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► To cite this version:

K Paul, G Restoux, Florence Phocas. Genome-wide detection of positive and balancing selection signatures shared by four domesticated rainbow trout populations (*Oncorhynchus mykiss*). 2023. hal-04217772

HAL Id: hal-04217772

<https://hal.inrae.fr/hal-04217772>

Preprint submitted on 26 Sep 2023

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1 *Molecular ecology*

2

3 **Genome-wide detection of positive and balancing selection signatures shared**
4 **by four domesticated rainbow trout populations (*Oncorhynchus mykiss*)**

5 Paul, K.¹, Restoux, G.¹, Phocas, F.¹

6 1. Université Paris-Saclay, INRAE, AgroParisTech, GABI, 78350 Jouy-en-Josas, France

7 Corresponding author: Florence Phocas - florence.phocas@inrae.fr

8

9 **Abstract**

10 Evolutionary processes leave footprints across the genome over time. Highly homozygous
11 regions may correspond to positive selection of favourable alleles, while maintenance of
12 heterozygous regions may be due to balancing selection phenomena. We analyzed 176 genomes
13 coming from 20 sequenced US fish and 156 fish from three different French lines that were
14 genotyped using a HD Axiom Trout Genotyping 665K SNP Array. Using methods based on
15 either Run of Homozygosity or Extended Haplotype Homozygosity, we detected selection
16 signals in four domesticated rainbow trout populations. Nine genomic regions composed of 253
17 genes, mainly located on chromosome 2 but also on chromosomes 12, 15, 16, and 20, were
18 identified under positive selection in all four populations. In addition, four heterozygous regions
19 containing 29 genes putatively under balancing selection were also shared by the four
20 populations and located on chromosomes 10, 13, and 19. Whatever the homozygous or
21 heterozygous nature of the region, we always found some genes highly conserved among
22 vertebrates due to their critical roles in cellular and nuclear organisation, embryonic
23 development or immunity. We identify new promising candidate genes involved in rainbow

24 trout fitness, as well as genes already detected under positive selection in other fishes (*auts2*,
25 *atp1b3*, *zp4*, *znf135*, *igf-1α*, *brd2*, *col9a2*, *mrp2*, *pbx1*, *emilin-3*). These findings represent a
26 genome-wide map of signatures of selection common over rainbow trout populations, which is
27 the foundation to understand the processes in action and to identify what kind of diversity
28 should be preserved, or conversely avoided in breeding programs, in order to maintain or
29 improve essential biological functions in domesticated rainbow trout populations.

30

31 Keywords: Runs of Homozygosity, Extended Haplotype Homozygosity, domestication, fitness,
32 selection, fish.

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44 **1| Introduction**

45 Any population, whether animal or plant, wild or domesticated, evolved through continuous
46 and cumulative changes over time (Wright, 1931). It relies on various evolutionary forces,
47 mutation, migration, selection, and genetic drift, whose relative effects may vary depending on
48 population history and structure. For example, genetic drift is more substantial when the
49 effective population size is small and randomly induces fixation of alleles, which may lead to
50 degeneration and extinction due to the fixation of deleterious alleles in small populations (Smith
51 & Haigh, 1974). When modifications of environmental conditions occur, allele frequencies will
52 change to a new relevant equilibrium, as a result of natural selection. Indeed, favorable alleles
53 in a particular environment due to either new mutations or standing variation, will be positively
54 selected. In wild populations, favourable alleles are generally affecting fitness through
55 individual survival, mating, or fertility (East, 1918; Fisher, 1958). Natural selection can also act
56 by negative (or purifying) selection that hinders the spread of deleterious alleles (Charlesworth
57 et al., 1995). These two processes tend to reduce the genetic diversity at the target genes but
58 had different effect on the genome, positive selection leading to stronger selection signatures
59 (selective sweep) than negative one. Conversely, the population's polymorphism can be actively
60 maintained in some rare genomic regions through balancing selection that keeps an equilibrium
61 in the frequencies of alleles. The two main biological causes of balancing selection are
62 heterozygote advantage at a single locus, known as overdominance effect, and frequency-
63 dependent selection with a rare-allele advantage that tends to restore a frequency equilibrium
64 between alleles at the population level (Charlesworth, 2006, Fijarczyk & Babik, 2015).

