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Supplementary material

SUPPLEMENTARY MATERIAL

Disentangling the pathways of land use impacts on the functional structure of fish assemblages in Amazon streams

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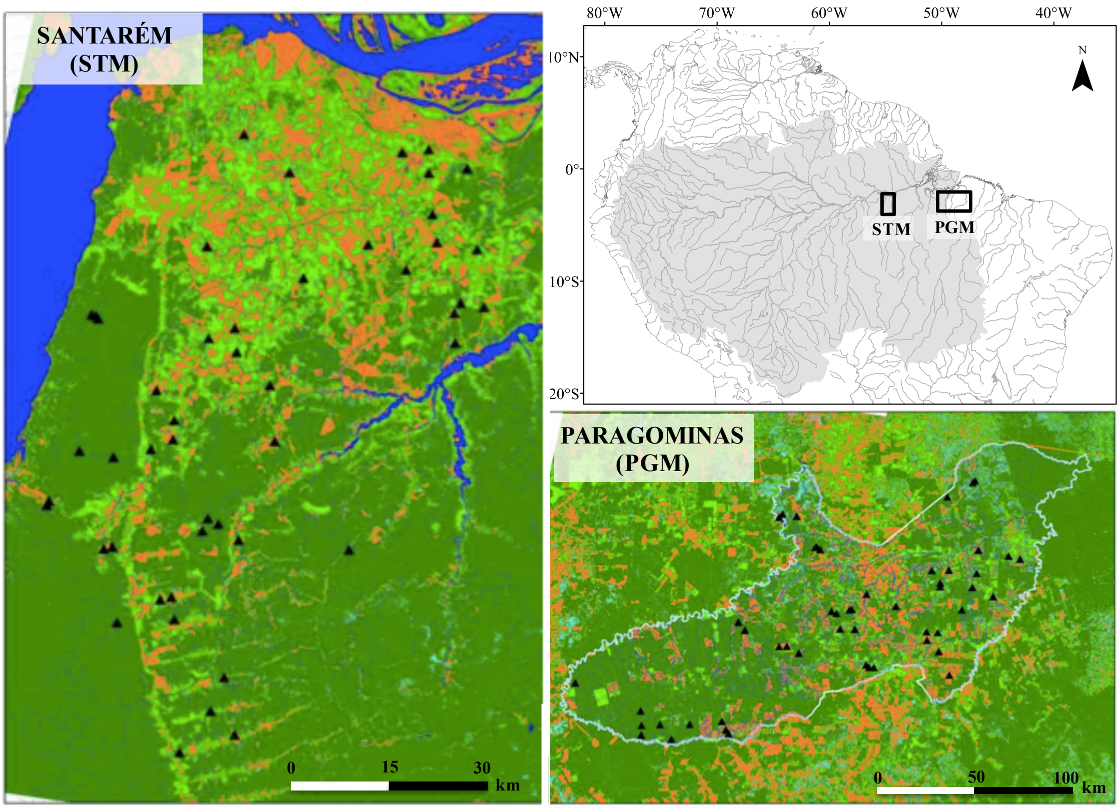

Figure A1. Sampling sites (black triangles) distributed across gradients of land use in the municipalities of Santarém (*c.* 1 million ha; 45 sites) and Paragominas (*c.* 1.9 million ha; 49 sites), eastern Brazilian Amazon. Land use classification derived from Landsat 2010 imagery, showing primary forest (dark green), secondary forest (light green), and deforested areas (orange). Gray polygon in the top right map indicates the Amazon Basin. Some sampled streams in the eastern portion of Paragominas do not flow directly, but are connected, to the Amazon Basin *sensu stricto*.

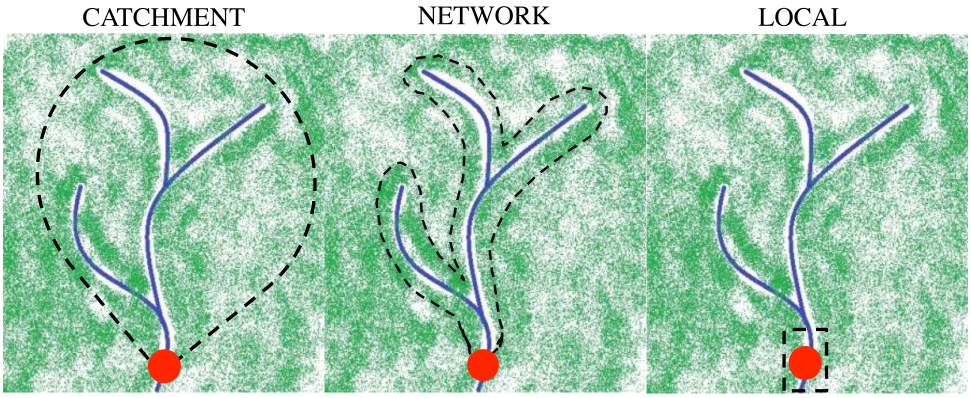

Figure A2. Representation of the three different spatial scales (dashed lines) considered for landscape analyses: the whole catchment upstream from sample site (“catchment”); 100-m wide buffer along the entire drainage network upstream from sample site (“riparian network”), and 100-m wide buffer around the sampled site (“local”). Sample site is a 150-m long stream reach (red dot).

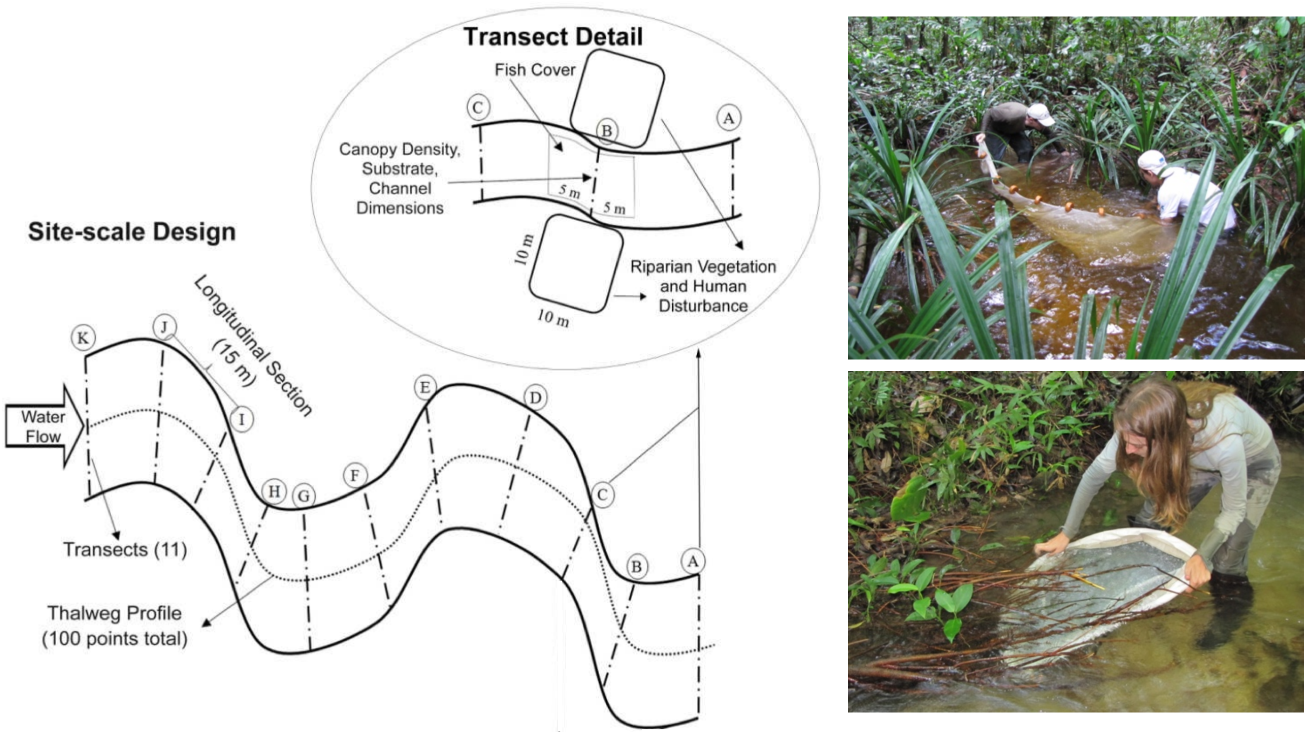

Figure A3. Schematic representation of the sampled stream reach. Each transect was named from the downstream ("A") to upstream ("K") and marked with flags along the stream stretch. A total of 11 transects and 10 longitudinal sections of 15 m were established. Fishes were captured using seines (top-right) and semi-circular hand nets (bottom-right).

