

Full Length Research Paper

## Genetic relationships between captive and wild subpopulations of *Arapaima gigas* (Schinz, in Cuvier, 1822)

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*Arapaima gigas*, also known as pirarucu, is endemic to the Amazon basin. There is currently considerable effort being made to cultivate this species to reduce pressure on natural populations. We characterized the diversity and genetic structure of subpopulations of wild and captive *A. gigas* based on 19 microsatellite loci. Captive subpopulations of *A. gigas* exhibited less diversity than wild individuals. We also verified the existence of outlier loci under selective pressure in both subpopulations, indicating the occurrence of local adaptation in some individuals of *A. gigas*. Furthermore, we identified a high-level genetic structure among the subpopulations, with no mixing between subpopulations. The lack of mixing between populations, the local adaptation, and the genetic structure indicate that these subpopulations should be managed and isolated to prevent captive individuals from escaping into the wild, which would reduce the diversity of the wild subpopulations. We suggest a program for the genetic management of captive subpopulations to avoid the random loss of genetic variability and the selection of characteristics that are undesirable for commercial and conservation purposes.

**Key words:** Allelic diversity, osteoglossidae, conservation and management, heterozygosity, osteoglossiformes.

### INTRODUCTION

The future of aquaculture largely depends upon the effective management of the genetic resources of farmed fish. Maintaining an appropriate level of genetic diversity is critical to aquaculture production and value, and is

necessary to ensure the availability of affordable products for human consumption in poor areas worldwide. Unfortunately, most farmed fish species in Brazil have not been fully domesticated, and their wild relatives are

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preferentially used for breeding programs and related research. Furthermore, there are many species (possibly hundreds) that might have potential for aquaculture (Pullin, 2007), including *Arapaima gigas*, which is a potential candidate for Brazilian aquaculture, particularly in Northern Brazil.

*A. gigas* (pirarucu) is endemic to the Amazon basin and is the longest freshwater fish in the world, reaching 3 m in length and more than 200 kg in weight (Castello, 2004). Because of its high economic importance in the fisheries of Northern Brazil, *A. gigas* has recently been introduced into fish farms to facilitate its reproduction and rearing in captivity. This effort has increased in recent years due to the ability of *A. gigas* to adapt to a confined environment and improvements in facility management. Because *A. gigas* is the largest freshwater scaled fish in the world, it has high commercial value and has been overexploited for more than two decades (Viana et al., 2007). Near the principal cities of the Brazilian Amazon, *A. gigas* is considered commercially extinct, and fishermen have reported difficulties in catching *A. gigas* in certain areas (Goulding, 1980; Castello, 2008; Oliveira et al., 2005).

The International Union for the Conservation of Nature (IUCN) has included *A. gigas* on the red list of endangered species (Ortiz et al., 2007) and classified it in Appendix II of the Convention on the International Trade of Endangered Species of Wild Fauna and Flora (CITES), which lists species that are not necessarily extinct but may become extinct if their trade is not controlled (Viana et al., 2007).

To prevent overfishing and preserve the species, the Brazilian Institute of Environment and Natural Resources (IBAMA), a Brazilian government agency, established a minimum size of *A. gigas* for capture (1.5 m total length) in 1989. In 1990, the IBAMA enforced a fishing ban from December 1<sup>st</sup> to May 31<sup>st</sup>, which corresponds to the reproductive phase of the species. Since 1996, IBAMA and the Amazonas State Environmental Agency (SDS - Sustainable Development State Secretary) have prohibited the fishing and commercialization of *A. gigas*; fish from managed areas and fish farms are exempted from this prohibition (Arantes et al., 2007). These conservation actions were implemented concurrently with the creation of Sustainable Development Reserves (SDR) in Amazonas State, where fishing occurs with the direct involvement of local fishermen in the management of populations of this species. Therefore, annual portions (quotas) are permitted for the capture of *A. gigas* during a certain period of the year, according to the minimum size limitations. These actions have resulted in reduced fish extraction from the wild environment and increased the interest of fish farmers in the artificial management of breeders.

A new species of *Arapaima* was discovered in the Central Amazon of Brazil (Stewart, 2013a), and it was believed that the *Arapaima* was considered monotypic since 1868, with *A. gigas* is the only recognized species

(Stewart, 2013b). This species was collected near the confluence of the Solimões and Purus Rivers, and comparisons with the pirarucus Development Mamirauá shows that there are at least two species of *Arapaima* in the Amazon State.

The cultivation of freshwater fish in Brazil is expanding rapidly due to the availability of favorable areas for cultivation, the existence of an enormous river network, and the high adaptive potential of many native species in captivity. However, aquaculture practices have reduced the genetic variability of captive animals as a result of unassisted breeding or the use of a small number of founders in fish farms (Wasko et al., 2004). Both practices alter genotype frequencies over generations and result in adaptation of the species to the confinement conditions (Santos et al., 2012).

The demand for *A. gigas* is high; therefore, large-scale data on the genetic features of wild and cultivated populations are needed. The sizes of founder populations are generally limited by farming constraints, which results in the use of a few individuals as broodstock. This practice may lead to erosion of the genetic diversity of the stocks, thereby compromising industrial performance. Due to the relatively short history of large-scale *A. gigas* commercial culture, the phenotypic effects of this erosion are not yet clear.

The present study is the first to address the genetic variability of captive *A. gigas* subpopulations. This study aimed to (i) define the genetic structure of *A. gigas* populations in a selected areas by measuring the genetic heterogeneity among wild and captive populations and (ii) estimate the degree of genetic erosion of reared stocks by comparing their genetic variability with that of geographically close wild stocks.

## MATERIALS AND METHODS

### Ethics committee

The group leader, Adalberto Luis Val was granted a license for capture under the umbrella project ADAPTA (SISBIO License #29837-4). Samples from wild subpopulations were collected according to the guidelines set by the IBAMA of the Ministry of Environment. All samples were collected from anesthetized animals according to the guidelines from Brazilian Council for Ethics in the use of Experimental Animals (CONCEA) and the Ministry of Science, Technology and Innovation.

### Collection of samples

Wild *A. gigas* individuals were captured from the SDR during the legal period for managed fishing with the help of a harpoon, which was the only gear allowed. Local fishermen are licensed to harpoon the fish body (never the head) and, subsequently place fish in ice boxes to commercialize them. The spear catch is a traditional (cultural) way used by locals to minimize damage in fish meat. Captive individuals were captured with trawls with permission from two private farm owners and with the permission Ceara State Aquaculture Facility. Because these fish were intended for the local



**Figure 1.** Geographical locations of the *Arapaima gigas* sample collection sites in the Brazilian Amazon (North) and Northeastern Brazil: (A) Departamento Nacional de Obras Contra as Secas (DNOCS) Pentecoste - Ceará; (B) Fishfarm Porto Velho (PPV), Porto Velho - Rondônia, (C) Sustainable Development Reserve Mamirauá (SDRM) Tefé - Amazonas; (D) Sustainable Development Reserve Fonte Boa (SDRFB), Fonte Boa - Amazonas and (E) Fishfarm FrigoPesca (PFP-1, -2 and -3), Manacapuru - Amazonas.

market, they were anesthetized and euthanized in ice water prior to the collection of tissue samples. A total of 10 g of white muscle was collected from each *A. gigas* sample using the tweezers process for the stiletos and then transferred to sterile eppendorf tubes and immersed in liquid nitrogen. The samples were stored at a low temperature ( $-80^{\circ}\text{C}$ ) until subsequent DNA analysis.

Samples of white muscle were collected from 218 wild (two subpopulations) and captive (five subpopulations) *A. gigas* individuals from Northern and Northeastern Brazil (Figure 1). The wild individuals were collected from the SDR in Mamirauá (SDRM; 25 samples) ( $01^{\circ} 49' 00'' \text{ S}$  and  $65^{\circ} 42' 00'' \text{ W}$ ) and Fonte Boa (SDRFB; 18 samples) ( $02^{\circ} 30' 52'' \text{ S}$   $66^{\circ} 05' 33'' \text{ W}$ ) in Amazonas. All samples of captive individuals were taken from  $F_1$  progeny and acquired from three fish farms: FrigoPesca (Amazonas), from which samples were collected three different times (every 6 months) between 2009 and 2010 (PFP-1: 47 samples, PFP-2: 18 samples, and PFP-3: 32 samples) ( $03^{\circ} 17' 39'' \text{ S}$  and  $60^{\circ} 38' 04'' \text{ W}$ ); Porto Velho (Rondonia State) (PPV: 48 samples) ( $08^{\circ} 45' 43'' \text{ S}$  and  $63^{\circ} 54' 07'' \text{ W}$ ); and Estação de Piscicultura do Departamento Nacional de Obras Contra as Secas (Ceará State) (DNOCS: 30 samples) ( $03^{\circ} 47' 29'' \text{ S}$  and  $39^{\circ} 15' 58'' \text{ W}$ ).

#### DNA extraction and PCR amplification

Total genomic DNA was extracted from the 218 tissue samples using the protocol described by Sambrook et al. (1989) with some modifications. Approximately, 100 mg of tissue was digested overnight at  $37^{\circ}\text{C}$  in 0.7 ml of lysis buffer (6 M urea, 10 mM Tris-HCl, 125 mM NaCl, 1% SDS, 10 mM EDTA, pH 7.5); 10  $\mu\text{l}$  of proteinase K (Fermentas - Thermo Fisher Scientific - Suwanee, GA

USA), RNase A (Invitrogen - Life Technologies- Grand Island, NY) and 1,4-dithiothreitol (Biosynth<sup>®</sup> Chemistry and Biology Rietlistr, Switzerland) were then added. After digestion, the samples were washed with phenol-chloroform-isoamyl alcohol (Invitrogen) and isopropanol on ice. The pellet was resuspended in 50  $\mu\text{l}$  DNase-free  $\text{H}_2\text{O}$ . The quality of the extracted DNA was verified by electrophoresis in a 1.5% agarose gel using GelRed<sup>®</sup> (Invitrogen) and visualization using an L-PIX Molecular Image transilluminator (Loccus Biotecnologia - São Paulo, Brazil). The DNA was quantified using a NanoDrop<sup>®</sup> 2000 spectrophotometer (Thermo Scientific - Suwanee, GA USA).

