

Ecography

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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**

Rafael P. Leitão, Jansen Zuanon, David Mouillot, Cecília G. Leal, Robert M. Hughes, Philip R. Kaufmann, Sébastien Villéger, Paulo S. Pompeu, Daniele Kasper, Felipe R. de Paula, Silvio F. B. Ferraz, and Toby A. Gardner

**Mailing address:** Rafael P. Leitão. Instituto Nacional de Pesquisas da Amazônia, CBIO, Av. André Araújo, 2936, 69060–001 Manaus, Brazil. E-mail: ecorafa@gmail.com

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## Appendix 1. Supplementary figures

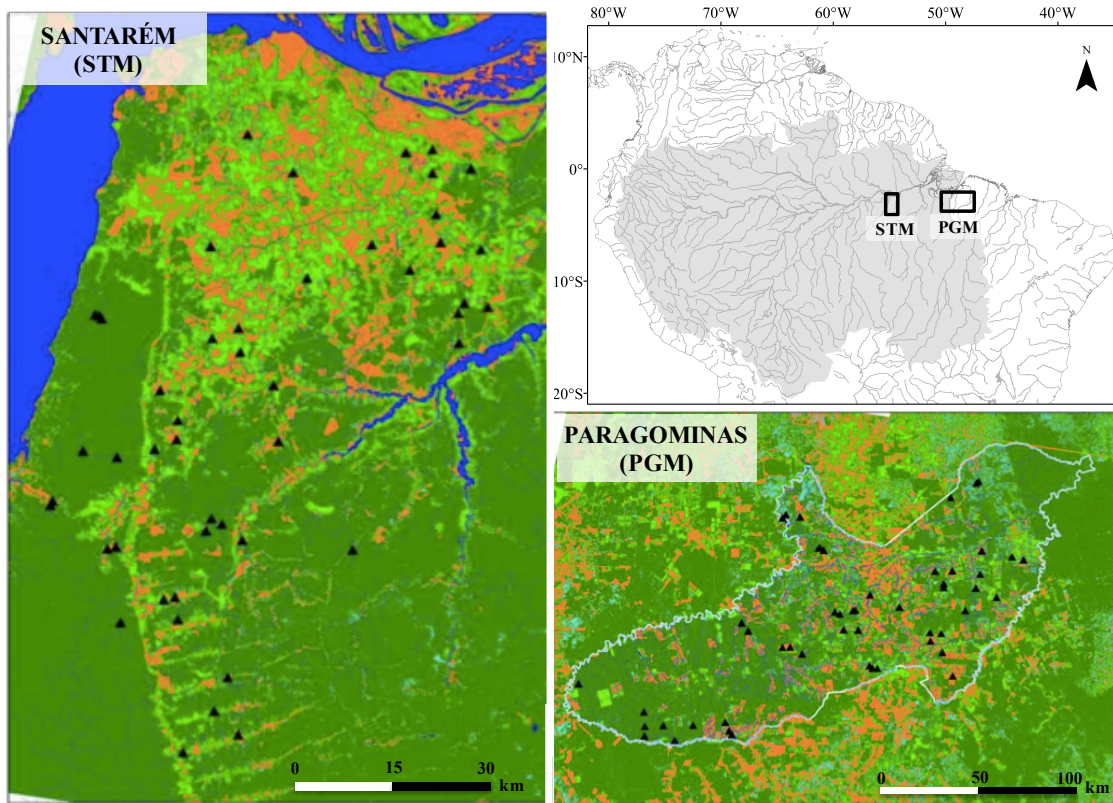


Figure A1. Sampling sites (black triangles) distributed across gradients of land use in the municipalities of Santarém (*c.* 1 million ha; 45 sites) and Paragominas (*c.* 1.9 million ha; 49 sites), eastern Brazilian Amazon. Land use classification derived from Landsat 2010 imagery, showing primary forest (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*.

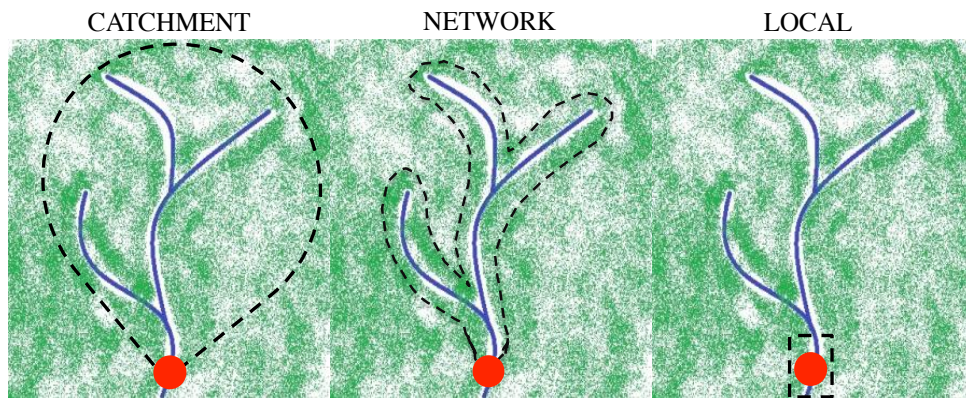


Figure A2. Representation of the three different spatial scales (dashed lines) considered for landscape analyses: the whole catchment upstream from sample site (“catchment”); 100-m wide buffer along the entire drainage network upstream from sample site (“riparian network”), and 100-m wide buffer around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