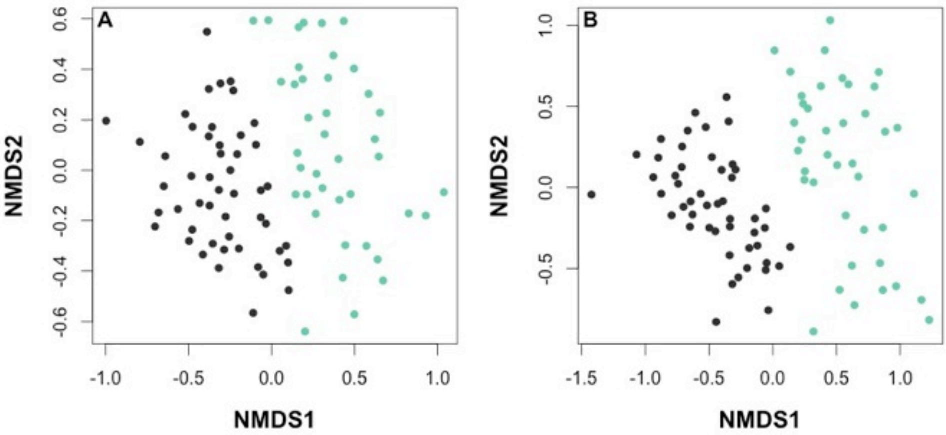

Figure A4. Non-metric Multidimensional Scaling (NMDS) ordination of sites from Santarém (n = 40; green dots) and from Paragominas (n = 49; dark gray dots) based on fish species presence/absence (A) and abundance (B) within streams.

a

	PCoA1	
Multicuspid	Teeth shape	*Viliform/Conic*
Low	Number of teeth	*High*
Deep	Oral-gape shape	*Wide*
Large	Eye size	*Small*
Lateral	Eye position	*Up*
Low	Pectoral-fin position	*High*
Elongated	Aspect ratio of pectoral fin	*Rounded*
High	Caudal-peduncle throttling	*Small*
Crescent-like	Aspect ratio of the caudal fin	*Rounded*
	PCoA2	
Long	Mouth-protrusion length	*Short/Absent*
Large	Eye size	*Small*
Pectoral-fin rowing	Fins surface ratio	*Caudal-fin/Body propulsion*
Large	Fins surface to body size	*Small*
	PCoA3	
Conic	Teeth shape	*Viliform/Comb-shaped*
Compressed	Body transversal shape	*Depressed*
Elongated	Body transversal surface	*Compact*
	PCoA4	
-	Teeth shape	*Canine*
Compact	Body transversal surface	*Elongated*
Small	Body mass	*Large*

b

	PCoA1	
Multicuspid	Teeth shape	*Viliform*
Deep	Oral-gape shape	*Wide*
Up	Oral-gape position	*Down*
Large	Eye size	*Small*
Lateral	Eye position	*Up*
Compressed	Body transversal shape	*Depressed*
Low	Pectoral-fin position	*High*
Elongated	Aspect ratio of pectoral fin	*Rounded*
Crescent-like	Aspect ratio of the caudal fin	*Rounded*
	PCoA2	
Comb-shaped	Teeth shape	*Absent*
Pectoral-fin rowing	Fins surface ratio	*Caudal-fin/Body propulsion*
Large	Fins surface to body size	*Small*
	PCoA3	
Conic	Teeth shape	*Viliform/Comb-/Spoon-shaped*
Long	Mouth-protrusion length	*Short/Absent*
	PCoA4	
-	Teeth shape	*Multicuspid*
Elongated	Body transversal surface	*Compact*
Large	Body mass	*Small*

Figure A5. Position of the predominant state of each ecomorphological trait along each Principal Coordinate (PCoA) axis that composes the multidimensional functional spaces for fish species pools in Santarém (a) and Paragominas (b) sites. The functional identity (CWM) for each local assemblage is the abundance-weighted average value for each of the PCoA axes. See details in Fig. A6, Fig. A7, and Table A5.

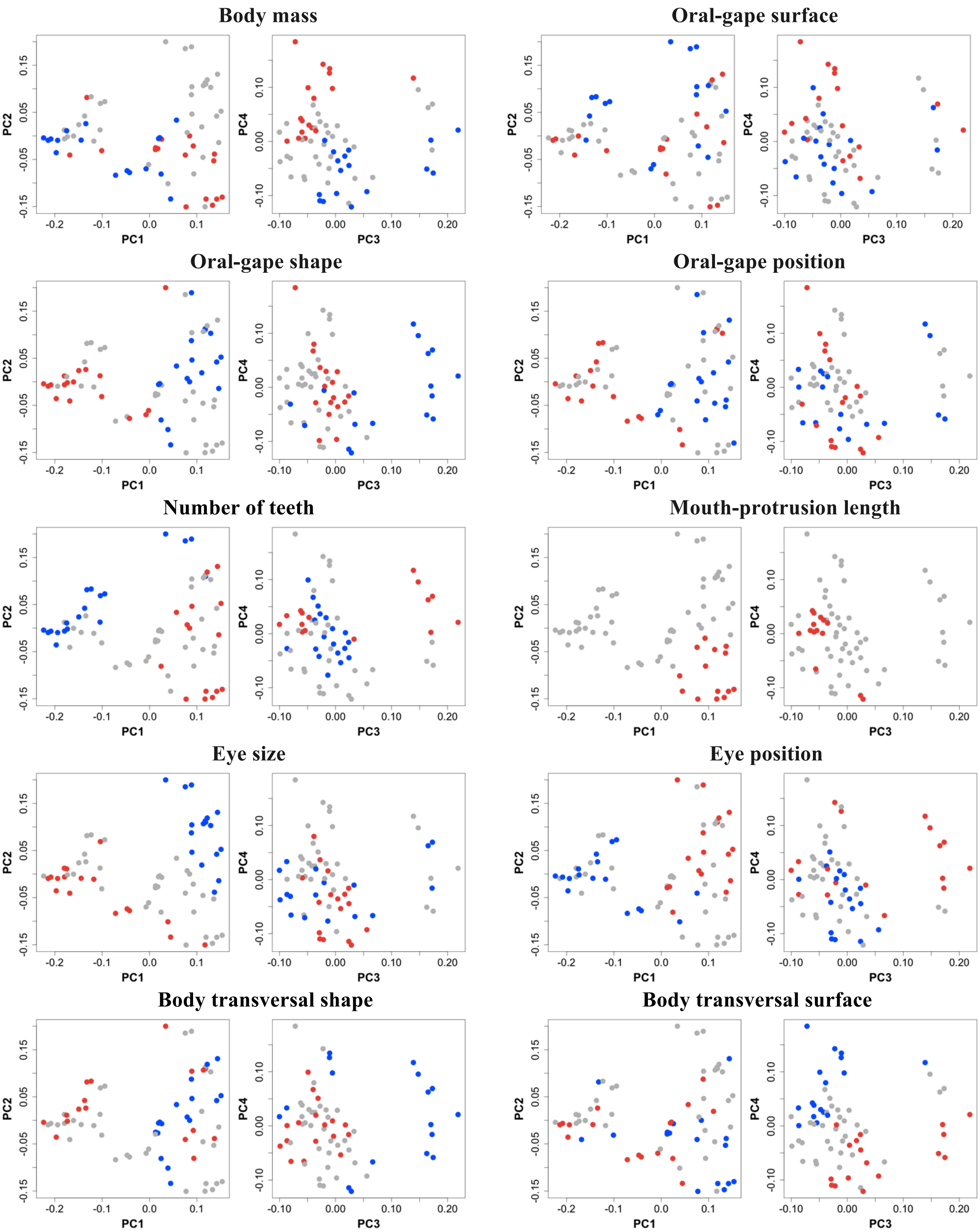

Figure A6. Four-dimensional representation of the functional space of the regional pool of stream fishes from Santarém (67 species), highlighting the distribution of each ecomorphological trait (as indicated above each pair of plots). Each plot represents two axes of a Principal Coordinate Analysis (PC), where species are plotted with dots according to their respective trait values. Species with high (superior quartile) and low (inferior quartile) values for each continuous trait are highlighted in red and blue, respectively. See specific legend for ordinal and nominal traits below their respective plots.