The *A. gigas* samples were genotyped using the 10 microsatellite loci identified by Farias et al. (2003) (AgCTm1, AgCTm3, AgCTm4, AgCTm5, AgCTm7, AgCTm8, AgCam4, AgCam16, AgCam18, and AgCam26) and the 9 loci identified by Molecular Ecology Resources Primer Development (Consortium et al., 2011) (AG\_01, AG\_02, AG\_03, AG\_07, AG\_09, AG\_11, AG\_12, AG\_13, and AG\_15). Polymerase chain reactions (PCR) were performed using a 96-well Veriti<sup>™</sup> Thermal Cycler (Applied Biosystems - Life Technologies - Grand Island, NY) in a final reaction volume of 10  $\mu\text{l}$ . Each PCR contained 1.5  $\mu\text{l}$  of genomic DNA (50 ng/ $\mu\text{l}$ ), 1.0  $\mu\text{l}$  of forward primer (0.4 mM), 1.5  $\mu\text{l}$  of reverse primer (0.4 mM), 1.0  $\mu\text{l}$  6-FAM fluorescent M13 primer [14] (0.4 mM), and 5.0  $\mu\text{l}$  PCR Master Mix 2X (Fermentas) containing Taq DNA polymerase (0.05 U),  $\text{MgCl}_2$  (1.5 mM), and dNTPs (0.4 mM). The PCR cycling conditions were as follows:  $94^{\circ}\text{C}$  for 3 min; 20 cycles at  $94^{\circ}\text{C}$  for 20 s, 56 to  $58^{\circ}\text{C}$  for 20 s, and  $68^{\circ}\text{C}$  for 30 s; 25 cycles at  $94^{\circ}\text{C}$  for 20 s,  $53^{\circ}\text{C}$  for 20 s, and  $68^{\circ}\text{C}$  for 30 s, and a final extension at  $72^{\circ}\text{C}$  for 10 min. The amplified PCR products were confirmed by electrophoresis in a 1.5% agarose gel using GelRed<sup>®</sup> (Invitrogen) and visualization using an L-PIX Molecular Image transilluminator (Loccus

Biotechnology). The amplified products were genotyped on an ABI 3130xl Genetic Analyzer (Applied Biosystems) using the GeneScan Liz-500 (-250) size standard (Applied Biosystems) to determine fragment length. The alleles were scored based on the consistent pattern of their stutter peaks and the peak intensity in each individual at each locus using GeneMapper v4.0 (Applied Biosystems).

## Data analysis

### Genetic diversity

The genetic diversity of the *A. gigas* subpopulations was estimated based on the following parameters: the observed ( $H_O$ ) and expected ( $H_E$ ) heterozygosities (Fstat v2.9.3.2) (Goudet, 2001); the number of alleles per locus (Genetix v4. 5.2) (Belkhir et al., 2004); the number of private alleles or the fixation index ( $F_{IS}$ ) (GDA v1.1) (Lewis and Zaykin, 2000); the polymorphism information content (PIC) (Cervus v3.0.3) (Kalinowski et al., 2007); and the effective number of alleles per locus ( $A_E$ ). To calculate the effective number of alleles, we used the following mathematical formula:  $A_E = 1/(1 - H_E)$ . Micro-Checker v2.3 software (van Oosterhout et al., 2004) was used to test for the presence of null alleles, and their frequencies were calculated using Cervus v3.0.3 software (Kalinowski et al., 2007). The linkage disequilibrium ( $LD$ ) and Hardy-Weinberg equilibrium ( $HWE$ ) were calculated using the Fstat software, with sequential Bonferroni corrections to minimize the errors of type I microsatellite markers (Rice, 1989). The significance level was  $\alpha = 0.05$ .

### Genetic differentiation

The levels of genetic differentiation among sampling sites were analyzed using the  $F$  statistics of Wright ( $F_{IT}$ ,  $F_{IS}$  and  $F_{ST}$ ) (Weir and Cockerham, 1984) using the software Fstat and Arlequin v3.5 (Excoffier and Lischer, 2010). The indices of genetic differentiation,  $F_{ST}$  (Weir and Cockerham, 1984) and  $R_{ST}$  (Slatkin, 1995), were applied to better address the mutational models for the microsatellite data (e.g., IAM for  $F_{ST}$  (Kimura and Crow, 1964) and SMM for  $R_{ST}$  (Kimura and Ohta, 1978)). We also applied 3 estimators of genetic differentiation,  $G_{STest}$  (Nei and Chesser, 1983),  $G'_{STest}$  (Hedrick, 2005), and  $D_{est}$  (Jost, 2008). These estimators were calculated using Smogd v1.2.4 software (Crawford, 2010). Analysis of molecular variance (AMOVA) (Excoffier and Slatkin, 1995) was performed for the 7 *A. gigas* subpopulations using Arlequin software.

### Analysis of population structure

Structure v2.3.1 software (Pritchard et al., 2000; Falush et al., 2003) was used to verify the level of genetic structure among the *A. gigas* subpopulations under the ancestral admixture model, which correlates gene frequencies between subpopulations. Subsequently, the data generated a burn-in of 50,000 steps per 200,000 using the Markov chain Monte Carlo (MCMC) test for inference. We used the Structure Harvest v0.6.8 software (Earl and Holdt, 2012) to check the value of  $\Delta K$  (according to Evanno et al., 2005), which represents the highest level of hierarchy of the genetic divisions. Furthermore, we conducted a run for each test with  $K = 1$  and  $K =$  the number of sampled populations +2, with 3 replicates for each  $K$ . To complement the analysis of genetic structure, we performed a factorial correspondence analysis (FCA) (Benzecri, 1973) of the genetic distances between subpopulations using Genetix software, allowing the program to identify potential outlier individuals. The values of  $F_{ST}$  (Weir and Cockerham, 1984) and the

genetic distance ( $D_A$ ) (Nei, 1978; Cavalli-Sforza and Edwards, 1967) in pairs were constructed after comparing the subpopulations of *A. gigas*. A neighbor-joining tree (NJ) was constructed using GDA software based on genetic distance according to Nei (1978).

### Bottlenecks and detection of outlier loci ( $F_{ST}$ -outlier method)

We analyzed the occurrence of bottleneck populations (with an excess of heterozygotes) in the wild and captive *A. gigas* subpopulations using Bottleneck software (Cornuet and Luikart, 1996; Piry et al., 1999). This analysis was used to detect potential bottleneck populations of no more than  $2N_E - 4N_E$  for past generations, depending on the severity of the bottleneck and the rate of change of the loci analyzed. In this study, we applied 2 mutational models [Stepwise mutation model (SMM) and Two phase model (TPM)]. These models are the most appropriate for evaluating microsatellite data (di Rienzo et al., 1994) and were implemented at 95% (SMM) and 5% (TPM) for the various stages of mutation, ranging 12% among several steps, as recommended by Piry et al. (1999).

Outlier loci were detected using 2 different approaches. First, a coalescent-based simulation approach was used to identify outlier loci with unusually high and low  $F_{ST}$  values by comparing the observed  $F_{ST}$  values with the values expected under neutrality (Beaumont and Nichols, 1996), as implemented in the Lositan selection workbench (Antao et al., 2008). We performed an initial run with 100,000 simulations on all loci using the mean neutral  $F_{ST}$  as the preliminary value. A more accurate estimate of the mean neutral  $F_{ST}$  was obtained after the first run by excluding all loci outside the 95% confidence interval because their distribution could result from selection rather than neutral evolution. This refined estimate was used for a final set of 100,000 simulations of all loci. In addition, we used the method described by Vitalis et al. (2001), which investigates outliers in a pairwise fashion based on subpopulation-specific  $F$ -statistics. The coalescent simulations were performed with Detsel v1.0 (Vitalis et al., 2003). The null distributions were generated using the following parameters: population size before the split  $N_0 = 500$ ; mutation rate  $\mu = 0.0001$  and  $0.00001$ ; ancestral population size  $N_e = 500, 1000$  and  $10000$ ; time since the bottleneck  $T_0 = 50, 100$  and  $1000$ ; and time since the population split  $t = 100$ . The outliers were determined based on an empirical  $p$  value for each locus array of  $50 \times 50$  square cells (Vitalis et al., 2001).

## RESULTS

### Genetic diversity of wild and captive subpopulations

Summaries of the genetic and allelic diversities of the *A. gigas* subpopulations are presented in Tables 1 and S1 (Supporting information). We observed the presence of null alleles for loci AG\_03 (PPV) and AG\_15 (PPV, RDSFB and RDSM). A total of 146 alleles were observed for the 19 microsatellites markers, with an average of 7.68 alleles per locus. The total number of alleles ranged from 49 (2.58 alleles/loci; DNOCS) to 88 (4.63 alleles/loci; SDRM). We also detected the occurrence of 49 private alleles (Table 2), 23 of which had a frequency of greater than 5%. The SDRM (wild) subpopulation showed higher values for the mean number of alleles (MNA = 4.632) and allelic richness (AR = 4.258), whereas the group from DNOCS (captive) showed the

**Table 1.** Genetic diversity indices for wild and captive subpopulations of *Arapaima gigas* based on 19 microsatellite loci.