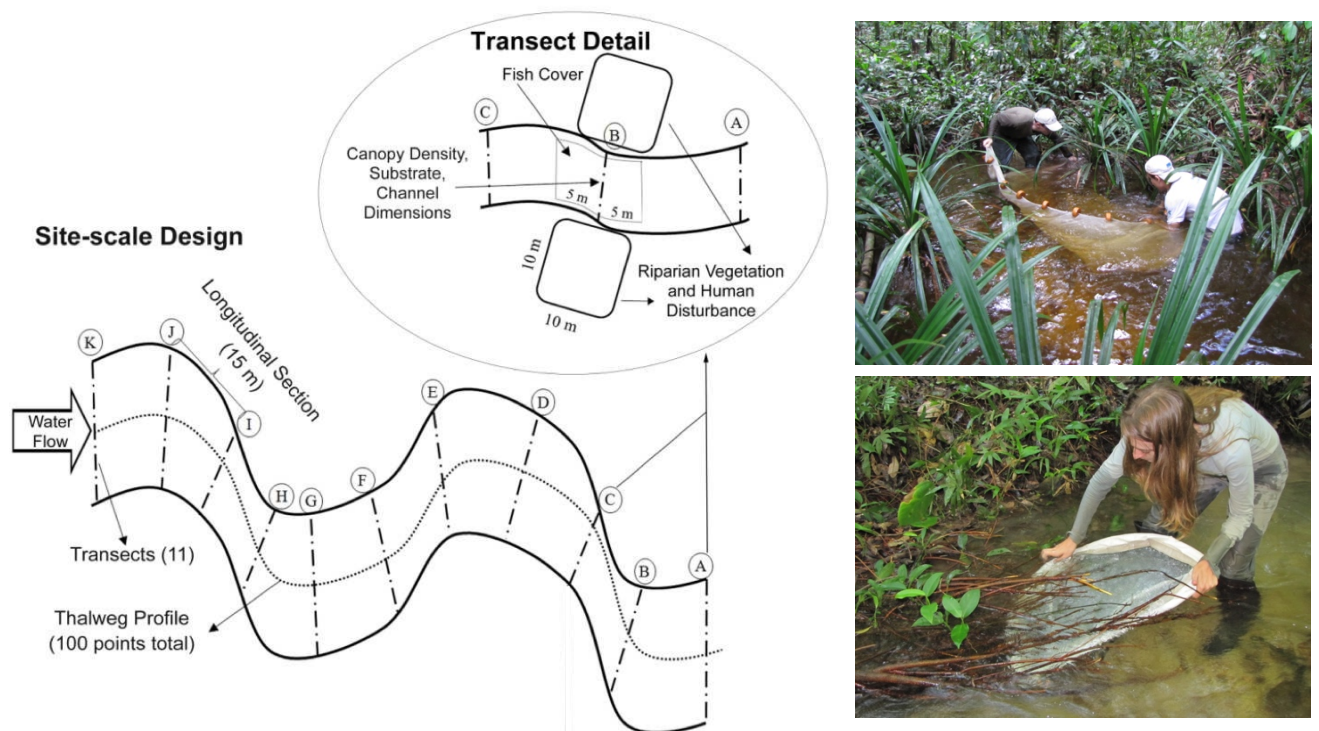


Figure A3. Schematic representation of the sampled stream reach. Each transect was named from the downstream (“A”) to upstream (“K”) and marked with flags along the stream stretch. A total of 11 transects and 10 longitudinal sections of 15 m were established. Fishes were captured using seines (top-right)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

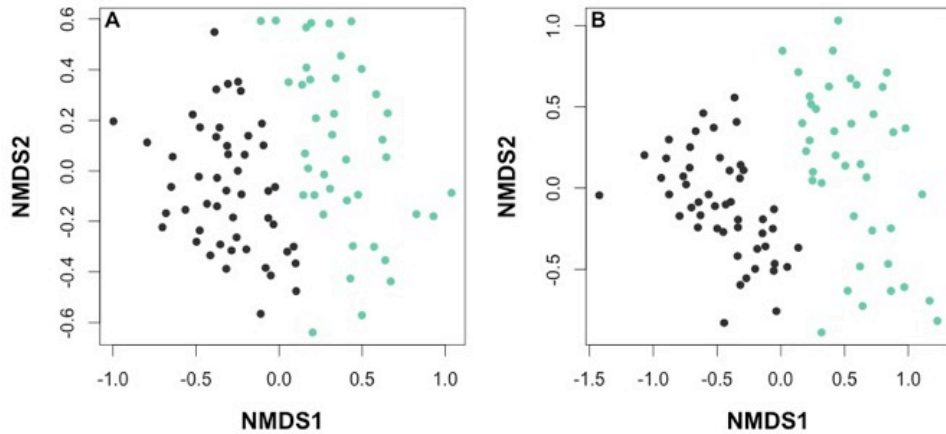


Figure A4. Non-metric Multidimensional Scaling (NMDS) ordination of sites from Santarém (n = 40; green dots) and from Paragominas (n = 49; dark gray dots) based on fish species presence/absence (A) and abundance (B) within streams.