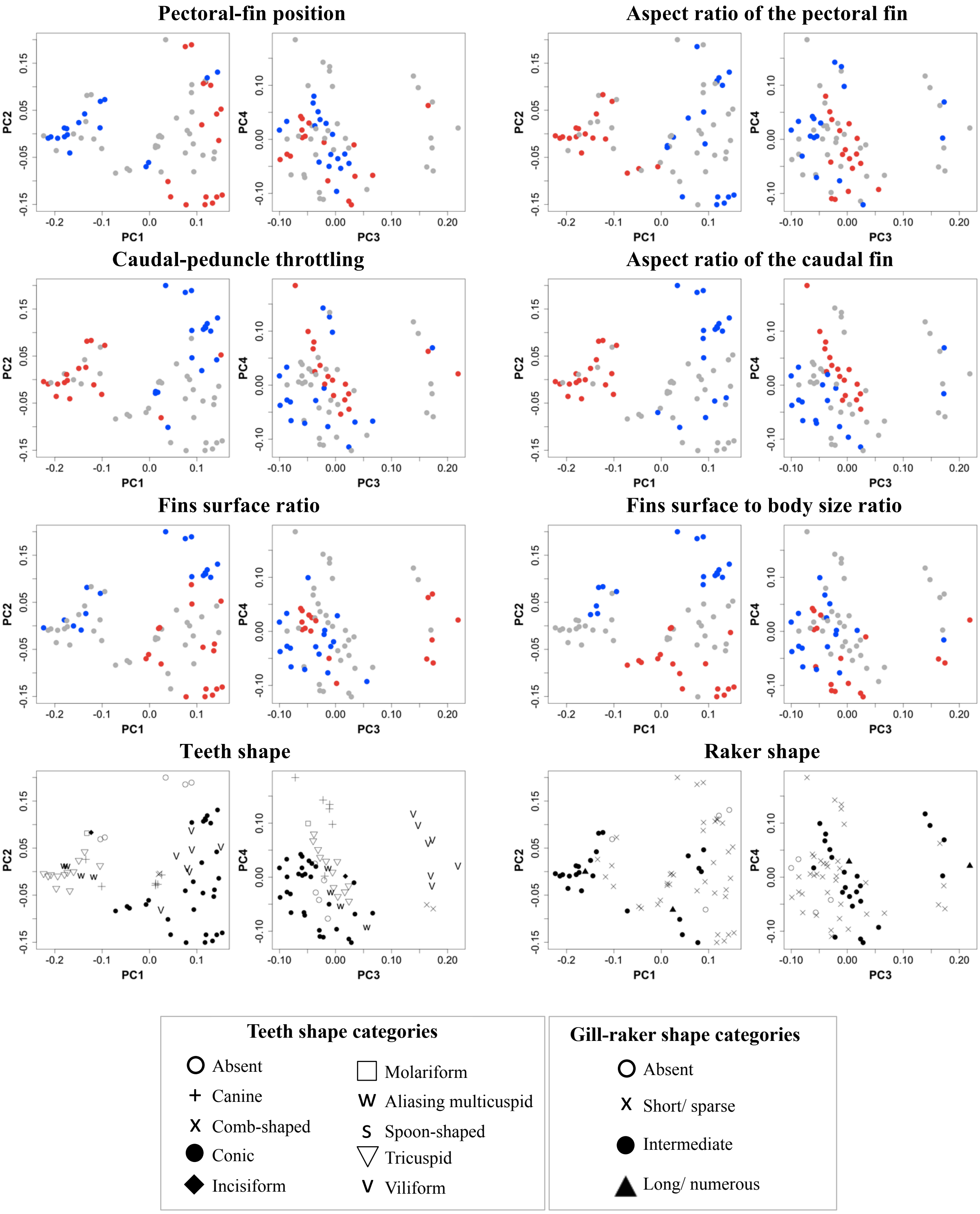

Figure A6. (continuation)

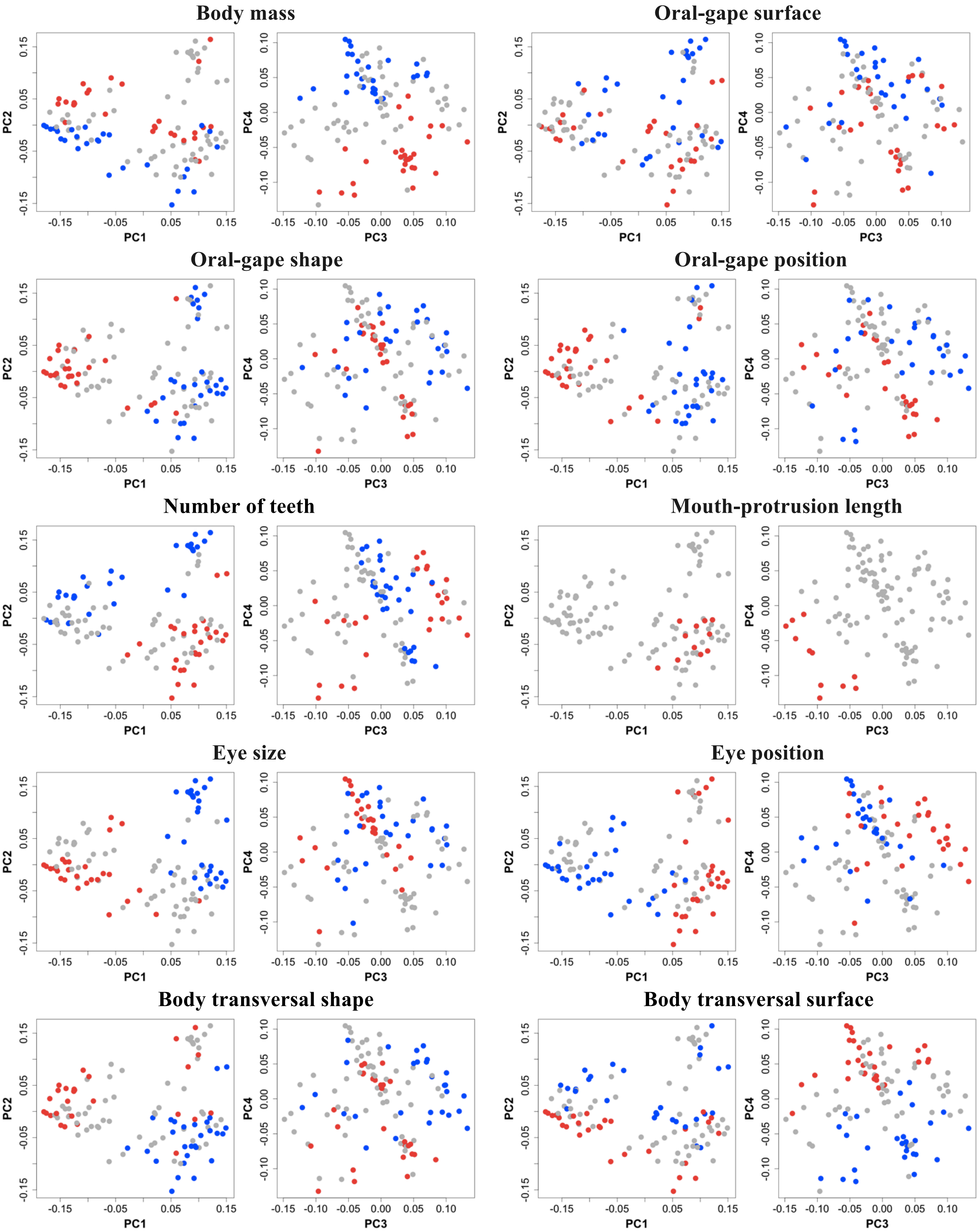

Figure A7. Four-dimensional representation of the functional space of the regional pool of stream fishes from Paragominas (112 species), highlighting the distribution of each ecomorphological trait (as indicated above each pair of plots). Each plot represents two axes of a Principal Coordinate Analysis (PC), where species are plotted with dots according to their respective trait values. Species with high (superior quartile) and low (inferior quartile) values for each continuous trait are highlighted in red and blue, respectively. See specific legend for ordinal and nominal traits below their respective plots.