Origin	Subpopulations	Allelic diversity					Genetic diversity			
		<i>N</i>	<i>TNA</i>	<i>MNA</i>	<i>NEA</i>	<i>NPA</i>	<i>AR</i>	<i>H<sub>E</sub></i>	<i>H<sub>O</sub></i>	<i>F<sub>IS</sub></i>
Captive	PPF-1	47	51	2.684	1.621	5	2.587	0.383	0.473	-0.225**
	PPF-2	18	59	3.105	2.066	9	3.060	0.516	0.695	-0.317**
	PPF-3	32	52	2.737	1.852	4	2.680	0.460	0.551	-0.179**
	DNOCS	30	49	2.632	1.730	3	2.562	0.422	0.542	-0.266**
	PPV	48	50	2.684	1.684	5	2.567	0.406	0.482	-0.177**
Wild	SDRFB	18	75	3.947	2.004	7	3.815	0.501	0.559	-0.085 <sup>(1)</sup> **
	SDRM	28	88	4.632	2.268	16	4.258	0.559	0.591	-0.035 <sup>(1)</sup> **

*N*, sample size; *TNA*, total number of alleles; *MNA*, mean number of alleles; *NEA*, number of effective alleles; *NPA*, number of private alleles; *AR*, allelic richness; *H<sub>E</sub>*, genic diversity (expected heterozygosity in Hardy-Weinberg equilibrium); *H<sub>O</sub>*, observed heterozygosity; *F<sub>IS</sub>*, inbreeding coefficient of population; (n), number of loci that deviated from Hardy-Weinberg equilibrium (HWE); level of significance, \*\**p* < 0.05.

**Table 2.** Values of the genetic differentiation indices for the 7 subpopulations of *Arapaima gigas* based on 19 microsatellite loci.

Locos	<i>PIC</i>	<i>F<sub>IT</sub></i>	<i>F<sub>IS</sub></i>	<i>F<sub>ST</sub></i>	<i>R<sub>ST</sub></i>	<i>G<sub>Stest</sub></i>	<i>G'<sub>Stest</sub></i>	<i>D<sub>est</sub></i>
<i>AgCTm1</i>	0.454	0.381*	-0.106	0.441*	0.544*	0.358*	0.534*	0.275*
<i>AgCTm3</i>	0.657	0.157*	-0.155	0.270*	0.430*	0.204*	0.526*	0.405*
<i>AgCTm4</i>	0.707	-0.214	-0.425	0.148*	0.855*	0.143*	0.495*	0.410*
<i>AgCTm5</i>	0.823	0.347*	-0.064	0.387*	0.440*	0.306*	0.828*	0.752*
<i>AgCTm7</i>	0.235	0.214*	0.097	0.130*	0.160*	0.113*	0.148*	0.039*
<i>AgCTm8</i>	0.557	0.225*	-0.430	0.458*	0.411*	0.397*	0.645*	0.411*
<i>AgCAm4</i>	0.299	-0.210	-0.572	0.230*	0.230*	0.192*	0.285*	0.115*
<i>AgCAm16</i>	0.848	0.420*	0.091	0.362*	0.347*	0.305*	0.860*	0.798*
<i>AgCAm18</i>	0.198	-0.008	-0.080	0.067*	0.083*	0.052*	0.068*	0.017*
<i>AgCAm26</i>	0.623	-0.080	-0.174	0.216*	0.152*	0.162*	0.426*	0.315*
<i>AG_01</i>	0.756	0.277*	-0.110	0.349*	0.335*	0.306*	0.754*	0.646*
<i>AG_02</i>	0.447	0.179*	0.012	0.169*	0.156*	0.174*	0.343*	0.205*
<i>AG_03</i>	0.628	0.036	-0.298	0.257*	0.106*	0.190*	0.463*	0.337*
<i>AG_07</i>	0.653	0.128*	-0.192	0.268*	0.192*	0.219*	0.545*	0.418*
<i>AG_09</i>	0.600	0.297	-0.034	0.320*	0.433*	0.265*	0.577*	0.424*
<i>AG_11</i>	0.462	0.040	-0.238	0.225*	0.326*	0.203*	0.370*	0.210*
<i>AG_12</i>	0.733	0.243*	-0.224	0.382*	0.366*	0.330*	0.745*	0.620*
<i>AG_13</i>	0.726	-0.213	-0.501	0.192*	0.135*	0.162*	0.486*	0.387*
<i>AG_15</i>	0.452	0.337*	0.110*	0.255*	0.408*	0.257*	0.470*	0.286*
All	0.571	0.156	-0.185	0.288	0.327	0.228	0.504	0.277

*PIC*, Polymorphism information content; *F<sub>IT</sub>*, fixation index of the total population; *F<sub>IS</sub>*, fixation index of the subpopulations; *F<sub>ST</sub>*, fixation index result for the comparison of the subpopulations to the total populations; *R<sub>ST</sub>*, analogous to *F<sub>ST</sub>* of microsatellite markers; *G<sub>Stest</sub>*, estimator of relative differentiation; *G'<sub>Stest</sub>*, standardized measure of genetic differentiation; *D<sub>est</sub>*, current estimate of differentiation; level of significance, \**p* < 0.05.

lowest values (*MNA* = 2.632 and *AR* = 2.562).

The indices of genetic diversity in this study ranged from 0.473 to 0.695 (*H<sub>O</sub>*), 0.383 to 0.559 (*H<sub>E</sub>*), 0.198 to 0.848 *PIC*, and -0.317 to -0.035 (*F<sub>IS</sub>*). Of the 19 studied loci, 13 were highly informative (Table 2). However, 6 loci were monomorphic in some subpopulations of *A. gigas* (Table S1). Only the wild subpopulations had *F<sub>IS</sub>* values

close to 0 (Table 1), indicating that these subpopulations tended to approach Hardy-Weinberg equilibrium (*F<sub>IS</sub>* ~ 0; *H<sub>O</sub>* ~ *H<sub>E</sub>*). The loci *AG\_09* (RDSFB) and *AG\_15* (RDSM) significantly deviated from Hardy-Weinberg equilibrium (HWE) (*P* < 0.05, Bonferroni correction 0.0004). However, we did not detect linkage disequilibrium (LD) for the analyzed pairs of loci (*p* > 0.05).

**Table 3.**  $F_{ST}$  (above) and genetic distance values (below) for *A. gigas* subpopulations based on 19 microsatellite loci.

Variables	PFP-1	PFP2	PFP3	DNOCS	PPV	SDRFB	SDRM
PFP1	-	0.278	0.255	0.338	0.364	0.318	0.299
PFP2	0.341(0.341)	-	0.270	0.265	0.284	0.223	0.230
PFP3	0.281(0.000)	0.439(0.281)	-	0.280	0.341	0.242	0.241
DNOCS	0.422(0.000)	0.377(0.433)	0.374(0.396)	-	0.312	0.298	0.266
PPV	0.477(0.422)	0.390(0.000)	0.502(0.000)	0.397(0.000)	-	0.261	0.299
SDRFB	0.433(0.000)	0.371(0.440)	0.360(0.000)	0.458(0.377)	0.332(0.000)	-	0.135
SDRM	0.440(0.477)	0.458(0.000)	0.408(0.439)	0.429(0.000)	0.481(0.371)	0.207(0.458)	-

The genetic distances calculated according to Nei (1978) are shown; the distances calculated according to Cavalli-Sforza and Edwards (1967) are shown within parentheses.

**Table 4.** Analysis of molecular variance (AMOVA) for the 7 subpopulations of *Arapaima gigas* based on 19 microsatellite loci.

Source of variation	% var	F-stat	F-value	Standard error	p-value
Within individuals	0.866	$F_{IT}$	0.134	0.044	-
Between individuals	-0.081	$F_{IS}$	-0.103	0.043	1.000
Between populations	0.215	$F_{ST}$	0.215	0.016	0.001*

\*Indicates a significant difference at  $p < 0.05$ .

### Genetic differentiation and population structure

The indices of genetic differentiation ( $F_{ST}$ ,  $R_{ST}$ ,  $G_{Stest}$ ,  $G'_{Stest}$  and  $D_{est}$ ) were significant for all examined loci ( $p < 0.05$ ). The locus AgCam18 was the only marker that showed low ( $D_{est} = 0.017$ ) and moderate ( $R_{ST} = 0.083$ ) genetic differentiation. The average value of  $F_{ST}$  (0.288) was very close to the  $G_{Stest}$  (0.228) and  $D_{est}$  (0.277) indices (Table 2). The  $F_{ST}$  values between pairs of *A. gigas* subpopulations ranged from 0.135 to 0.364, revealing that the level of genetic differentiation between the analyzed pairs varied from high to extremely high (Table 3). The AMOVA revealed that the distribution of genetic variability was 21.5% among the subpopulations and 86.6% among individuals of the subpopulations (Table 4).

We verified the occurrence of genetic structure among the *A. gigas* subpopulations with distinct groups (Figure 2); the clusters were based on the data inferred from differences in allelic frequencies. The average association coefficient ( $q$ ) for each subpopulation ( $K = 7$ ) showed that the individuals of *A. gigas* are distributed (Table S2) in specific agglomerations ( $q > 0.9$ ), resulting in a high-resolution  $q$  value and indicating that no subpopulation was mixed. The FCA yielded values of 6.61 and 6.32% for Axes 1 and 2, respectively; the dispersion graph of those parts is shown in Figure 3. Notably, there was a clear separation of subpopulations in the wild, with Axis 1  $> 0$  and Axis 2  $< 0$ , and the formation of two *A. gigas* populations: one group consisting of the subpopulations PFP-1, PFP-2, PFP-3,

and DNOCS (group 1; Axis 1  $< 0$ ), and a second group consisting of the PPV, SDRM, and SDRFB subpopulations (group 2, Axis 1  $> 0$ ) (Figure 3). The separation of the subpopulations into these two distinct groups by FCA was consistent with the data obtained for the NJ tree based on the genetic distances between the subpopulations (Figure 4).