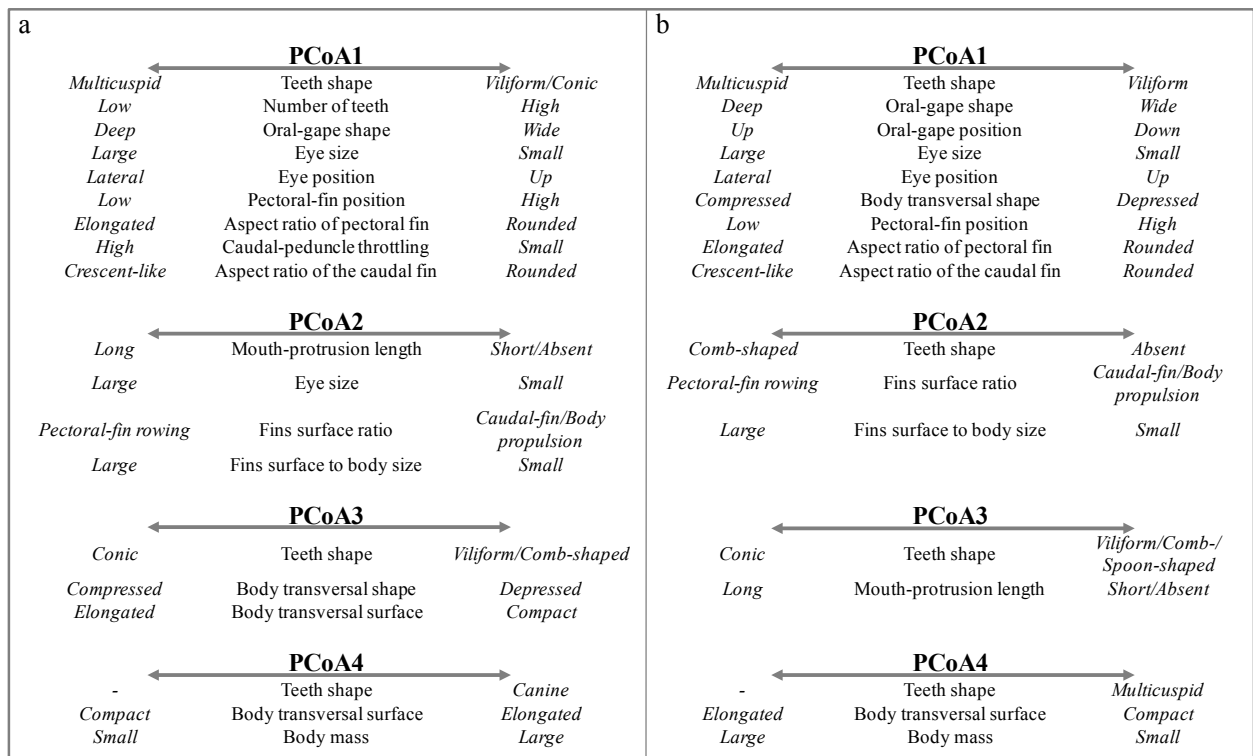


Figure A5. Position of the predominant state of each ecomorphological trait along each Principal Coordinate (PCoA) axis that composes the multidimensional functional spaces for fish species pools in Santarém (a) and Paragominas (b) sites. The functional identity (CWM) for each local assemblage is the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

