fig. 7** Uruguay River basin, Brazil. Historical distributional pattern of large migratory fish species (*Salminus brasiliensis*, *Prochilodus lineatus*, *Leporinus obtusidens* and *Pseudoplatystoma corruscans*) according to altitude and basin area. Colour scale represents the presence of one to four species in the same area. Light-blue spots are large operating dams, and white spots are planned large dams for Uruguay main channel. Dams are, from left to right, Itapiranga, Iraí, Foz do Chapecó, Itá, Machadinho, Barra Grande and Pai-Querê. (ANEEL 2012: http://sigel.aneel.gov.br/). The white box represents an area where new multinational dams (Brazil–Argentina) are been planned.

improved with more complicated models, the two-parameter models offered here have the advantage of using relatively easily obtained independent variables. We also considered inclusion of natural barriers to upstream migration in this analysis of historical distributions, but this proved to be unworkable given the available satellite information. Although several natural barriers were identified during the sampling programme, the resolution of the digital elevation model, which used radar altitude data in a matrix of 92 by 92 m, proved inadequate to identify some effective barriers to fish passage.

Modelling historical distributions is valuable to both support reintroduction programmes and identify potential impacts of damming. A map of the historical presence data from this study and the position of current and planned dams on the main channel of the Uruguay River (Fig. 7) reveal all current dams must be limiting the distributions of migratory fishes. Of the new hydropower dams planned for the Uruguay main channel, Pai-Querê is near the upper altitudinal threshold identified for migratory fishes and does not represent a major threat to migratory fish populations. However, the planned Itapiranga and Iraí dams would further limit the upstream migration of the fishes we studied. Also, the Garabi multinational complex, on the Brazil–Argentina boundary (Fig. 7, white box), which is still under study, could further limit the distribution of migratory fishes in the Uruguay River basin, beginning at only 94 m above sea level, well below the altitudinal limits identified for all migratory fish species.

Considering the current exclusion of migratory fishes from the upper Uruguay River main channel and dams being considered for several of the main tributaries, the situation appears ripe for the application of the cumulative effects concept. Tributaries large enough and with adequate environmental quality to maintain viable migratory fish populations could continue to make valuable contributions to biodiversity, while other already impacted reaches could be preferential candidates for the installation of additional dams.

## Acknowledgments

The authors thank Jim Baldwin for the statistical advice. Financial support was provided by scholarships from CNPq to NF Fontoura, LG Silva & JRS Barradas and research funds to NF Fontoura.

## References

Alves T.P. & Fontoura N.F. (2009) Statistical distribution models for migratory fish in Jacuí Basin, South Brazil. *Neotropical Ichthyology*, **7**, 647–658.

Barletta M., Jaureguizar A.J., Baigun C., Fontoura N.F., Agostinho A.A., Almeida-Val V.M.F. *et al*. (2010) Fish and aquatic habitat conservation in South America: a continental overview with emphasis on Neotropical systems. *Journal of Fish Biology*, **76**, 2118–2176.

Bertoletti J.J. (1987) Contribuição ao conhecimento de passagens de peixes em barragens no Rio Grande do Sul. *Comunicações do Museu de Ciências e Tecnologia da PUCRS*, **42**, 131–138.

Burnham K.P. & Anderson D.R. (2002) *Model Selection and Multimodel Inference: A Practical Information-Theoretic Approach*. Springer-Verlag, New York.

Capeleti A.R. & Petrere M. (2006) Migration of the curimbatá *Prochilodus lineatus* (Valenciennes, 1836) (Pisces, Prochilodontidae) at the waterfall ''Cachoeira das Emas'' of the Mogi Guaçu river – São Paulo, Brazil. *Biosciences*, **66**, 651–659.

Carosfeld J. & Harvey B. (2003) Fishes of the floods. In: *Migratory Fishes of South America: Biology, Fisheries and Conservation Status* (Eds J. Carosfeld, B. Harvey, C. Ross & A. Baer), pp. 3–11. World Fisheries Trust/World Bank/IDRC, Victoria.

Franklin J. (2009) *Mapping Species Distributions*, 320 p. Cambridge University Press, Cambridge.

Garutti V. (1988) Distribuição longitudinal da ictiofauna em um córrego da região noroeste do Estado de São Paulo, bacia do rio Paraná. *Revista Brasileira de Biologia*, **48**, 747–759.

Godinho A.L. & Kynard B. (2008) Migratory fishes of Brazil: life history and fish passage needs. *River Research and Applications*, **25**, 702–712.

Guisan A. & Zimmermann N.E. (2000) Predictive habitat distribution models in ecology. *Ecological Modelling*, **135**, 147–186.

Hahn L. (2007) *Deslocamento de peixes migradores no rio Uruguai e no sistema misto de migração da barragem de Itaipu*. PhD Thesis. Fundação Universidade Estadual de Maringá, Maringá.

Joy M.K. & Death R.G. (2004) Predictive modelling and spatial mapping of freshwater fish and decapod assemblages using GIS and neural networks. *Freshwater Biology*, **49**, 1036–1052.

Leathwick J.R., Rowe D., Richardson J., Elith J. & Hastie T. (2005) Using multivariate adaptive regression splines to predict the distributions of New Zealand's freshwater diadromous fish. *Freshwater Biology*, **50**, 2034–2052.

Pearce J. & Ferrier S. (2000) Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling*, **133**, 225–245.

Porter M.S., Rosenfeld J. & Parkinson E.A. (2000) Predictive models of fish species distribution in the blackwater drainage, British Columbia. In: *Proceedings of a Conference on the Biology and Management of Species and Habitats at Risk, Volume Two* (ed. L.M. Darling), pp. 599–608. Kamloops, BC, 15–19 February 1999. BC Ministry of Environment, Lands and Parks, Victoria, BC and University College of the Cariboo, Kamloops, BC.

Pouilly M., Barrera S. & Rosales C. (2006) Changes of taxonomic and trophic structure of fish assemblages along an environmental gradient in the upper Beni watershed (Bolivia). *Journal of Fish Biology*, **68**, 137–156.

Ringuelet R.A., Aramburu R.H. & Aramburu A.A. (1967) *Los peces argentinos de água dulce*. Editora de la Plata, La Plata.

Syartinilia S.T. & Tsuyuki S. (2008) GIS-Based modelling of Javan Hawk-Eagle distribution using logistic and autologistic regression models. *Biological Conservation*, **141**, 756–769.

Turner W., Spector S., Gardiner N., Fladeland M., Sterling E. & Steininger M. (2003) Remote sensing for biodiversity science and conservation. *Trends in Ecology and Evolution*, **18**, 306–314.

Weber E., Hasenack H. & Ferreira C.J.S. (2004) *Adaptação do modelo digital de elevação do SRTM para o sistema de referência oficial brasileiro e recorte por unidade da federação*. Centro de Ecologia da UFRGS, Porto Alegre.

Zaniboni-Filho E. & Schultz U.H. (2003) Migratory fishes of the Uruguay River. In: *Migratory Fishes of South America* (Eds J. Carosfeld, B. Harvey, C. Ross & A. Baer), pp. 157–194. World Fisheries Trust/World Bank/IDRC, Victoria.

*(Manuscript accepted 21 July 2012)*