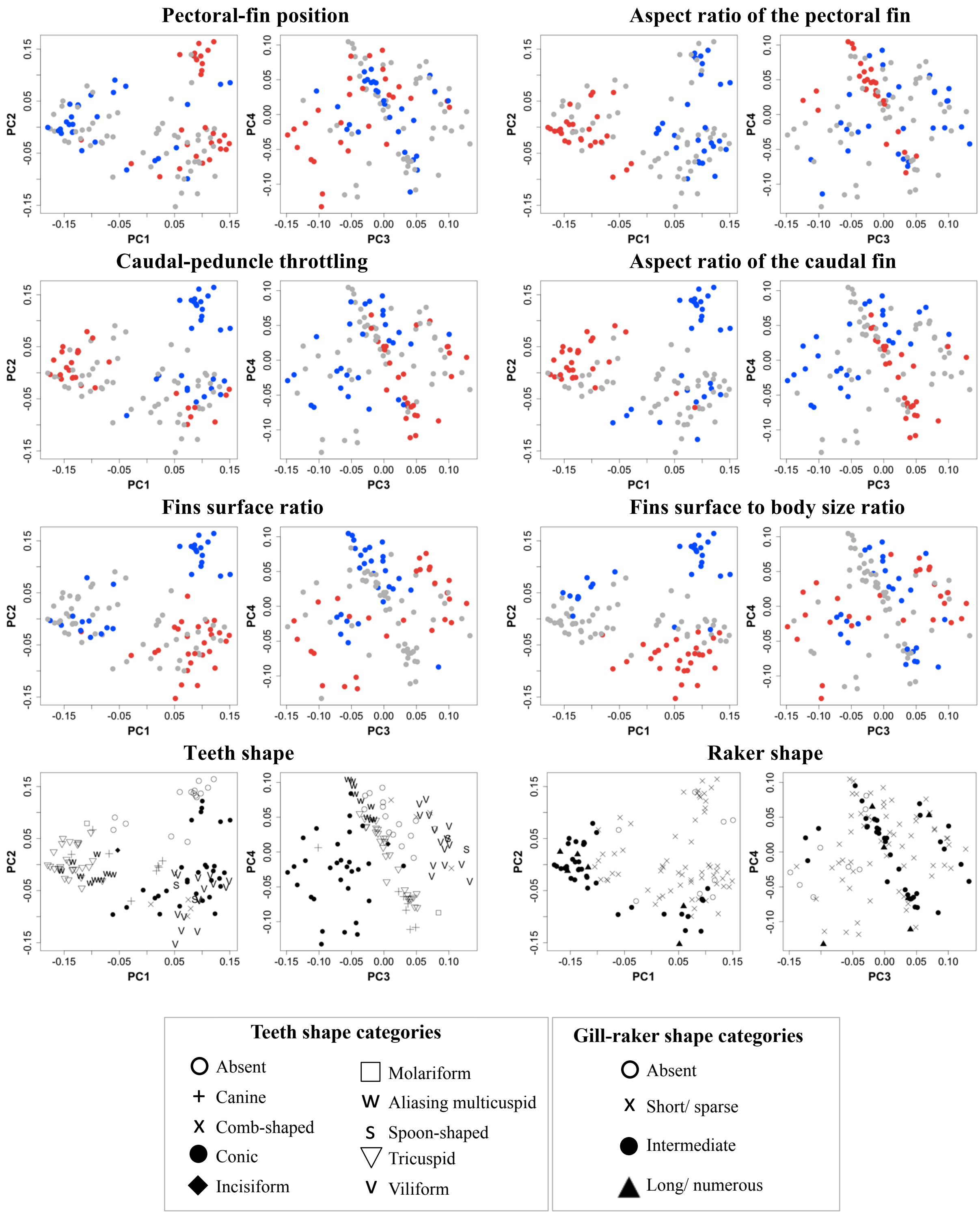

Figure A7. (continuation)

Appendix 2: Supplementary tables

Table A1. Mean and range (minimum – maximum) values of the landscape and instream habitat variables used in the Structural Equation Model of Santarém (n = 40) and Paragominas (n = 49) stream sites, Amazon.

Variable	Unit	SANTAREM			PARAGOMINAS		
		Mean	Min	Max	Mean	Min	Max
Natural factors							
Catchment area	ha	2741.3	83.0	22726.0	1251.0	44.3	5045.3
Distance to large river	m	5614.4	304.5	17465.6	4741.5	50.1	19780.
Land use							
Catchment deforestation	%	29.3	0.0	70.1	31.6	0.0	97.3
Riparian network deforestation	%	35.3	0.0	100.0	37.8	0.0	95.9
Local deforestation	%	35.2	0.0	92.0	62.8	0.0	100.0
Mechanized agriculture	%	7.1	0.0	59.5	2.6	0.0	44.0
Upstream road crossings	$nbr.ha^{-1}.10^{-3}$	2.1	0.0	12.0	3.1	0.0	22.6
Downstream road crossings	$nbr.ha^{-1}.10^{-3}$	0.7	0.0	5.4	2.1	0.0	45.1
Instream habitat							
Mean water-column depth	mm	37.8	9.4	99.2	40.2	11.6	78.5
Bankfull width/depth ratio	m/m	18.2	0.8	86.0	8.1	2.7	38.6
Bottom complexity	m/m	0.4	0.0	0.8	0.4	0.3	0.7
Relative bed stability	log_{10}(mm/m)	-2.3	-3.5	0.1	-1.7	-3.0	0.3
Wood volume	mm^3/m^2	1.6	0.0	10.5	3.2	0.0	14.3
Coarse litter cover	%	23.3	0.0	95.2	16.7	0.0	64.8
Standing cover	%	38.0	1.8	98.0	39.3	5.9	117.0
Channel shading	%	80.3	8.2	99.3	65.7	2.7	99.5
Water temperature	°C	25.1	23.5	27.7	25.6	23.7	29.2
Aquatic vegetation cover	%	5.0	0.0	52.3	13.5	0.0	76.4

Table A2. Total and indirect effects (i.e., mediated by instream conditions) of land use on the structure of stream fish assemblages in Santarém (n=40), Amazon. S: taxonomic richness; J: taxonomic evenness; FRic: functional richness; FEve: Functional evenness; FDiv: Functional divergence; CWM1-4: Functional identity. Only significant path coefficients from the Structural Equation Model are included. See also Fig. 2.

Variable	S	J	FRic	FEve	FDiv	CWM1	CWM2	CWM3	CWM4
Local riparian deforestation	**-0.35**	**-**	**-0.34**	**-0.15**	**-**	**-0.07**	**0.15**	**-**	**-**
Bottom complexity	-0.06	-	-	-0.06	-	-0.07	-	-	-
Wood volume	-	-	-	-	-	-	0.15	-	-
Coarse litter	-0.29	-	-	-	-	-	-	-	-
Aquatic vegetation cover	-	-	-	-0.09	-	-	-	-	-
Species richness	-	-	-0.34	-	-	-	-	-	-
Upstream fragmentation	**0.00**	**0.05**	**0.00**	**-0.06**	**-**	**-0.06**	**-**	**-**	**-0.05**
Water-column depth	-	0.05	-	-	-	0.04	-	-	-
Relative bed stability	0.06	-	-	-	-	-0.04	-	-	-0.05
Bottom complexity	-0.06	-	-	-0.06	-	-0.06	-	-	-
Species richness	-	-	0.00	-	-	-	-	-	-
Downstream fragmentation	**-0.13**	**-0.20**	**-0.22**	**-0.45**	**-0.28**	**0.19**	**-0.55**	**0.41**	**-0.43**
Downstream fragmentation*	-0.13	-0.20	-0.09	-0.45	-0.28	0.19	-0.55	0.41	-0.43
Species richness	-	-	-0.13	-	-	-	-	-	-
Catchment area	**0.46**	**-0.21**	**0.44**	**-**	**-**	**-0.53**	**-**	**-**	**-**
Catchment area*	**0.46**	-	-	-	-	-0.35	-	-	-
Water-column depth	-	-0.21	-	-	-	-0.18	-	-	-
Species richness	-	-	0.44	-	-	-	-	-	-
River distance	**-0.32**	**-**	**-0.30**	**-**	**-**	**-**	**-**	**-**	**-**
River distance*	-0.32	-	-	-	-0.32	-	-	-	-
Species richness	-	-	-0.30	-	-	-	-	-	-

Note: boldface type in gray rows indicates total effects.
** Direct effect of landscape on fish assemblage structure*

Table A3. Total and indirect effects (i.e., mediated by instream conditions) of land use on the structure of stream fish assemblages in Paragominas (n=49), Amazon. S: taxonomic richness; J: taxonomic evenness; FRic: functional richness; FEve: Functional evenness; FDiv: Functional divergence; FOri: Functional originality; CWM1-4: Functional identity. Only significant path coefficients from the Structural Equation Model are included. See also Fig. 3.