### Bottlenecks and detection of outlier loci ( $F_{ST}$ -outlier method)

To detect bottlenecks, we eliminated the loci that drifted from Hardy-Weinberg equilibrium because the presence of these loci could strongly influence the final results and because of the effect of selection on the over-dominant loci with an excess of heterozygotes (Luikart and Cornuet, 1998). Furthermore, we verified the minimum number of microsatellite markers needed for an analysis of recent genetic bottlenecks, as the model for mutational markers could influence the final results if an inappropriate number of SSR loci were used.

We detected a recent population bottleneck in all analyzed subpopulations of *A. gigas*. Both the Sign and Wilcoxon tests showed a significant excess of heterozygotes for the TPM mutational model. However, only the captive subpopulations showed an excess of heterozygotes using the Sign test. The mutational model SMM was significant only for the subpopulations PFP-2 and PFP-3 using the Wilcoxon test.

We observed 10 outlier loci in the *A. gigas* subpopulations;

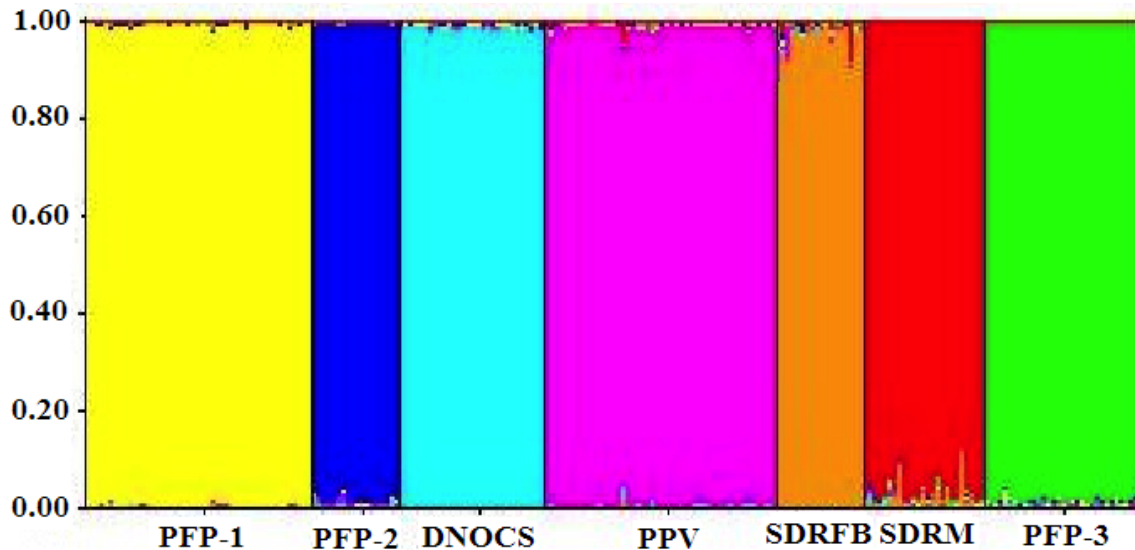


Figure 2. Structural analysis results for the 7 subpopulations based on 19 microsatellite loci. K = 7.

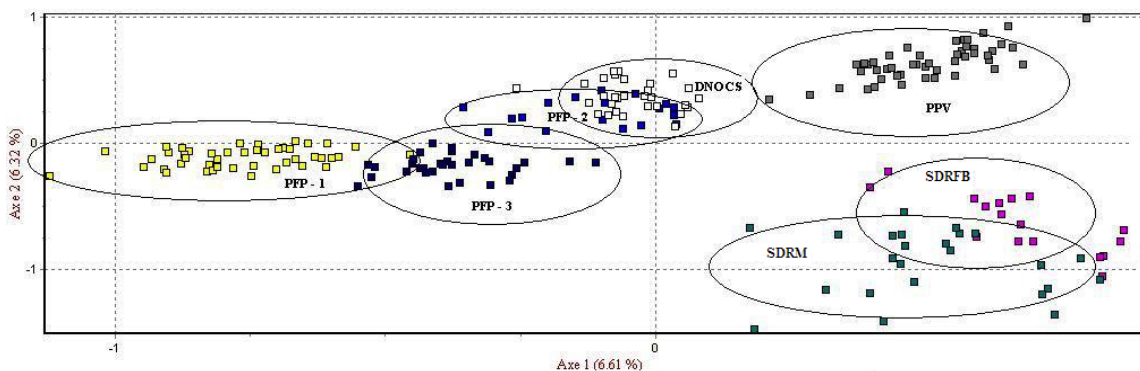


Figure 3. Factorial correspondence analysis (FCA) of the 7 subpopulations based on 19 microsatellite loci.

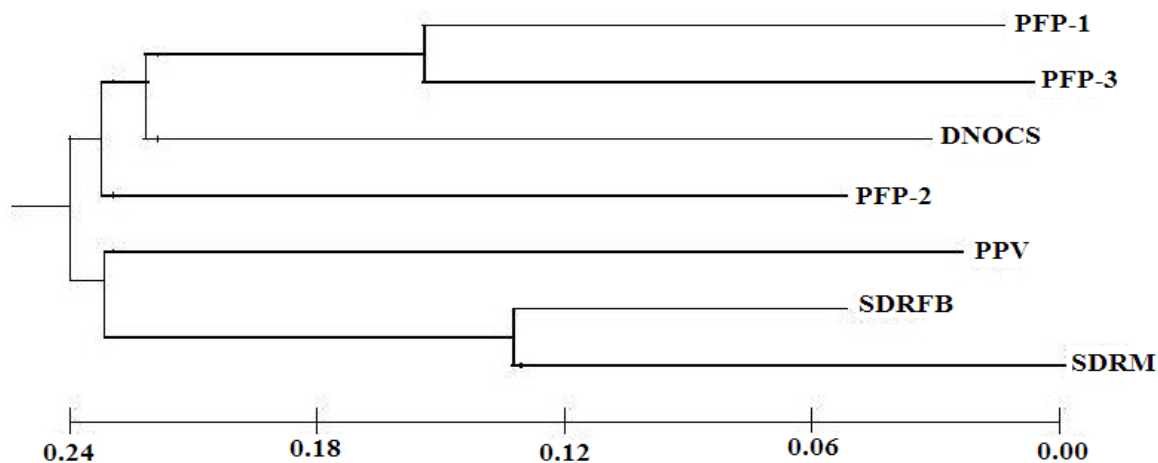
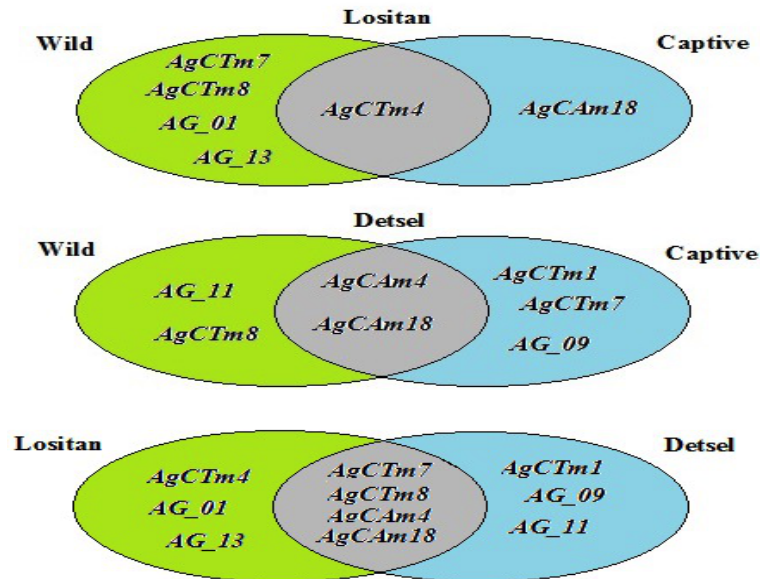


Figure 4. Neighbor-joining dendrogram for wild and captive subpopulations of *Arapaima gigas* based on 19 microsatellite loci.





**Figure 5.** Outlier loci detected among the 7 studied subpopulations according to Beaumont and Nichols (1996) and Vitalis et al. (2001) using Lositan (Antao et al. 2008) and Detsel v1.0 (Vitalis et al. 2003), respectively.

four of these loci were identified as common to all subpopulations by Lositan and Detsel software (Figure 5), which suggests that these four loci may be related to the local adaptation of *A. gigas*. The Lositan program identified four outlier loci with balanced selective pressure for the 2 subpopulations of wild and captive specimens. Furthermore, we detected a locus with positive selective pressure for wild individuals, while the remaining loci were considered neutral markers (Figure S1).

## DISCUSSION

### Genetic differences between wild and captive subpopulations

According to Ellegren and Sheldon (2008), populations are usually in evolutionary equilibrium; however, evolutionary responses may be hidden due to deterioration or loss of the environment. In addition, the connectivity between populations plays a crucial role in the maintenance of genetic variation, particularly in small populations strongly affected by genetic drift (Broquet et al., 2010). Genetic analyses of 7 subpopulations of *A. gigas* using 19 microsatellite markers revealed that most of the markers were highly polymorphic, with 13 loci showing values of PIC > 0.5 (Table 2). The results also revealed the occurrence of moderate genetic diversity in *A. gigas* subpopulations, indicating that the evolutionary potential of the wild individuals from the SDR is greater than that of the captive individuals, as expected (Table

1). Hedrick (2001) reported that the pattern of variation within a given variable population generally consists of neutral alleles, that is, the equilibrium is predicted by a reduction of variation through genetic drift and an increase in variation by random mutation. Therefore, even when a population is small, selection may act on the variation in a particular gene, but genetic drift acts more strongly than selection on the allele frequencies.