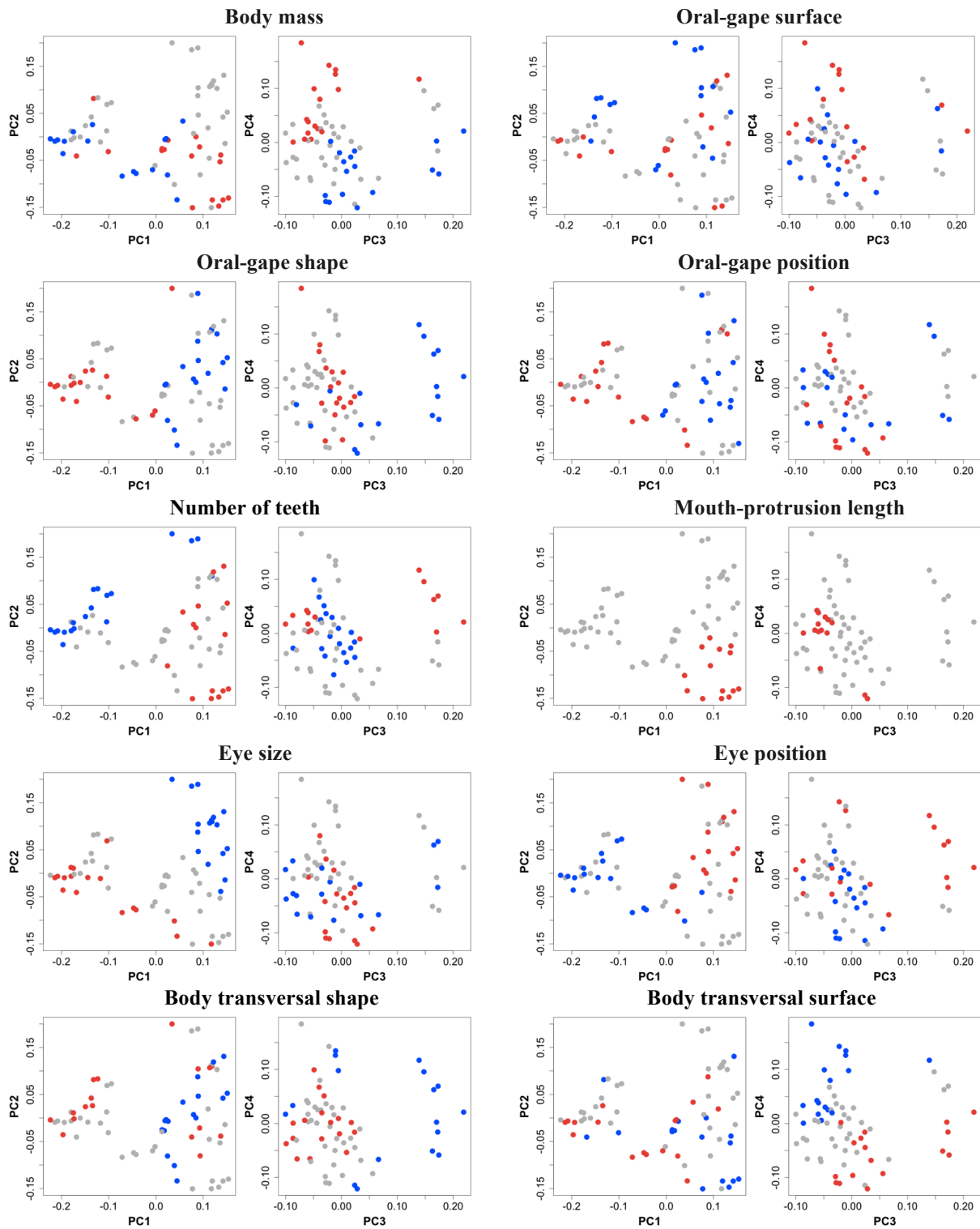


Figure A6. Four-dimensional representation of the functional space of the regional pool of stream fishes from Santarém (67 species), highlighting the distribution of each ecomorphological trait (as indicated above each pair of plots). Each plot represents two axes of a Principal Coordinate Analysis (PC), 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.

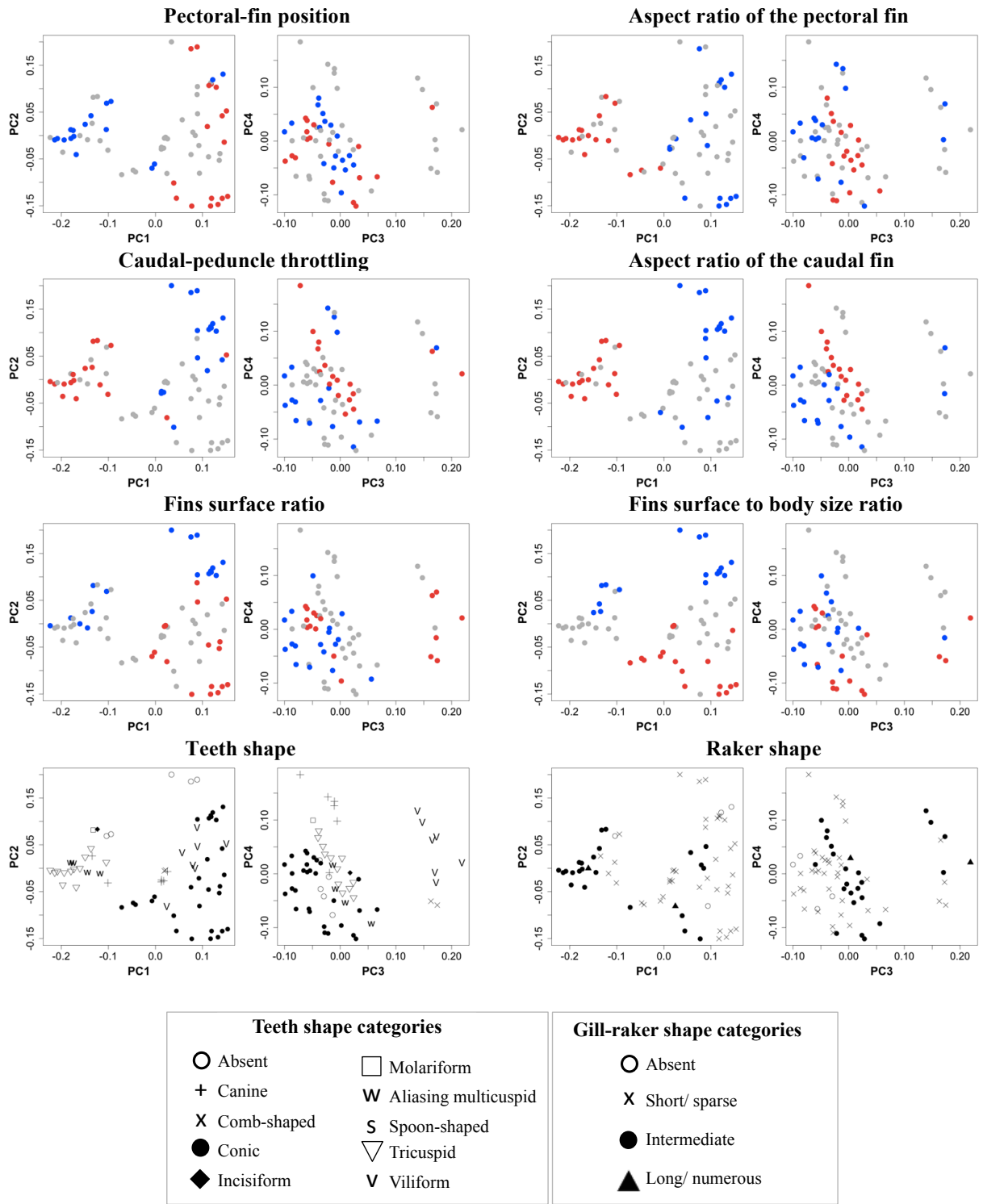


Figure A6. (continuation)