Variable	S	J	FRic	FEve	FDiv	FOri	CWM1	CWM2	CWM3	CWM4
Local riparian deforestation	**0.21**	**0.09**	**0.17**	**-0.19**	**-**	**0.03**	**0.08**	**-0.14**	**0.03**	**-**
Bankfull width/depth ratio	-	0.09	-	-	-	-	-	-0.14	-	-
Wood volume	0.21	-	-	-	-	0.16	0.14	-	-0.13	-
Water temperature	-	-	-	-	-	-	-0.06	-	-	-
Aquatic vegetation cover	-	-	-	-0.19	-	-0.13	-	-	0.16	-
Species richness	-	-	0.17	-	-	-	-	-	-	-
Network riparian deforestation	**-0.35**	**-**	**-0.28**	**-**	**-**	**-0.27**	**-0.23**	**-**	**0.22**	**-**
Wood volume	-0.35	-	-	-	-	-0.27	-0.23	-	0.22	-
Species richness	-	-	-0.28	-	-	-	-	-	-	-
Catchment deforestation	**0.34**	**-0.29**	**0.27**	**-**	**-**	**0.26**	**-0.01**	**-**	**-0.21**	**-**
Relative bed stability	-	-0.29	-	-	-	-	-	-	-	-
Wood volume	0.34	-	-	-	-	0.26	0.22	-	-0.21	-
Water temperature	-	-	-	-	-	-	-0.23	-	-	-
Species richness	-	-	0.27	-	-	-	-	-	-	-
Upstream fragmentation	**-**	**0.06**	**-**	**-**	**-**	**-**	**-**	**-0.10**	**-**	**-**
Bankfull width/depth ratio	-	0.06	-	-	-	-	-	-0.10	-	-
Downstream fragmentation	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**0.47**	**-**	**-**
Downstream fragmentation*	-	-	-	-	-	-	-	0.47	-	-
Catchment area	**-**	**-**	**-**	**-0.37**	**-0.60**	**-**	**-**	**0.30**	**0.51**	**-0.43**
Catchment area*	-	-	-	-0.37	-0.60	-	-	0.30	0.63	-0.43
Water-column depth	-	-	-	-	-	-	-	-	-0.12	-
River distance	**-**	**-**	**-**	**-**	**0.30**	**-**	**-**	**-0.56**	**-**	**-**
River distance*	-	-	-	-	0.30	-	-	-0.56	-	-

Note: boldface type in gray rows indicates total effects.

* *Direct effect of landscape on fish assemblage structure*

Table A4. Overall model explanation (R^2 values of the Structural Equation Model) for habitat and fish assemblage structure variables of Santarém and Paragominas streams, Amazon.

Variable	Code	SANTAREM	PARAGOMINAS
Instream habitat			
Mean water-column depth	DEPTH	0.45	0.35
Bankfull width/depth ratio	BFWD_RAT	0.20	0.22
Bottom complexity	COMPLEXITY	0.14	0.06
Relative bed stability	LRBS	0.21	0.08
Wood volume	WOOD	0.35	0.22
Coarse litter cover	LITTER	0.30	0.07
Standing cover	COVER	0.02	0.01
Channel shading	SHADE	0.21	0.37
Water temperature	TEMPERATURE	0.22	0.50
Aquatic vegetation cover	MAGRAL	0.29	0.52
Assemblage structure			
Taxonomic richness	S	0.83	0.36
Taxonomic evenness	J	0.33	0.42
Functional richness	FRic	0.84	0.78
Functional evenness	FEve	0.64	0.36
Functional divergence	FDiv	0.45	0.40
Functional originality	FOri	0.15	0.46
Functional identity (PCoA1)	CWM1	0.54	0.32
Functional identity (PCoA2)	CWM2	0.62	0.56
Functional identity (PCoA3)	CWM3	0.54	0.56
Functional identity (PCoA4)	CWM4	0.44	0.22

Table A5. Correlation between each continuous morphological trait and the four axes of the Principal Coordinate Analysis (PCoA) used to build the functional space of stream fishes from Santarém and Paragominas. The traits the most negatively and the most positively correlated with each PCoA axis are in blue and red, respectively. See ecological meaning of each trait in Appendix A3.

Trait	**SANTAREM**				**PARAGOMINAS**			
	PCoA1	**PCoA2**	**PCoA3**	**PCoA4**	**PCoA1**	**PCoA2**	**PCoA3**	**PCoA4**
Number of teeth	**0.51**	-0.24	0.37	0.26	0.44	-0.44	0.27	-0.18
Mouth-protrusion length	0.41	**-0.62**	-0.30	-0.05	0.27	-0.20	**-0.54**	-0.40
Oral-gape surface	0.02	-0.27	-0.08	0.44	-0.10	-0.24	-0.09	-0.19
Oral-gape shape	**-0.62**	-0.24	**-0.47**	0.10	**-0.59**	-0.07	-0.30	-0.18
Oral-gape position	-0.40	-0.13	-0.28	-0.08	**-0.60**	0.15	-0.21	-0.23
Eye size	**-0.64**	**-0.63**	-0.12	-0.10	**-0.72**	-0.44	-0.28	0.04
Eye position	**0.63**	**0.24**	**0.49**	0.34	**0.71**	-0.06	**0.41**	0.00
Body transversal shape	-0.42	**0.19**	**-0.56**	-0.03	**-0.59**	**0.45**	-0.18	-0.31
Body transversal surface	-0.27	-0.05	**0.57**	**-0.52**	-0.06	-0.27	-0.22	**0.50**
Pectoral-fin position	**0.75**	-0.13	0.04	-0.15	**0.58**	0.06	-0.20	0.01
Aspect ratio of the pectoral fin	**-0.82**	-0.09	0.07	-0.26	**-0.79**	-0.14	-0.19	0.23
Caudal-peduncle throttling	**-0.65**	-0.30	0.26	0.30	-0.27	-0.41	**0.46**	-0.12
Aspect ratio of the caudal fin	**-0.76**	-0.19	0.06	0.36	**-0.74**	-0.14	**0.38**	-0.29
Fins surface ratio	0.26	**-0.62**	0.37	0.13	0.22	**-0.61**	0.16	-0.27
Fins surface to body size ratio	0.20	**-0.84**	0.25	-0.10	0.15	**-0.87**	-0.01	-0.03
Body mass	0.38	-0.22	**-0.43**	**0.71**	0.15	0.25	0.30	**-0.77**

Appendix 3: Functional trait assessment

We conducted an ecomorphological analysis to evaluate the functional structure of fish assemblages by characterizing species for three key functions: food acquisition, locomotion, and habitat preference. Body mass and morphometric measures (Fig. A8) were taken on specimens from 141 species (5 to 12 individuals per species), and then combined into 15 ecomorphological traits (Table A6). These traits, except the log-transformed mass, are expressed as unitless ratios to prevent trivial correlation with body-size. We also assessed the number and shape of teeth and gill rakers on one individual per species.

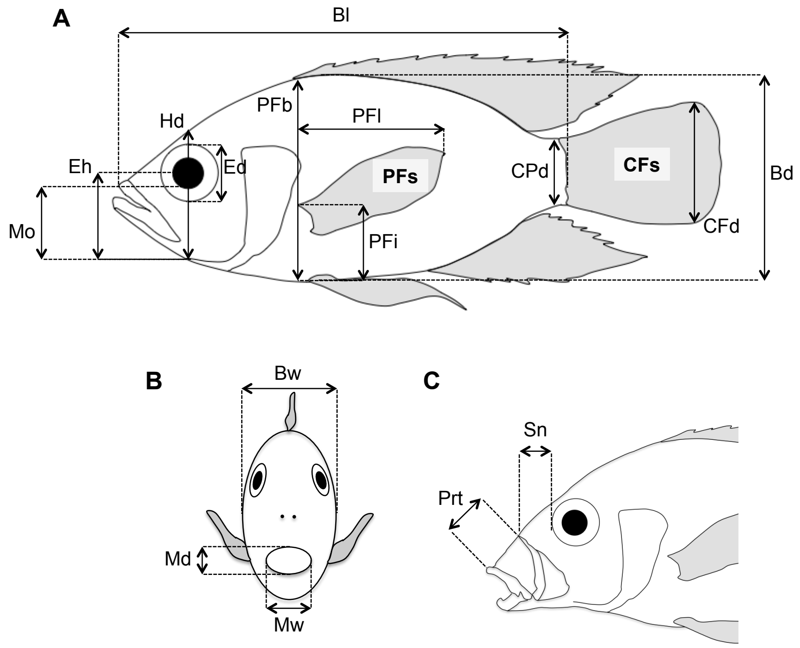

Figure A8. Morphological traits measured for fish from digital pictures (A): *Bd* body depth, *CPd* caudal-peduncle minimal depth, *CFd* caudal-fin depth, *CFs* caudal-fin surface, *PFi* distance between the insertion of pectoral fin to the bottom of the body, *PFb* body depth at the level of the pectoral-fin insertion, *PFl* pectoral-fin length, *PFs* pectoral-fin surface, *Hd* head depth along the vertical axis of the eye, *Ed* eye diameter, *Eh* distance between the center of the eye to the bottom of the head, *Mo* distance from the top of the mouth to the bottom of the head along the head depth axis; and with digital caliper (B, C): *Bw* body width, *Md* mouth depth, *Mw* mouth width, *Sn* snout length, *Prt* protrusion length.