An excess of heterozygotes was observed in all *A. gigas* populations (Table 1). We also observed decreased heterozygosity at the *AgCAm16* locus in all the domesticated and wild populations, which suggests a recent evolutionary history because this locus is predicted to be under intensive selective pressure. According to Barroso et al. (2005), deficiency in heterozygous loci may occur due to positive selection, improvement of the relatedness between individuals, and population structure. We observed higher allelic richness in wild subpopulations (SDRFB and SDRM) compared to the captive subpopulations; the observed values are consistent with those reported by Silva (2008) for individuals of *A. gigas* in the Jarauá and Maraã lakes (SDRM). Araripe et al. (2013) investigated the wild subpopulations of *A. gigas* in a large geographical area; based on analyses of 7 informative microsatellite regions, they proposed that the genetic differentiation between subpopulations should increase with increasing geographical distance between them and that the differences among populations separated by geographical distances greater than 1300 km could be caused by historical bottlenecks in population size, in



light of the sedentary behavior of the species.

Here, we observed that the average genetic differentiation among all subpopulations ( $F_{ST}$ ) was 21.5% ( $p < 0.05$ ), demonstrating the high discrimination of the seven studied subpopulations (Figure 2) and the absence of mixtures (Table S2). This genetic differentiation suggests that the captive subpopulations are increasingly isolated due to lack of gene flow between fish farms, which merits further consideration. However, gene flow is also limited between individuals of the wild subpopulations of the SDR. According to Teixeira (2008), *A. gigas* individuals caught in the wild may not represent the total population because a group may have descended from one pair of individuals. According to Glover et al. (2011), genetic differences have been observed between Atlantic salmon fry in fish sites populated for commercial reproduction from farms of the same company, indicating that the captive environment accelerates genetic differentiation. However, Hedrick (1999) reported that the number of highly polymorphic microsatellite  $F_{ST}$  might be underestimated and that such an underestimate could influence the observed proportion of heterozygotes in subpopulations compared to the total population. In this context, Hartl and Clark (2010) reported that the estimated  $F$  statistic must correct the effects of sampling and the limited number of subpopulations, and suggested that new indices would provide a correction of the values of  $F_{ST}$ .

The recent bottleneck in captive subpopulations is certainly due to the founder effect, which results from the use of a small number of individuals to establish reproductive stocks in fish farms. Furthermore, the lack of allelic richness in captive subpopulations may have contributed to the genetic signature of a new bottleneck (Broquet et al., 2010). These results reinforce the idea that the small number of breeding stations in fish farms may contribute to the genetic deterioration of captive populations.

The bottleneck detected in wild subpopulations is likely due to intense fishing activity in recent years. Furthermore, the practice of selective fishing in the SDR has likely decreased breeding inventories and, subsequently, the effective population size. A decrease in wild fish stocks was reported in the mid-1990s, when the *A. gigas* production reached 207.5 tons, compared with the previous decade, when production was 1,751 tons (Venturiere and Bernardino, 1999). Luikart and Cornut (1998) reported that natural populations show changes in the frequency of heterozygotes when a stock experiences a recent bottleneck.

We observed that the *A. gigas* subpopulations are undergoing selection, leading to local adaptation to the new environmental conditions that the species has been recently exposed to (Figure 5). We observed four loci with balanced and positive selection in the wild groups. In the captive groups, we identified two loci with balanced selection. However, when all groups were considered, we

observed six loci with positive selection, indicating the existence of local adaptive processes in the wild and captive subpopulations. According to Orr (1998), genotyping many loci is likely important to identify complex adaptive differences between populations. The adaptive complexity provided by genotypic differentiation is directly related to balanced selection, which is common in confined populations but rare in wild populations. Furthermore, balanced selection, which favors heterozygotes, is more frequent than selection favoring homozygotes, thereby maintaining this variation (Amos and Balmford, 2001). The balanced selection of wild *A. gigas* populations observed in this study is likely due to a recent bottleneck experienced by these subpopulations due to over-fishing.

Local adaptations might be lost through intraspecific hybridization; therefore, actions that increase the amount of genetic exchange among locally adapted populations could be harmful. According to Utter (2004) and Einum and Fleming (1997), the release of individuals from hatcheries or their escape from aquaculture ponds could harm wild populations through intraspecific hybridization and the loss of local adaptations. Nunes et al. (2011) suggested that the identification of loci with adaptive importance is a key step toward understanding the process of speciation in natural populations because these loci are responsible for phenotypic variations that affect the fitness of the species in different environments. According to Sønstebo et al. (2007) and Vasemägi et al. (2005), analysis of the genetic differences between the captive broodstocks and wild populations is also important because the specific genes of each population reflect local adaptability; consequently, the survival of juveniles will be affected if the populations are mixed. Our results indicate that this species requires management and conservation.

### Implications for management and conservation

There is a global need to preserve genetic resources by maintaining species and their genetic diversities. The identification of actions that will minimize the effects of genetic changes (or losses) within biological populations is one of the primary mechanisms for maintaining variable and genetically healthy populations (Boettcher et al., 2010). According to He et al. (2012), microsatellite markers, in combination with recent statistical methodologies, represent a useful tool for the conservation and management of endangered species. For *A. gigas* subpopulations, allelic richness should be maintained and conserved, with a particular focus on preserving the existing rare alleles within populations, as suggested by Pérez-Ruzafa et al. (2006). Genetic information is also needed to aid the understanding of the current level of conservation of endangered species (Laikre et al., 2009).

Conservation projects focusing on the management and conservation of the genetic diversity of endangered species must consider the likely environmental changes (Boettcher et al., 2010) caused by stochastic events or human activity. Our results suggest that subpopulations of *A. gigas* have had independent evolutionary trajectories, and thus effective conservation measures should focus on preserving the genetic integrity of each subpopulation separately. Therefore, we suggest a more detailed management of breeding groups and periodic monitoring of wild populations.

Hrbek et al. (2005) proposed the use of a large group of matrices of *A. gigas* (founders) in fish farms, regardless of their geographical origin, thereby minimizing the potential loss of genetic diversity due to founder effects. Furthermore, it has been suggested that confined populations be supplemented with wild individuals from selected areas to maintain high genetic diversity in confinement systems. However, before we consider maintaining or restoring the genetic diversity, we should be alert to individuals collected from nature that served as new breeding on fish farms, as these new breeding, can they bring in parasites from fish farms that might jeopardize the survival of older breeding and consequently reduce the effective size and negatively affect the genetic diversity of these populations.

In addition, we suggest the rotation of *A. gigas* groups within and between fish farms to maintain the evolutionary potential of the species and avoid greater adaptation to captive systems. *A. gigas* fingerlings from several wild and captive breeders could also be distributed to fish farmers. However, the formation of closely related couples should be avoided to reduce consanguinity, which could compromise the genetic health of *A. gigas* lots for future distribution.

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## Conflict of Interest

The author(s) have not declared any conflict of interest.