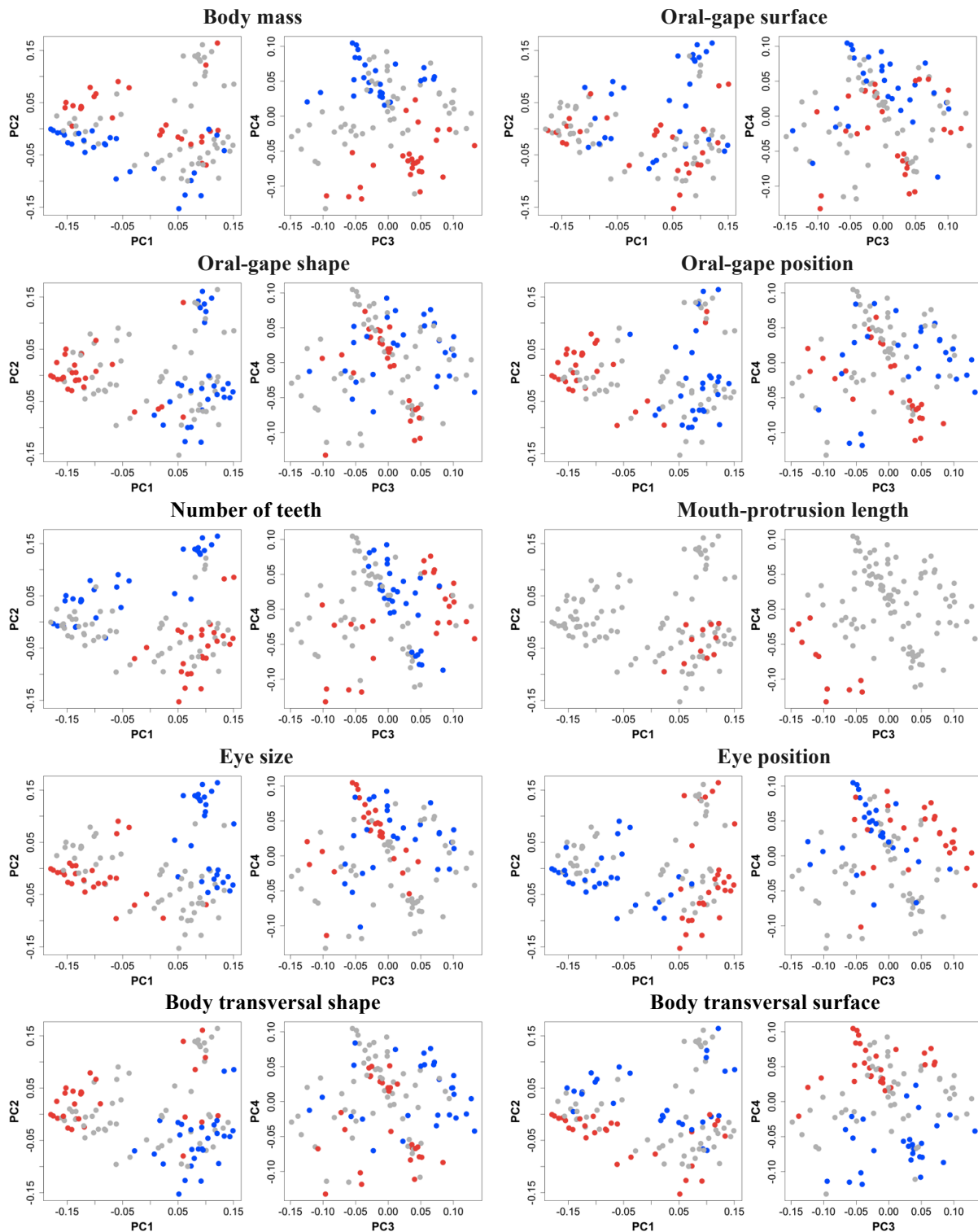


Figure A7. Four-dimensional representation of the functional space of the regional pool of stream fishes from Paragominas (112 species), highlighting the distribution of each ecomorphological trait (as indicated above each pair of plots). Each plot represents two axes of a Principal Coordinate Analysis (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.