We weighed specimens using an electronic balance (0.001 g). Body width, mouth width, mouth depth, snout length and protrusion length were measured with a digital caliper (0.1 mm). The other morphological measures were obtained through the use of digital pictures analyzed in Image J software (0.1 mm). We evaluated gill-raker and teeth characteristics under a binocular microscope.

Although this standard protocol was designed to cover a broad range of morphologies among fish groups (Villéger *et al.* 2010), we had to use some particular conventions. Synbranchiformes and Gymnotiformes (except Apteronotidae) have no caudal fin, so the *Aspect ratio of the caudal fin*, *Fins surface ratio*, and *Caudal peduncle throttling* were fixed to 0. Synbranchiformes also have no pectoral fins, so *Pectoral fin position*, *Aspect ratio of the pectoral fin*, and *Fins surface to body size ratio* were fixed to 0.

Table A6. List of the 18 functional traits measured for stream fishes from the eastern Amazon. Codes for morphological measures are shown in Fig. A8.

Morphological trait	Calculation/ Class	Nature	Ecological meaning	References
Teeth shape	Absent Canine Comb-shaped Conic Incisiform Molariform Multicuspid Spoon-shaped Tricuspid Viliform	Nominal	Nature of food items captured and feeding method	adapted from Gatz (1979); Keenleyside (1979); Sazima (1986)
Number of teeth	Mean number of teeth in upper and lower jaws	Continuous	Nature of food items captured and feeding method	adapted from Gatz (1979)
Gill-raker shape	Absent Short/ sparse Intermediate Long/ numerous	Ordinal	Filtering ability and gill protection	adapted from Sibbing & Nagelkerke (2001)
Mouth-protrusion length	$\frac{Prt}{Sn}$	Continuous	Nature of food items captured and feeding method	adapted from Gatz (1979)
Oral-gape surface	$\frac{Mw \times Md}{Bw \times Bd}$	Continuous	Nature/Size of food items captured	adapted from Karpouzi & Stergiou (2003)
Oral-gape shape	$\frac{Md}{Mw}$	Continuous	Method to capture food items	Karpouzi & Stergiou (2003)
Oral-gape position	$\frac{Mo}{Hd}$	Continuous	Feeding method in the water column	adapted from Sibbing & Nagelkerke (2001)
Eye size	$\frac{Ed}{Hd}$	Continuous	Prey detection	adapted from Boyle & Horn (2006)
Eye position	$\frac{Eh}{Hd}$	Continuous	Vertical position in the water column	Gatz (1979)
Body transversal shape	$\frac{Bd}{Bw}$	Continuous	Vertical position in the water column and hydrodynamism	Sibbing & Nagelkerke (2001)

Body transversal surface	$\frac{\ln\left[\left(\frac{\pi}{4} \times Bw \times Bd\right) + 1\right]}{ln\ (\text{Mass} + 1)}$	Continuous	Mass distribution along the body for hydrodynamism	Villéger *et al.* (2010)
Pectoral-fin position	$\frac{PFi}{PFb}$	Continuous	Pectoral fin use for maneuverability	Dumay *et al.* (2004)
Aspect ratio of the pectoral fin	$\frac{PFl^2}{PFs}$	Continuous	Pectoral fin use for propulsion	adapted from Fulton *et al.* (2001)
Caudal-peduncle throttling	$\frac{CFd}{CPd}$	Continuous	Caudal propulsion efficiency through reduction of drag	Webb (1984)
Aspect ratio of the caudal fin	$\frac{CFd^2}{CFs}$	Continuous	Caudal fin use for propulsion and/or direction	Webb (1984)
Fins surface ratio	$\frac{2 \times PFs}{CFs}$	Continuous	Main type of propulsion between caudal and pectoral fins	Villéger *et al.* (2010)
Fins surface to body size ratio	$\frac{(2 \times PFs) + CFs}{\frac{\pi}{4} \times Bw \times Bd}$	Continuous	Acceleration and/or maneuverability efficiency	Villéger *et al.* (2010)
Body mass	log (Mass +1)	Continuous	Metabolism, endurance and swimming ability	Villéger *et al.* (2010)

References:

Boyle, K. S. and Horn, M. H. 2006. Comparison of feeding guild structure and ecomorphology of intertidal fish assemblages from central California and central Chile. – MEPS 319: 65–84.

Dumay, O. et al. 2004. Functional groups of lagoon fish species in Languedoc Roussillon, southern France. – J. Fish Biol. 64: 970–983.

Fulton, C. J. et al. 2001. The relationship between swimming ability and habitat use in wrasses (Labridae). – Mar. Biol. 139: 25–33.

Gatz, A. J. 1979. Community organization in fishes as indicated by morphological features. – Ecology 60: 711–718.

Karpouzi, V. S. and Stergiou, K. I. 2003. The relationships between mouth size and shape and body length for 18 species of marine fishes and their trophic implications. – J. Fish Biol. 62: 1353–1365.

Keenleyside, M. H. A. 1979. Diversity and adaptation in fish behaviour. – Springer.

Sazima, I. 1986. Similarities in feeding behaviour between some marine and freshwater fishes in two tropical communities. – J. Fish Biol. 29: 53–65.

Sibbing, F.A. and Nagelkerke, L. A. J. 2001. Resource partitioning by Lake Tana barbs predicted from fish morphometrics and prey characteristics. – Rev. Fish Biol. Fisher. 10: 393–437.

Villéger, S. et al. 2010. Contrasting changes in taxonomic vs. functional diversity of tropical fish communities after habitat degradation. – Eco Appl. 20: 1512–1522.

Webb, P. W. 1984. Form and function in fish swimming. – Sci. Am. 251: 72–82.

Appendix 4: Complementary analysis combining datasets from two regions

We conducted a complementary analysis to investigate a possible pattern of functional responses of stream fish assemblages to overall land-use changes in the eastern Amazon. We reran all analytical procedures by combining datasets from Santarém (STM) and Paragominas (PGM) regions. All procedures were exactly the same as described in Methods, except the multidimensional functional space, which was based on a single pool of species merging both regions. Using a single pool of species is necessary to adequately compare different local assemblages, because species functional traits in the pool will constrain the range of functional-diversity values (Villéger et al. 2008). We kept the first four Principal Coordinate axes, as this was the minimum number of axes that provided a high-quality functional space.

When using the combined STM and PGM data in the analysis, the observed data were not well-fitted by the structural model; i.e. the model predictions and observed data are significantly different from each other (χ^2 = 455.9, df = 180, p = 0.01). Therefore, although we identified multiple pathways of land-use impacts on instream habitat and assemblage structure, the results on the interrelationships among factors should be interpreted with caution.

Increased upstream fragmentation reduced water-column depth, increased catchment mechanized agriculture increased the bankfull width/depth ratio and decreased bed stability, and increased catchment deforestation increased water temperature (Fig. A9). Increased local deforestation reduced wood volume, coarse litter cover, and channel shading, thereby increasing water temperature and aquatic vegetation cover (Fig. A9). Riparian network deforestation had no significant effect on habitat metrics in the merged dataset.

Increased local deforestation decreased functional evenness (FEve) and originality (FOri), because FEve decreased with reduced wood volume and FOri decreased with increased aquatic vegetation cover (Fig. A9, Table A7). On the other hand, local deforestation increased functional richness (FRic), via species richness, because the latter metric was negatively correlated with increased wood volume. Both FRic (via species richness) and FOri were reduced by increased mechanized agriculture mediated by increased bankfull width/depth ratio and decreased bed stability, respectively. FRic was also reduced by increased upstream fragmentation, mediated by reduced water-column depth and species richness, and by distance to large rivers, but increased by increased catchment area (Fig. A9, Table A7). Functional divergence (FDiv) was not affected by land use, downstream fragmentation had no significant effect on the structure of the merged fish assemblage datasets, nor did complexity, litter, or temperature.

As opposed to the 'meso-scale' approach, the merged dataset detected few significant pathways of land-use effects on the functional identity of fish assemblages. Small-body species related to the occupation of mid/upper layers of water column (i.e., low CWM1 and CWM4) were reduced by increased upstream fragmentation via reductions in channel depth (Fig. A9, Table A7, Table A8). Mediated by increased bankfull width/depth ratio, increased mechanized agriculture reduced species with small and upper-positioned eyes and poorly developed fins (Fig. A9, Table A7, Table A8). Catchment area affected CWM1, CWM2, and CWM4 directly and indirectly, and river distance increased CWM2 scores.