## REFERENCES

- Agata K, Alassad S, Almeida-Val VMF, Álvarez-Dios JA, Barbisan F, Beadell JS, Beltrán JF, Benítez M, Bino G, Bleay C, Bloor P, Bohlmann J, Booth W, Boscarri E, Caccone A, Campos T, Carvalho BM, Clímaco GT, Clobert J, Congiu L, Cowger C, Dias G, Doadrio I, Farias IP, Ferrand N, Freitas FD, Fusco G, Galetti PM, Gallardo-Escárate C, Gaunt MW, Ocampo ZG, Gonçalves H, Gonzales EG, Haye P, Honnay O, Hyseni C, Jacquemyn H, Jowers MJ, Kakezawa A, Kawaguchi E, Keeling C, Kwan Y-S, la Spina M, Lee W-O, Lesniewska M, Li Y, Liu H, Liu X, Lopes S, Martínez P, Meeus S, Murray BW, Nunes AG, Okedi LM, Ouma JO, Pardo BG, Parks R, Paula-Silva MN, Pedraza-Lara C, Perera OP, Pino-Querido A, Richard M, Rossini BC, Samarasekera NG, A Sánchez, Sanchez JA, Santos CHA, Shinohara W, Soriguer RC, Sousa ACB, Sousa CFS, Steves VM, Tejedo M, Valenzuela-Bustamante M, van de Vliet MS, Vandepitte K, Vera M, Wandeler P, Wang W, Won Y-J, Yamashiro A, Yamashiro T, Zhu C. Molecular Ecology Resources Primer Development Consortium (2011). Permanent genetic resources added to molecular ecology resources database 1 December 2010 – 31 January 2011. *Mol. Ecol. Resour.* 11:586-589. <http://dx.doi.org/10.1111/j.1755-0998.2011.03004.x>
- Amos W, Balmford A (2001). When does conservation genetics matter? *Heredity* 87:257-265. <http://dx.doi.org/10.1046/j.1365-2540.2001.00940.x>
- Antao T, Lopes A, Lopes RJ, Beja-Pereira A, G Luikart (2008). LOSITAN: a workbench to detect molecular adaptation based on a FST-outlier method. *BMC Bioinformatics* 9:323. <http://dx.doi.org/10.1186/1471-2105-9-323>
- Arantes CC, Castello L, Garcez DS (2007). Variações entre contagem de *Arapaima gigas* (Schinz) (Osteoglossomorpha, Osteoglossidae) feitas por pescadores individualmente em Mamirauá, Brasil. *Pan-Am. J. Aquat. Sci.* 2(3):263-269.
- Araripe J, Rêgo PS, Queiroz H, Sampaio I, Schneider H (2013). Dispersal capacity and genetic structure of *Arapaima gigas* on different geographic scales using microsatellite markers. *Plos One* 8(1):e54470. <http://dx.doi.org/10.1371/journal.pone.0054470>
- Barroso RM, Hilsdorf AWS, Moreira HLM, Cabello PH, Traub-Cseko YM (2005). Genetic diversity of wild and cultured populations of *Brycon opalinus* (Cuvier, 1819) (Characiforme, Characidae, Bryconinae) using microsatellites. *Aquaculture* 247:51-65. <http://dx.doi.org/10.1016/j.aquaculture.2005.02.004>
- Beaumont MA, Nichols RA (1996). Evaluating loci for use in the genetic analysis of population structure. *Proc. R. Soc. B* 363:1619-1626. <http://dx.doi.org/10.1098/rspb.1996.0237>
- Belkhir K, Borsari P, Chikhi L, Raufaste N, Bonhomme F (2004). GENETIX 4.05, logiciel sous Windows TM pour la génétique des populations. Montpellier, France: Laboratoire Génome, Populations, Interactions, CNRS UMR 5171, Université de Montpellier II.
- Benzecri JP (1973). L'Analyse des données. Vol 2: L'Analyse des Correspondances. Paris: Dunod.
- Boettcher PJ, Tixier-Boichard M, Toro MA, Simianer H, Eding H, Gandini G, Joost S, Garcia D, Coli L, Ajmone-Marsan P, GLOBALDIV Consortium (2010). Objectives, criteria and methods for using molecular genetic data in priority setting for conservation of animal genetic resources. *Anim. Genet.* 41:64-77. <http://dx.doi.org/10.1111/j.1365-2052.2010.02050.x>
- Broquet T, Angelone S, Jaquiere J, Joly P, Lena JP, Lengagne T, Plenet S, Luquet E, Perrin N (2010). Genetic bottlenecks driven by population disconnection. *Conserv. Biol.* 24(6):1596-1605. <http://dx.doi.org/10.1111/j.1523-1739.2010.01556.x>
- Castello L (2008). Lateral migration of *Arapaima gigas* in floodplains of the Amazon. *Ecol. Freshw. Fish* 17:38-46. <http://dx.doi.org/10.1111/j.1600-0633.2007.00255.x>
- Castello L (2004). A method to count pirarucu: fishers, assessment and management. *N. Am. J. Fish Manage* 24:379-389. <http://dx.doi.org/10.1577/M02-024.1>
- Cavalli-Sforza LL, Edwards AWF (1967). Phylogenetic analysis: models and estimation procedures. *Am. J. Hum. Genet.* 19:233-257.
- Cornuet JM, Luikart G (1996). Description and power analysis of two tests for detecting recent population bottlenecks from allele frequency data. *Genetics* 144:2001-2014.
- Crawford NG (2010). SMOGD: software for the measurement of genetic diversity. *Mol. Ecol. Res.* 10:556-557. <http://dx.doi.org/10.1111/j.1755-0998.2009.02801.x>
- di Rienzo A, Peterson AC, Garza JC, Valdes AM, Slatkin M, Freimer NB (1994). Mutational processes of simple sequence repeat loci in human populations. *Proc. Natl. Acad. Sci. USA* 91:3166-3170. <http://dx.doi.org/10.1073/pnas.91.8.3166>
- Earl DA, von Holdt BM (2012). Structure Harvester: a website and

- program for visualizing structure output and implementing the Evanno method. *Conserv. Gen. Res.* 4(2):359-361. <http://dx.doi.org/10.1007/s12686-011-9548-7>
- Einum S, Fleming IA (1997). Genetic divergence and interactions in the wild among native, farmed and hybrid Atlantic salmon. *J. Fish Biol.* 50:634-651. <http://dx.doi.org/10.1111/j.1095-8649.1997.tb01955.x>
- Ellegren H, Sheldon BC (2008). Genetic basis of fitness differences in natural populations. *Nature* 452:169-175. <http://dx.doi.org/10.1038/nature06737>
- Evanno G, Regnaut S, Goudet J (2005). Detecting the number of clusters of individuals using the software structure: a simulation study. *Mol. Ecol.* 14(8):2611-2620. <http://dx.doi.org/10.1111/j.1365-294X.2005.02553.x>
- Excoffier L, Lischer HEL (2010). Arlequin suite ver 3.5: a new series of programs to perform population genetics analyses under Linux and Windows. *Mol. Ecol. Res.* 10:564-567. <http://dx.doi.org/10.1111/j.1755-0998.2010.02847.x>
- Excoffier L, Slatkin M (1995). Maximum-likelihood estimation of molecular haplotype frequencies in a diploid population. *Mol. Biol. Evol.* 12:921-927.
- Falush D, Stephens M, Pritchard JK (2003). Inference of population structure using multilocus genotype data: linked loci and correlated allele frequencies. *Genetics* 164:1567-1587.
- Farias IP, Hrbek T, Brinkmann H, Sampaio I, Meyer A (2003). Characterization and isolation of DNA microsatellite primers for *Arapaima gigas*, an economically important but severely over-exploited fish species of the Amazon basin. *Mol. Ecol. Notes* 3:128-130. <http://dx.doi.org/10.1046/j.1471-8286.2003.00375.x>
- Goudet J (2001). FSTAT, a program to estimate and test gene diversities and fixation indices (version 2.9.3.2). Updated from Goudet J (1995) FSTAT version 1.2: a computer program to calculate F-statistics. *J. Hered.* 86:485-486.
- Goulding M (1980). *The fishes and the forest*. Los Angeles, CA, USA: University of California Press. P. 200.
- Glover KA, Skaala Ø, Søvik AGE, TA Helle (2011). Genetic differentiation among Atlantic salmon reared in sea-cages reveals a non-random distribution of genetic material from a breeding programme to commercial production. *Aquac. Res.* 42:1323-1331. <http://dx.doi.org/10.1111/j.1365-2109.2010.02720.x>
- Hartl DL, Clark AG (2010). *Princípios de genética de populações*, 4th Edition. Porto Alegre: Artmed. P. 660.
- He L, Xie Y-N, Lu W, Wang Y, Chen L-L, Mather PB, Zhao Y-L, Wang Y-P, Wang Q (2012). Genetic diversity in three redclaw crayfish (*Cherax quadricarinatus*, von Martens) lines developed in culture in China. *Aquac. Res.* 43:75-83. <http://dx.doi.org/10.1111/j.1365-2109.2011.02802.x>
- Hedrick PW (2005). A standardized genetic differentiation measure. *Evolution* 59:1633-1638. <http://dx.doi.org/10.1111/j.0014-3820.2005.tb01814.x>
- Hedrick PW (2001). Conservation genetics: where are we now? *Trends Ecol. Evol.* 16(11):629-636. [http://dx.doi.org/10.1016/S0169-5347\(01\)02282-0](http://dx.doi.org/10.1016/S0169-5347(01)02282-0)
- Hedrick PW (1999). Perspective: highly variable loci and their interpretation in evolution and conservation. *Evolution* 53:313-318. <http://dx.doi.org/10.2307/2640768>
- Hrbek T, Farias IP, Crossa M, Sampaio I, Porto JIR, Meyer A (2005). Population genetic analysis of *Arapaima gigas*, one of the largest freshwater fishes of the Amazon basin: implications for its conservation. *Anim. Conserv.* 8:297-308. <http://dx.doi.org/10.1017/S1367943005002210>
- Jost L (2008). GST and its relatives do not measure differentiation. *Mol. Ecol.* 17(18):4015-4026. <http://dx.doi.org/10.1111/j.1365-294X.2008.03887.x>
- Kalinowski ST, Taper ML, Marshall TC (2007). Revising how the computer program CERVUS accommodates genotyping error increases success in paternity assignment. *Mol. Ecol.* 16:1099-1106. <http://dx.doi.org/10.1111/j.1365-294X.2007.03089.x>
- Kimura M, Crow J (1964). The number of alleles that can be maintained in a finite population. *Genetics* 49:725-738.
- Kimura M, Ohta T (1978). Stepwise mutation model and distribution of allelic frequencies in a finite population. *Proc. Natl. Acad. Sci. USA* 75:2868-2872. <http://dx.doi.org/10.1073/pnas.75.6.2868>
- Laikre L, Nilsson T, Primmer CR, Ryman N, Allendorf FW (2009). Importance of genetics in the interpretation of favourable conservation status. *Conserv. Biol.* 23(6):1378-1381. <http://dx.doi.org/10.1111/j.1523-1739.2009.01360.x>
- Lewis PO, Zaykin D (2000). *Genetic Data Analysis: computer program for the analysis of allelic Data*, Version 1.0. (d15). Storrs, CT: University of Connecticut.
- Luikart G, Cornut JM (1998). Empirical evaluation of a test for identifying recently bottlenecked populations from allele frequency data. *Conserv. Biol.* 12:228-237. <http://dx.doi.org/10.1111/j.1523-1739.1998.96388.x>
- Nei M (1978). Estimation of average heterozygosity and genetic distance from a small number of individuals. *Genetics* 89: 583-590.
- Nei M, Chesser RK (1983). Estimation of fixation indices and gene diversities. *Ann. Hum. Genet.* 47(3):253-259. <http://dx.doi.org/10.1111/j.1469-1809.1983.tb00993.x>
- Nunes VL, Beaumont MA, Butlin RK, Paulo OS (2011). Multiple approaches to detect outlier in a genome scan for selection in ocellated lizards (*Lacerta lepida*) along an environmental gradient. *Mol. Ecol.* 20:193-205. <http://dx.doi.org/10.1111/j.1365-294X.2010.04936.x>
- Oliveira V, Poletto SL, Venere PC (2005). Feeding of juvenile pirarucu (*Arapaima gigas*, Arapaimidae) in their natural environment, lago Quarto Bocas, Araguaiana – MT, Brazil. *Neotrop Ichthyol* 3(2):312-314. <http://dx.doi.org/10.1590/S1679-62252005000200010>
- Orr HA (1998). The population genetics of adaptation: the distribution of factors fixed during adaptive evolution. *Evolution* 52:935-949. <http://dx.doi.org/10.2307/2411226>
- Ortiz WS, Salcedo RDL, Ruiz LC, Macías JNL (2007). Potencial acuícola de pirarucu (*Arapaima gigas*) em la cueca Amazónica. *Rev. Elect. Ing. Prod. Acuic.* 2:75-83.
- Pérez-Ruzafa A, González-Wangüemert M, Lenfant P, Marcos C, García-Charton JA (2006). Effects of fishing protection on the genetic structure of fish populations. *Biol. Conserv.* 129:244-255. <http://dx.doi.org/10.1016/j.biocon.2005.10.040>
- Piry S, Luikart G, Cornuet JM (1999). Bottleneck: a computer program for detecting recent reductions in the effective population size using allele frequency data. *J. Hered.* 90:502-503. <http://dx.doi.org/10.1093/jhered/90.4.502>
- Pritchard JK, Stephens M, Donnelly P (2000). Inference of population structure using multilocus genotype data. *Genetics* 155:945-959.
- Pullin RSV (2007). Genetic resources for aquaculture: status and trends. In: Bartley DM, Harvey BJ, Pullin RSV (editors). *Workshop on status and trends in aquatic genetic resources: A basic for international policy: 8-10 May 2006, Victoria, British Columbia, Canada*. Rome: Food & Agriculture Org.
- Rice WR (1989). Analyzing tables of statistical tests. *Evolution* 43:223-225. <http://dx.doi.org/10.2307/2409177>
- Sambrook J, Fritsch EF, Maniatis T (1989). *Molecular cloning: a laboratory manual*, 2nd ed. Cold Spring Harbor, NY: Cold Spring Harbor Laboratory.
- Santos CHA, Leitão MAB, Sousa CFS, Santana GX, Paula-Silva MN, Almeida-Val VMF (2012). Genetic variability of wild and captivity populations of *Colossoma macropomum* (Cuvier, 1818). *Acta Sci. Biol. Sci.* 34(2):191-197. <http://dx.doi.org/10.4025/actascibiolsci.v34i2.7149>
- Silva JAG (2008). *Genética de populações de pirarucus (Arapaima gigas) da Reserva de Mamirauá e considerações sobre a estrutura genética para a espécie*. Tese (Doutorado em Zoologia) 101. Belém, Brasil: Museu Paraense Emilio Goeldi, Universidade Federal do Pará.
- Slatkin MA (1995). A measure of population subdivision based on microsatellite allele frequencies. *Genetics* 130:457-462.
- Sønsteby JH, Borgstrøm R, Heun M (2007). Genetic structure of brown trout (*Salmo trutta* L.) from the Hardangervidda mountain plateau (Norway) analyzed by microsatellite DNA: a basic for conservation guidelines. *Conserv. Gen.* 8:33-44. <http://dx.doi.org/10.1007/s10592-006-9145-6>
- Stewart DJ (2013a). A new species of *Arapaima* (Osteoglossomorpha: Osteoglossidae) from the Solimões river, Amazonas State, Brazil. *Copeia* 3:470-476. <http://dx.doi.org/10.1643/CI-12-017>