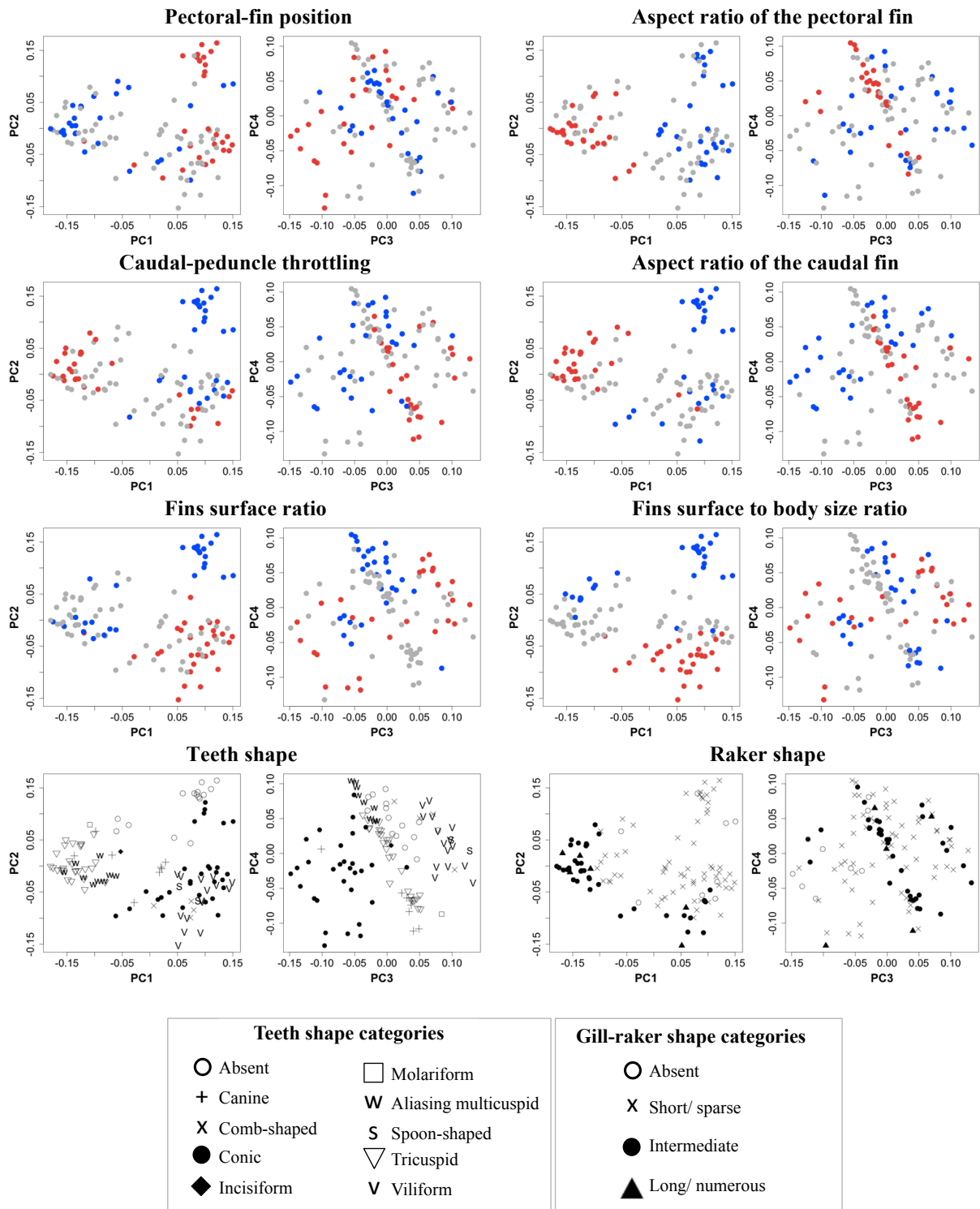


Figure A7. (continuation)

## 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
<b>Natural factors</b>							
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.
<b>Land use</b>							
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 <sup>-1</sup> .10 <sup>-3</sup>	2.1	0.0	12.0	3.1	0.0	22.6
Downstream road crossings	nbr.ha <sup>-1</sup> .10 <sup>-3</sup>	0.7	0.0	5.4	2.1	0.0	45.1
<b>Instream habitat</b>							
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 <sub>10</sub> (mm/m)	-2.3	-3.5	0.1	-1.7	-3.0	0.3
Wood volume	mm <sup>3</sup> /m <sup>2</sup>	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
<b>Local riparian deforestation</b>	<b>-0.35</b>	-	<b>-0.34</b>	<b>-0.15</b>	-	<b>-0.07</b>	<b>0.15</b>	-	-
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	-	-	-	-	-	-
<b>Upstream fragmentation</b>	<b>0.00</b>	<b>0.05</b>	<b>0.00</b>	<b>-0.06</b>	-	<b>-0.06</b>	-	-	<b>-0.05</b>
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	-	-	-	-	-	-
<b>Downstream fragmentation</b>	<b>-0.13</b>	<b>-0.20</b>	<b>-0.22</b>	<b>-0.45</b>	<b>-0.28</b>	<b>0.19</b>	<b>-0.55</b>	<b>0.41</b>	<b>-0.43</b>
Downstream fragmentation*	-0.13	-0.20	-0.09	-0.45	-0.28	0.19	-0.55	0.41	-0.43
Species richness	-	-	-0.13	-	-	-	-	-	-
<b>Catchment area</b>	<b>0.46</b>	<b>-0.21</b>	<b>0.44</b>	-	-	<b>-0.53</b>	-	-	-
Catchment area*	<b>0.46</b>	-	-	-	-	-0.35	-	-	-
Water-column depth	-	-0.21	-	-	-	-0.18	-	-	-
Species richness	-	-	0.44	-	-	-	-	-	-
<b>River distance</b>	<b>-0.32</b>	-	<b>-0.30</b>	-	-	-	-	-	-
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
<b>Local riparian deforestation</b>	<b>0.21</b>	<b>0.09</b>	<b>0.17</b>	<b>-0.19</b>	-	<b>0.03</b>	<b>0.08</b>	<b>-0.14</b>	<b>0.03</b>	-
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	-	-	-	-	-	-	-
<b>Network riparian deforestation</b>	<b>-0.35</b>	-	<b>-0.28</b>	-	-	<b>-0.27</b>	<b>-0.23</b>	-	<b>0.22</b>	-
Wood volume	-0.35	-	-	-	-	-0.27	-0.23	-	0.22	-
Species richness	-	-	-0.28	-	-	-	-	-	-	-
<b>Catchment deforestation</b>	<b>0.34</b>	<b>-0.29</b>	<b>0.27</b>	-	-	<b>0.26</b>	<b>-0.01</b>	-	<b>-0.21</b>	-
Relative bed stability	-	-0.29	-	-	-	-	-	-	-	-
Wood volume	0.34	-	-	-	-	0.26	0.22	-	-0.21	-
Water temperature	-	-	-	-	-	-	-0.23	-	-	-
Species richness	-	-	0.27	-	-	-	-	-	-	-
<b>Upstream fragmentation</b>	-	<b>0.06</b>	-	-	-	-	-	<b>-0.10</b>	-	-
Bankfull width/depth ratio	-	0.06	-	-	-	-	-	-0.10	-	-
<b>Downstream fragmentation</b>	-	-	-	-	-	-	-	<b>0.47</b>	-	-
Downstream fragmentation*	-	-	-	-	-	-	-	0.47	-	-
<b>Catchment area</b>	-	-	-	<b>-0.37</b>	<b>-0.60</b>	-	-	<b>0.30</b>	<b>0.51</b>	<b>-0.43</b>
Catchment area*	-	-	-	-0.37	-0.60	-	-	0.30	0.63	-0.43
Water-column depth	-	-	-	-	-	-	-	-	-0.12	-
<b>River distance</b>	-	-	-	-	<b>0.30</b>	-	-	<b>-0.56</b>	-	-
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.