Table A7. Total and indirect effects (i.e., mediated by instream conditions) of land use on the structure of stream fish assemblages in Santarém and Paragominas regions (n=89), Amazon. S: taxonomic richness; J: taxonomic evenness; FRic: functional richness; FEve: Functional evenness; FOri: Functional originality; CWM1-4: Functional identity. Only significant path coefficients from the Structural Equation Model are included. See also Fig. A9.

Variable	S	J	FRic	FEve	FOri	CWM1	CWM2	CWM4
Local riparian deforestation	**0.20**	**-**	**0.18**	**-0.05**	**-0.03**	**-**	**-**	**-**
Wood volume	0.04	-	-	-0.05	0.05	-	-	-
Aquatic vegetation cover	0.16	-	-	-	-0.07	-	-	-
Species richness	-	-	0.18	-	-	-	-	-
Species evenness	-	-	-	-	-	-	-	-
Mechanized agriculture	**-0.11**	**-**	**-0.10**	**-**	**-0.04**	**-**	**0.11**	**-**
Relative bed stability	-	-	-	-	-0.04	-	-	-
Bankfull width/depth ratio	-0.11	-	-	-	-	-	0.11	-
Species richness	-	-	-0.10	-	-	-	-	-
Upstream fragmentation	**-0.05**	**0.06**	**-0.04**	**0.02**	**-**	**0.08**	**-**	**0.06**
Water-column depth	-0.05	0.06	-	-	-	0.08	-	0.06
Species richness	-	-	-0.04	-	-	-	-	-
Species evenness	-	-	-	0.02	-	-	-	-
Catchment area	**0.11**	**0.08**	**0.10**	**0.02**	**-**	**-**	**-0.32**	**0.24**
Catchment area*	-	0.23	-	-	-	-	-0.32	0.39
Water-column depth	0.11	-0.15	-	-	-	-	-	-0.15
Species richness	-	-	0.10	-	-	-	-	-
Species evenness	-	-	-	0.02	-	-	-	-
River distance	**-0.17**	**-**	**-0.15**	**-**	**-**	**-**	**-**	**-**
River distance*	-0.17	-	-	-	-	-	0.28	-
Species richness	-	-	-0.15	-	-	-	-	-

Note: boldface type in gray rows indicates total effects.

* Direct effect of landscape on fish assemblage structure

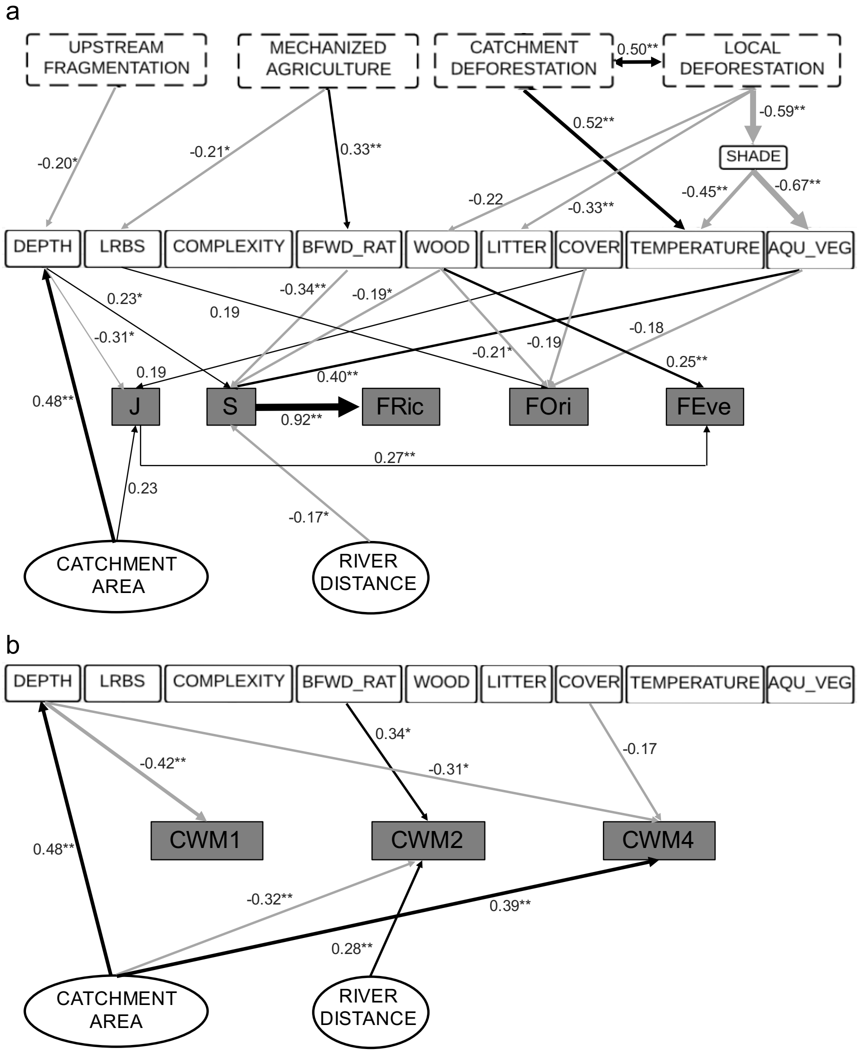

Figure A9. Structural Equation Model diagrams showing the effects of land cover and riverscape fragmentation (dashed-line rectangles), instream habitat characteristics (solid-line rectangles; see code meaning in Fig. 1), and natural landscape factors (ovals) on the structure of stream fish assemblages (n = 89) in the Santarém and Paragominas regions, Amazon. For the sake of graphical simplicity, biodiversity metrics are divided into two diagrams: a) species richness (S) and evenness (J), functional richness (FRic), functional evenness (FEve), and functional originality (FOri); b) functional identity (CWM1-4). Unidirectional arrows indicate positive (black) and negative (gray) significant direct effects ($p < 0.10$; *$p < 0.05$; **$p < 0.01$), with thickness proportional to their power (standardized path coefficients along arrows). Model fit: $\chi^2 = 455.9$, df = 180, p = 0.01.

Table A8. Correlation between each continuous morphological trait and the four axes of the Principal Coordinate Analysis (PCoA) used to build the functional space of stream fishes from Santarém and Paragominas. The traits that are the most negatively and the most positively correlated with each PCoA axis are in blue and red, respectively. See ecological meaning of each trait in Appendix A3.

Trait	PCoA1	PCoA2	PCoA3	PCoA4
Body transversal surface	-0.10	0.16	0.34	**-0.53**
Aspect ratio of the pectoral fin	**-0.80**	0.17	0.06	-0.27
Eye size	**-0.65**	**0.61**	0.05	-0.10
Pectoral-fin position	**0.64**	0.09	-0.20	-0.04
Oral-gape shape	-0.56	0.30	-0.26	0.04
Oral-gape position	-0.55	0.20	-0.37	0.09
Fins surface to body size ratio	0.25	**0.71**	0.47	0.10
Oral-gape surface	-0.06	0.28	0.01	0.13
Mouth-protrusion length	0.37	0.56	-0.37	0.18
Eye position	**0.68**	**-0.31**	0.32	0.19
Body transversal shape	-0.54	-0.11	**-0.60**	0.19
Number of teeth	0.49	0.24	0.33	0.33
Fins surface ratio	0.29	0.40	0.40	0.34
Caudal-peduncle throttling	-0.30	0.04	**0.50**	0.37
Aspect ratio of the caudal fin	**-0.73**	-0.03	0.18	0.48
Body mass	0.28	-0.08	-0.36	**0.75**

References:

Villéger, S. et al. 2008. New multidimensional functional diversity indices for a multifaceted framework in functional ecology. Ecology 89: 2290–2301.