- Stewart DJ (2013b). Re-escription of *Arapaima agassizii* (Valenciennes), a rare fish from Brazil (Osteoglossomorpha: Osteoglossidae). *Copeia* 1:38-51. <http://dx.doi.org/10.1643/C1-12-013>
- Teixeira AS (2008). The monotony of transferrin and esterase electrophoretic patterns in pirarucu, *Arapaima gigas* (Schinz, 1822) from Santa Cruz lake, Tefé River, Amazonas, Brazil. *Genet. Mol. Res.* 7(2):407-416. <http://dx.doi.org/10.4238/vol7-2gmr425>
- Utter F (2004). Population genetics, conservation and evolution in salmonids and other widely cultured fish; some perspectives over six decades. *Rev. Fish. Biol. Fisheries* 14:125-144. <http://dx.doi.org/10.1007/s11160-004-3768-9>
- van Oosterhout C, Hutchinson WF, Wills DPM, Shipley P (2004). Micro-Checker: software for identifying and correcting genotyping errors in microsatellite data. *Mol. Ecol. Notes* 4:535-538. <http://dx.doi.org/10.1111/j.1471-8286.2004.00684.x>
- Vasemägi A, Cross R, Paaver T, Koljonen ML, Nilsson J (2005). Extensive immigration from compensatory hatchery releases into wild Atlantic salmon population in the Baltic sea: spatio-temporal analysis over 18 year. *Heredity* 95:76-83. <http://dx.doi.org/10.1038/sj.hdy.6800693>
- Venturiere R, Bernardino G (1999). Pirarucu, espécie ameaçada pode ser salva através do cultivo. *Rev. Panor. Aquic.* 9:13-21.
- Viana JP, Castello L, Damasceno JMB, Amaral ESR, Estupi-án GMB, Arantes C, Batista GS, Garces DS, Barbosa S (2007). Manejo comunitário do pirarucu *Arapaima gigas* na Reserva de Desenvolvimento Sustentável de Mamirauá, Amazonas, Brasil. In: *Áreas protegidas como instrumento de gestão pesqueira*. Brasília MMA. pp. 239-261.
- Vitalis R, Dawson K, Boursot P, Belkhir K (2003). DetSel 1.0: a computer program to detect markers responding to selection. *J. Hered.* 94(5):429-431. <http://dx.doi.org/10.1093/jhered/esg083>
- Vitalis R, Dawson K, Boursot P (2001). Interpretation the heterogeneity of F values: a suggestion and a correction. *Genetics* 84:399-401.
- Wasko AP, Martins C, Oliveira C, Senhorini JA, Foresti F (2004). Genetic monitoring of the Amazonian fish matrinchá (*Brycon cephalus*) using RAPD markers: insights into supporting and conservation programmes. *J. Appl. Ichthyol.* 20:48-52. <http://dx.doi.org/10.1111/j.1439-0426.2004.00479.x>
- Weir BS, Cockerham CC (1984). Estimating F statistics for the analysis of population structure. *Evolution* 38:1358-1370. <http://dx.doi.org/10.2307/2408641>

## SUPPLEMENTARY

**Table S1.** Basic parameters for genetic diversity associated with subpopulations of *Arapaima gigas* based on 19 microsatellite loci.

Loci	Subpopulations						
	Captive					Wild	
	PFP-1	PFP-2	PFP-3	DNOCS	PPV	SDRFB	SDRM
AgCTm1							
$H_O$	0.540	0.944	0.040	0.000	0.381	0.133	0.300
$H_E$	0.470	0.577	0.039	0.000	0.363	0.124	0.460
A	2.000	5.000	2.000	1.000	2.000	2.000	3.000
$A_E$	1.887	2.364	1.040	1.000	1.570	1.142	1.852
$F_{IS}$	-0.136	-0.619	0.000	-	-0.038	-0.037	0.370
AgCTm3							
$H_O$	0.667	0.714	0.875	0.654	0.512	0.786	0.348
$H_E$	0.552	0.766	0.650	0.587	0.414	0.566	0.401
A	3.000	5.000	4.000	3.000	3.000	4.000	4.000
$A_E$	2.232	4.274	2.857	2.421	1.706	2.304	1.669
$F_{IS}$	-0.195	0.103	-0.327	-0.095	-0.226	0.355	0.154
AgCTm4							
$H_O$	1.000	1.000	0.926	1.000	0.775	0.875	0.947
$H_E$	0.636	0.611	0.593	0.680	0.537	0.793	0.813
A	4.000	4.000	3.000	4.000	3.000	7.000	7.000
$A_E$	2.747	2.571	2.457	3.125	2.160	4.831	5.348
$F_{IS}$	-0.563	-0.615	-0.625	-0.454	-0.434	-0.071	-0.139
AgCTm5							
$H_O$	0.667	0.722	0.478	0.654	0.244	0.611	0.920
$H_E$	0.554	0.619	0.593	0.499	0.219	0.775	0.818
A	3.000	3.000	4.000	3.000	3.000	6.000	10.000
$A_E$	2.242	2.625	2.457	1.996	1.280	4.444	5.494
$F_{IS}$	-0.193	-0.139	0.214	-0.242	-0.102	0.238	-0.104
AgCTm7							
$H_O$	0.000	0.000	0.000	0.083	0.364	0.556	0.417
$H_E$	0.000	0.000	0.000	0.079	0.469	0.438	0.448
A	1.000	1.000	1.000	2.000	3.000	3.000	3.000
$A_E$	1.000	1.000	1.000	1.086	1.883	1.779	1.812
$F_{IS}$	-	-	-	-0.022	0.236	-0.241	0.091
AgCTm8							
$H_O$	0.526	0.875	0.577	0.040	0.650	1.000	0.000
$H_E$	0.410	0.492	0.482	0.039	0.466	0.500	0.000
A	3.000	2.000	2.000	2.000	2.000	2.000	1.000
$A_E$	1.695	1.968	1.930	1.040	1.873	2.000	1.000
$F_{IS}$	-0.271	-0.765	-0.179	0.000	-0.383	-1.000	-
AgCAm4							
$H_O$	0.000	0.500	0.222	0.923	0.674	0.000	0.840
$H_E$	0.000	0.375	0.198	0.497	0.447	0.000	0.487
A	1.000	2.000	2.000	2.000	2.000	1.000	2.000
$A_E$	1.000	1.600	1.247	1.988	1.808	1.000	1.949

Table S1. Contd.