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

### 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.

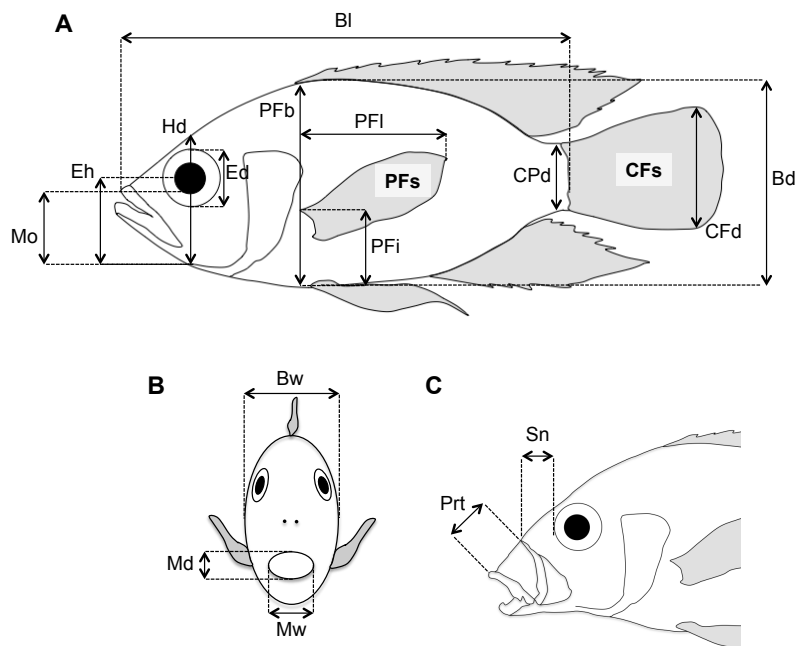


Figure A8. Morphological traits measured for fish from digital pictures (A): *Bd* body depth, *CPd* caudal-peduncle minimal depth, *CFd* caudal-fin depth, *CFs* caudal-fin surface, *PFI* distance between the insertion of pectoral fin to the bottom of the body, *Pfb* body depth at the level of the pectoral-fin 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 Apterodontidae) 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
<b>Teeth shape</b>	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)
<b>Number of teeth</b>	Mean number of teeth in upper and lower jaws	Continuous	Nature of food items captured and feeding method	adapted from Gatz (1979)
<b>Gill-raker shape</b>	Absent Short/ sparse Intermediate Long/ numerous	Ordinal	Filtering ability and gill protection	adapted from Sibbing & Nagelkerke (2001)
<b>Mouth-protrusion length</b>	$\frac{Prt}{Sn}$	Continuous	Nature of food items captured and feeding method	adapted from Gatz (1979)
<b>Oral-gape surface</b>	$\frac{Mw \times Md}{Bw \times Bd}$	Continuous	Nature/Size of food items captured	adapted from Karpouzi & Stergiou (2003)
<b>Oral-gape shape</b>	$\frac{Md}{Mw}$	Continuous	Method to capture food items	Karpouzi & Stergiou (2003)
<b>Oral-gape position</b>	$\frac{Mo}{Hd}$	Continuous	Feeding method in the water column	adapted from Sibbing & Nagelkerke (2001)
<b>Eye size</b>	$\frac{Ed}{Hd}$	Continuous	Prey detection	adapted from Boyle & Horn (2006)
<b>Eye position</b>	$\frac{Eh}{Hd}$	Continuous	Vertical position in the water column	Gatz (1979)
<b>Body transversal shape</b>	$\frac{Bd}{Bw}$	Continuous	Vertical position in the water column and hydrodynamism	Sibbing & Nagelkerke (2001)