Appendix 5: Taxonomic composition and fish species abundance in Santarém and Paragominas streams, eastern Amazon

ORDER	FAMILY	SPECIES	COD.SP	Santarem	Paragominas
Beloniformes	Belonidae	*Potamorrhaphis eigenmanni*	pot.eige	-	1
Characiformes	Acestrorhynchidae	*Acestrorhynchus falcatus*	ace.falc	3	28
	Anostomidae	*Leporinus friderici*	lep.frid	-	36
	Characidae	*Astyanax* cf. *bimaculatus*	ast.cf.bima	-	49
		Astyanax maculisquamis	ast.macu	23	-
		Bario steindachneri	bar.stei	-	8
		Bryconops caudomaculatus	bry.caud	284	612
		Bryconops melanurus	bry.mela	211	401
		Charax leticiae	cha.leti	-	46
		Gymnocorymbus thayeri	gym.thay	-	33
		Hemigrammus bellottii	hem.bell	-	526
		Hemigrammus guyanensis	hem.guya	-	539
		Hemigrammus levis	hem.levi	2	255
		Hemigrammus ocellifer	hem.ocel	275	230
		Hemigrammus rhodostomus	hem.rhod	-	68
		Hemigrammus rodwayi	hem.rodw	-	3355
		Hemigrammus sp. *"geisleri"*	hem.sp.geis	-	595
		Hemigrammus sp. *"prata"*	hem.sp.prat	-	58
		Hemigrammus stictus	hem.stic	1	-
		Hemigrammus vorderwinkleri	hem.vord	4	-
		Hyphessobrycon copelandi	hyp.cope	-	6
		Hyphessobrycon heterorhabdus	hyp.hete	566	2879
		Hyphessobrycon sp. *"túlio"*	hyp.sp.tuli	1222	-
		Iguanodectes rachovii	igu.rach	-	409
		Iguanodectes variatus	igu.vari	240	-
		Jupiaba anteroides	jup.ante	-	26
		Knodus cf. *victoriae*	kno.cf.vict	-	133
		Knodus savannensis	kno.sava	753	-
		Knodus sp.*n. "anal longa"*	kno.sp.anlo	-	183
		Microschemobrycon geisleri	mic.geis	-	14
		Moenkhausia celibela	moe.celi	9	-
		Moenkhausia collettii	moe.coll	-	1146
		Moenkhausia collettii "alta"	moe.coll.alta	1160	-
		Moenkhausia comma	moe.comm	23	54
		Moenkhausia oligolepis	moe.olig	-	388
		Moenkhausia sp. *"lepidura curta"*	moe.sp.lepcu	-	218
		Phenacogaster cf. *pectinatus*	phe.cf.pect	-	51
		Phenacogaster cf. *wayana*	phe.cf.waya	-	1
		Poptella brevispina	pop.brev	-	56
		Poptella compressa	pop.comp	-	6
		Pristella maxillaris	pris.maxi	-	69
		Serrapinnus aff. *piaba*	ser.aff.piab	-	646
	Crenuchidae	*Characidium* aff. *pteroides*	cha.aff.pter	18	-
		Characidium cf. *etheostoma*	cha.cf.ethe	-	257
		Crenuchus spilurus	cre.spil	13	5
		Melanocharacidium dispilomma	mel.disp	9	3
		Microcharacidium weitzmani	mic.weit	-	284
	Curimatidae	*Curimatopsis macrolepis*	cur.macr	33	45
		Cyphocharax gouldingi	cyp.goul	2	86
		Steindachnerina amazonica	ste.amaz	-	214
	Erythrinidae	*Erythrinus erythrinus*	ery.eryt	33	34
		Hoplerythrinus unitaeniatus	hop.unit	1	8
		Hoplias curupira	hop.curu	15	1
		Hoplias malabaricus	hop.mala	33	46
	Gasteropelecidae	*Gasteropelecus sternicla*	gas.ster	-	13
	Lebiasinidae	*Copella arnoldi*	cop.arno	-	140
		Copella nigrofasciata	cop.nigr	90	-
		Copella sp. *"pyrr"*	cop.sp.pyrr	11	-
		Nannostomus beckfordi	nan.beck	-	452
		Nannostomus eques	nan.eque	-	11
		Nannostomus marginatus	nan.marg	232	-
		Nannostomus nitidus	nan.niti	-	56
		Nannostomus trifasciatus	nan.trif	-	116
		Pyrrhulina aff. *brevis*	pyr.aff.brev	-	488
		Pyrrhulina zigzag	pyr.zigz	2	-
	Serrasalmidae	*Myloplus rubripinnis*	myl.rubr	3	13
		Serrasalmus rhombeus	ser.rhom	-	3
		Serrasalmus sp. *"robertsoni"*	ser.sp.robe	2	-
		Tometes sp.	tom.sp	3	-

ORDER	FAMILY	SPECIES	COD.SP	Santarem	Paragominas
Cyprinodontiformes	Rivulidae	*Rivulus* cf. *urophthalmus*	riv.cf.urop	27	103
		Rivulus dibaphus	riv.diba	341	-
Gymnotiformes	Apteronotidae	*Apteronotus albifrons*	apt.albi	1	-
	Gymnotidae	*Gymnotus carapo*	gym.cara	6	43
		Gymnotus coropinae	gym.coro	105	74
	Hypopomidae	*Brachyhypopomus beebei*	bra.beeb	-	2
		Brachyhypopomus brevirostris	bra.brev	5	22
		Brachyhypopomus sp. *"regani"*	bra.sp.rega	-	40
		Brachyhypopomus sp. *"royeroi"*	bra.sp.roye	-	7
		Brachyhypopomus sp. *electropomus*	bra.sp.elec	-	1
		Hypopygus lepturus	hyp.lept	54	77
		Microsternarchus bilineatus	mic.bili	-	15
		Steatogenys duidae	ste.duid	-	4
	Rhamphichthyidae	*Gymnorhamphichthys petiti*	gym.peti	59	76
		Rhamphichthys marmoratus	rha.marm	-	1
	Sternopygidae	*Eigenmannia* aff. *trilineata*	eig.aff.tril	8	469
		Sternopygus macrurus	ste.macr	3	30
Perciformes	Cichlidae	*Acaronia nassa*	aca.nass	1	-
		Aequidens epae	aeq.epae	84	-
		Aequidens tetramerus	aeq.tetr	113	225
		Apistogramma aff. *regani*	api.aff.rega	-	143
		Apistogramma agassizii	api.agas	-	17
		Apistogramma caetei	api.caet	-	347
		Apistogramma taeniata	api.taen	239	-
		Cichla kelberi	cic.kelb	-	1
		Crenicichla aff. *lepidota*	cre.aff.lepi	2	-
		Crenicichla aff. *menezesi*	cre.aff.mene	73	207
		Crenicichla inpa	cre.inpa	5	-
		Crenicichla johanna	cre.joha	1	-
		Crenicichla strigata	cre.stri	1	-
		Geophagus altifrons	geo.alti	-	11
		Heros notatus	her.nota	-	2
		Hypselecara temporalis	hyp.temp	5	-
		Mesonauta festivus	mes.fest	1	-
		Nannacara taenia	nan.taen	-	20
		Satanoperca jurupari	sat.juru	14	29
Siluriformes	Aspredinidae	*Bunocephalus* cf. *amaurus*	bun.cf.amau	4	3
		Bunocephalus coracoideus	bun.cora	-	3
	Auchenipteridae	*Tatia* aff. *dunni*	tat.aff.dunn	-	2
		Tatia intermedia	tat.inte	-	4
		Tetranematichthys wallacei	tet.wall	-	2
		Trachelyopterus galeatus	tra.gale	-	17
	Callichthyidae	*Callichthys callichthys*	cal.call	-	13
		Corydoras julii	cor.juli	-	26
		Corydoras sp. *"C24"*	cor.sp.c24	-	8
		Megalechis picta	meg.pict	-	14
	Cetopsidae	*Denticetopsis seducta*	den.sedu	18	2
		Helogenes marmoratus	hel.marm	119	129
	Doradidae	*Acanthodoras cataphractus*	aca.cata	2	8
	Heptapteridae	*Brachyglanis microphthalmus*	bra.micr	4	-
		Gladioglanis conquistador	gla.conq	-	5
		Imparfinis sp. *"linha continua"*	imp.sp.lico	-	19
		Imparfinis stictonotus	imp.stic	-	64
		Mastiglanis asopos	mas.asop	11	20
		Pimelodella sp. *"sem serra"*	pim.sp.sese	-	31
		Pimelodella sp. *"serra forte"*	pim.sp.sefo	-	264
		Rhamdia muelleri	rha.muel	3	14
		Rhamdia quelen	rha.quel	2	21
	Loricariidae	*Ancistrus* sp. *"bola"*	anc.sp.bl	-	36
		Farlowella platorynchus	far.plat	-	4
		Farlowella schreitmuelleri	far.schr	-	34
		Hemiodontichthys acipenserinus	hem.acip	-	1
		Hypostomus cf. *cochliodon*	hyp.cf.coch	-	1
		Otocinclus hoppei	oto.hopp	-	3
		Parotocinclus sp.	par.sp	2	-
		Parotocinclus sp. *"bicudinho"*	par.sp.bic	19	-
		Rineloricaria sp. 2 *"madeira"*	rin.sp2.mad	-	202
	Pseudopimelodidae	*Batrochoglanis raninus*	bat.rani	1	9
	Trichomycteridae	*Ituglanis amazonicus*	itu.amaz	3	148
		Trichomycterus hasemani	tri.hase	-	2
Synbranchiformes	Synbranchidae	*Synbranchus madeirae*	syn.made	19	22
		Synbranchus sp. *"pintado"*	syn.sp.pint	3	1