$F_{IS}$	-	-0.300	-0.106	-0.852	-0.500	-	-0.714
AgCAm16							
$H_O$	0.425	0.533	0.556	0.458	0.585	0.706	0.550
$H_E$	0.429	0.560	0.578	0.478	0.608	0.808	0.714
A	3.000	3.000	3.000	3.000	3.000	8.000	5.000
$A_E$	1.751	2.273	2.370	1.916	2.551	5.208	3.496
$F_{IS}$	0.021	0.082	0.058	0.063	0.050	0.156	0.254
AgCAm18							
$H_O$	0.000	0.357	0.259	0.423	0.275	0.000	0.250
$H_E$	0.000	0.304	0.226	0.429	0.237	0.000	0.224
A	1.000	3.000	2.000	3.000	2.000	1.000	3.000
$A_E$	1.000	1.437	1.292	1.751	1.311	1.000	1.289
$F_{IS}$	-	-0.140	-0.130	0.033	-0.147	-	-0.092
AgCAm26							
$H_O$	0.610	0.938	0.731	0.625	0.462	0.824	0.636
$H_E$	0.495	0.623	0.659	0.640	0.380	0.644	0.548
A	3.000	3.000	3.000	3.000	3.000	6.000	4.000
$A_E$	1.980	2.652	2.932	2.778	1.613	2.809	2.212
$F_{IS}$	-0.220	-0.480	-0.089	0.044	-0.201	-0.251	-0.140
AG_01							
$H_O$	0.456	0.929	0.581	0.440	0.727	0.733	0.591
$H_E$	0.416	0.600	0.564	0.343	0.664	0.624	0.606
A	3.000	3.000	3.000	2.000	3.000	3.000	3.000
$A_E$	1.712	2.500	2.293	1.522	2.976	2.660	2.538
$F_{IS}$	-0.087	-0.523	-0.013	-0.263	-0.083	-0.141	0.049
AG_02							
$H_O$	0.372	0.533	0.370	0.440	0.349	0.438	0.524
$H_E$	0.313	0.580	0.417	0.385	0.318	0.482	0.622
A	3.000	3.000	2.000	2.000	2.000	2.000	3.000
$A_E$	1.456	2.381	1.715	1.626	1.466	1.930	2.646
$F_{IS}$	-0.176	0.115	-0.123	-0.088	0.125	0.182	0.130
AG_03							
$H_O$	0.575	1.000	0.967	0.720	0.405	0.938	0.579
$H_E$	0.434	0.635	0.499	0.518	0.544	0.691	0.460
A	3.000	4.000	2.000	3.000	3.000	6.000	4.000
$A_E$	1.767	2.740	1.996	2.075	2.193	3.236	1.852
$F_{IS}$	-0.314	-0.553	-0.933	0.371	0.267	-0.327	-0.234
AG_07							
$H_O$	0.537	1.000	0.500	0.800	0.540	0.706	0.550
$H_E$	0.429	0.653	0.530	0.540	0.422	0.600	0.671
A	3.000	4.000	3.000	2.000	3.000	4.000	5.000
$A_E$	1.751	2.882	2.128	2.174	1.730	2.500	3.040
$F_{IS}$	-0.240	-0.511	0.077	-0.466	-0.269	-0.146	0.205
AG_09							
$H_O$	0.619	0.750	0.692	0.375	0.024	0.125	0.909
$H_E$	0.520	0.553	0.644	0.520	0.047	0.602	0.549



**Table S1.** Contd.

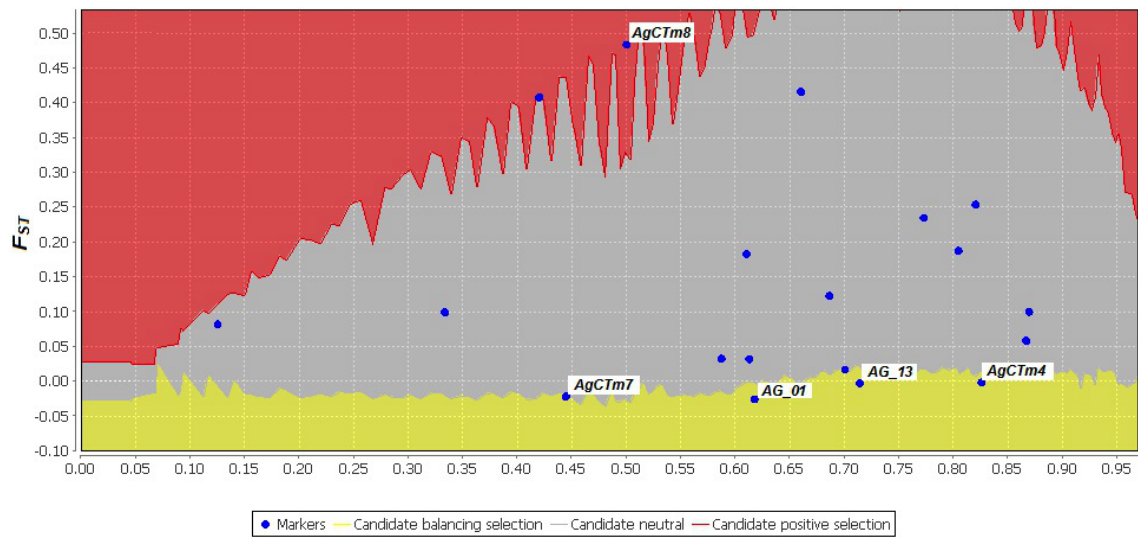
A	3.000	3.000	3.000	3.000	3.000	4.000	3.000
$A_E$	2.083	2.237	2.809	2.083	1.049	2.512	2.217
$F_{IS}$	-0.178	-0.328	-0.055	0.298	0.500	0.804*	-0.644
AG_11							
$H_O$	0.286	0.600	0.875	0.733	0.200	0.000	0.920
$H_E$	0.272	0.460	0.655	0.518	0.180	0.000	0.755
A	3.000	3.000	3.000	3.000	2.000	1.000	6.000
$A_E$	1.374	1.852	2.898	2.075	1.220	1.000	4.082
$F_{IS}$	-0.039	-0.273	-0.316	-0.402	-0.099	-	-0.199
AG_12							
$H_O$	0.415	0.429	0.577	0.593	0.780	0.750	0.783
$H_E$	0.362	0.400	0.467	0.450	0.535	0.589	0.751
A	3.000	3.000	3.000	3.000	3.000	6.000	11.000
$A_E$	1.567	1.667	1.876	1.818	2.150	2.433	4.016
$F_{IS}$	-0.133	-0.033	-0.218	-0.300	-0.449	-0.241	-0.019
AG_13							
$H_O$	1.000	0.882	1.000	0.962	0.909	1.000	0.920
$H_E$	0.725	0.493	0.627	0.499	0.598	0.650	0.748
A	4.000	2.000	4.000	2.000	3.000	4.000	6.000
$A_E$	3.636	1.972	2.681	1.996	2.488	2.857	3.968
$F_{IS}$	-0.370	-0.778	-0.583	-0.923	-0.511	-0.519	-0.211
AG_15							
$H_O$	0.300	0.500	0.240	0.370	0.310	0.444	0.250
$H_E$	0.255	0.506	0.339	0.308	0.262	0.633	0.539
A	2.000	3.000	3.000	3.000	2.000	5.000	5.000
$A_E$	1.342	2.024	1.513	1.445	1.355	2.725	2.169
$F_{IS}$	-0.164	0.044	0.311	-0.185	-0.171	0.323	0.554*
Total							
$H_O$	0.473	0.695	0.551	0.542	0.482	0.559	0.591
$H_E$	0.383	0.516	0.460	0.422	0.406	0.501	0.559
A	2.684	3.105	2.737	2.632	2.684	3.947	4.632
$A_E$	1.621	2.066	1.852	1.730	1.684	2.004	2.268
$F_{IS}$	-0.225	-0.317	-0.179	-0.266	-0.177	-0.085	-0.035

\*Locos with deviation for Hardy-Weinberg equilibrium (HWE),  $p < 0.05$  (Bonferroni correction; 0.0004).

**Table S2.** Member proportions of each population according to the seven clusters determined with Structure Software.

Populations/cluster	1	2	3	4	5	6	7
PFP-1	0.002	0.003	0.003	<b>0.984</b>	0.002	0.003	0.002
PFP-2	0.003	0.003	<b>0.978</b>	0.004	0.005	0.006	0.003
PFP-3	0.002	<b>0.980</b>	0.003	0.004	0.003	0.004	0.003
DNOCS	0.002	0.003	0.003	0.003	0.003	<b>0.983</b>	0.002
PPV	0.003	0.003	0.003	0.003	<b>0.981</b>	0.004	0.003
SDRFB	0.012	0.005	0.004	0.003	0.011	0.004	<b>0.961</b>
SDRM	<b>0.962</b>	0.004	0.004	0.004	0.004	0.004	0.019

(Contribution > 0.9 in bold).



**Figure S1.** Outlier loci with positive selective pressure for wild individuals.