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

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## 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 ( $\chi^2 = 455.9$ ,  $df = 180$ ,  $p = 0.01$ ). 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; FOr: 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	FOr	CWM1	CWM2	CWM4
<b>Local riparian deforestation</b>	<b>0.20</b>	-	<b>0.18</b>	<b>-0.05</b>	<b>-0.03</b>	-	-	-
Wood volume	0.04	-	-	-0.05	0.05	-	-	-
Aquatic vegetation cover	0.16	-	-	-	-0.07	-	-	-
Species richness	-	-	0.18	-	-	-	-	-
Species evenness	-	-	-	-	-	-	-	-
<b>Mechanized agriculture</b>	<b>-0.11</b>	-	<b>-0.10</b>	-	<b>-0.04</b>	-	<b>0.11</b>	-
Relative bed stability	-	-	-	-	-0.04	-	-	-
Bankfull width/depth ratio	-0.11	-	-	-	-	-	0.11	-
Species richness	-	-	-0.10	-	-	-	-	-
<b>Upstream fragmentation</b>	<b>-0.05</b>	<b>0.06</b>	<b>-0.04</b>	<b>0.02</b>	-	<b>0.08</b>	-	<b>0.06</b>
Water-column depth	-0.05	0.06	-	-	-	0.08	-	0.06
Species richness	-	-	-0.04	-	-	-	-	-
Species evenness	-	-	-	0.02	-	-	-	-
<b>Catchment area</b>	<b>0.11</b>	<b>0.08</b>	<b>0.10</b>	<b>0.02</b>	-	-	<b>-0.32</b>	<b>0.24</b>
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	-	-	-	-
<b>River distance</b>	<b>-0.17</b>	-	<b>-0.15</b>	-	-	-	-	-
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

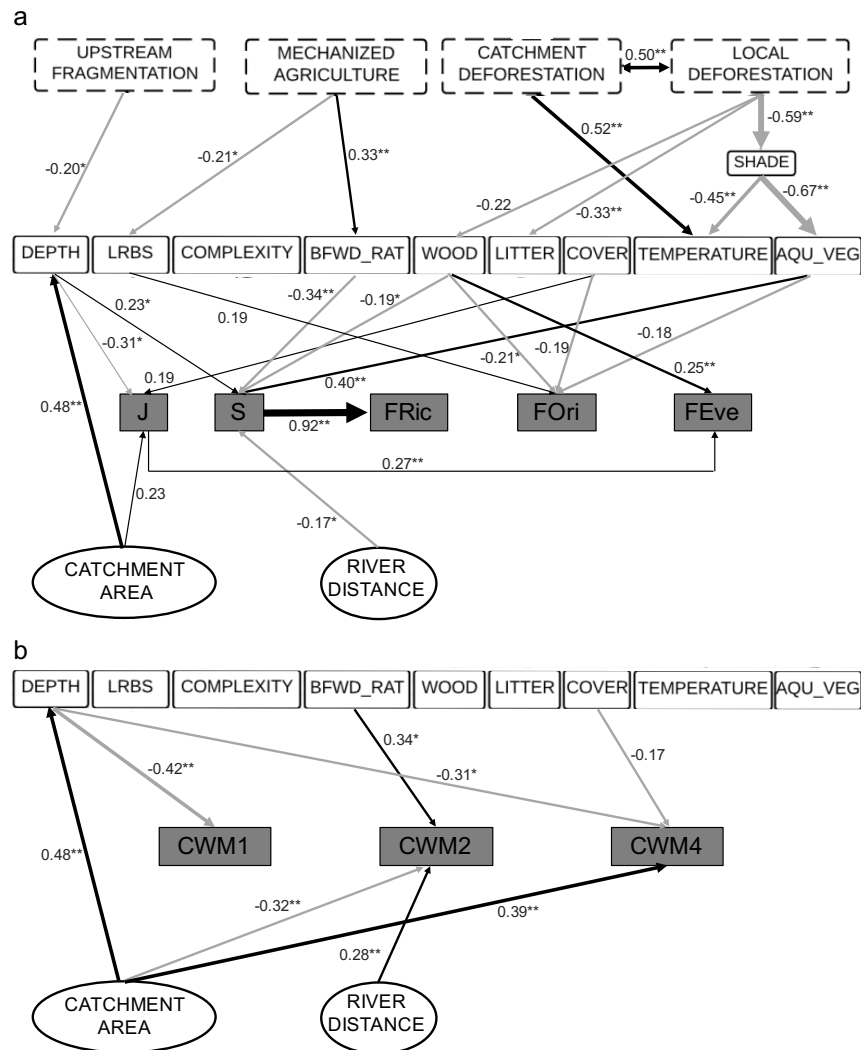


Figure A9. Structural Equation Model diagrams showing the effects of land cover and riverscape fragmentation (dashed-line rectangles), instream habitat characteristics (solid-line rectangles; see code meaning in Fig. 1), and natural landscape factors (ovals) on the structure of stream fish assemblages (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.

<b>Trait</b>	<b>PCoA1</b>	<b>PCoA2</b>	<b>PCoA3</b>	<b>PCoA4</b>
Body transversal surface	-0.10	0.16	0.34	<b>-0.53</b>
Aspect ratio of the pectoral fin	<b>-0.80</b>	0.17	0.06	-0.27
Eye size	<b>-0.65</b>	<b>0.61</b>	0.05	-0.10
Pectoral-fin position	<b>0.64</b>	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	<b>0.71</b>	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	<b>0.68</b>	<b>-0.31</b>	0.32	0.19
Body transversal shape	-0.54	-0.11	<b>-0.60</b>	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	<b>0.50</b>	0.37
Aspect ratio of the caudal fin	<b>-0.73</b>	-0.03	0.18	0.48
Body mass	0.28	-0.08	-0.36	<b>0.75</b>

### References:

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

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

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