65 Domestication is the evolutionary process of genetic adaptation over generations of a wild
66 population to handling by humans and breeding in captive environments (Darwin, 1859, 1868;
67 Price, 1984). During domestication, humans exert artificial selection pressure on the initial

68 population by choosing and organizing the reproduction of the most adapted individuals to
69 cohabitation or more globally to those whose aptitudes correspond the best to their expectations
70 (Price, 1999; Russell, 2002), such as a less fearfulness of humans (Price, 2002; Harri et al.,
71 2007). Domestication induces severe genetic bottlenecks due to the selection and reproduction
72 of only a few adapted animals from the wild population. Thus, many genetic evolutionary
73 processes, such as selection, genetic drift, and inbreeding, have a significant role in the
74 evolution of farmed animal populations (Helmer, 1992; Mignon-Grasteau et al., 2005). The
75 domestication process affects life history traits due to changes in morphological, physiological,
76 reproductive, behavioural, and immune functions (Mignon-Grasteau et al., 2005; Pulcini et al.,
77 2013; Milla et al., 2021 for review in fishes) compared to their wild relatives (Darwin, 1859,
78 1868). Wilkins et al. (2014) suggest that these specific modifications, called domestication
79 syndrome, may be due to mild deficit of neural-crest cells during embryonic development in
80 domesticated animals. In addition, both natural and artificial selection in domesticated species
81 leaves footprints across the genome, known as selection signatures, which can point to regions
82 harboring essential genes for domestication or natural fitness (Dobney & Larson, 2006; Qanbari
83 & Simianer, 2014; Wright, 2015).

84 Compared to domestication in terrestrial animals (Mignon-Grasteau et al., 2005), fish
85 domestication is recent and was first documented with carp about 2,000 years ago. The precise
86 date and location (Neolithic China or at the Roman period in Central and East Europe) of the
87 carp domestication are still debated (Balon, 1995; Balon, 2004). However, most farmed fish
88 species have only been domesticated since the last century. The rainbow trout is native to the
89 Pacific drainages of North America and to Kamchatka in Russia and its domestication started
90 in the 1870s in California (Hershberger, 1992; Gall & Crandel, 1992). It was then introduced
91 in Western Europe at the beginning of the 20th century (Fabrice, 2018).

92 Numerous studies have been carried out over the last ten years to detect signatures of selection
93 in farmed fish species (Channel Catfish: Sun et al., 2014; Atlantic salmon: Mäkinen et al.,
94 2015; Gutierrez et al., 2016; Liu et al., 2016; Pritchard et al., 2018; López et al., 2019; Carp: Su
95 et al., 2018; Nile Tilapia: Hong et al., 2015; Cádiz et al. 2020; Yu et al., 2022; Rainbow trout:
96 Cádiz et al., 2021; Coho salmon : López et al., 2021; Australasian snapper: Baesjou &
97 Wellenreuther, 2021; Brown trout: Magris et al., 2022) in order to identify genomic regions
98 involved in recent adaptation or domestication processes (Smith & Haigh, 1974; Pennings &
99 Hermisson, 2006). In this study, we were interested in farmed rainbow trout populations as it is
100 one of the oldest farmed fish and the analysis of genes under either positive or balancing
101 subsequent selection in. Indeed, only a few studies on selection signatures were performed in
102 rainbow trout. Three of them only focused on wild populations and showed signatures of
103 selection linked to life-history variation, egg development, spawning time (Martínez et al.,
104 2011), immune response (Limborg et al., 2012), and smoltification (Weinstein et al., 2019).
105 The first study in domesticated rainbow trout was performed on a single Chilean population
106 (Cádiz et al., 2021) genotyped with a 57K SNP array; identified signatures of selection were
107 associated with early development, growth, reproduction and immune system. Recently, a high-
108 density array (665K SNPs) was developed for rainbow trout (Bernard et al., 2022), allowing us
109 to potentially more accurately detect signatures of selection and to compare them across various
110 domesticated rainbow trout populations. The existence of signatures of selection shared by
111 farmed populations from different geographical areas is essential to understand the importance
112 of genetic diversity in several genomic regions in rainbow trout and then to identify genes
113 having key roles in either the domestication process or fitness because conserved by all
114 populations (Bruford et al., 2003; Yáñez et al., 2022).

115 Various approaches have been developed to reveal selection signatures within population based
116 on site frequency spectrum, linkage disequilibrium (LD), or reduction of local variability (Vitti
117 et al., 2013; Saravanan et al., 2020). Among these approaches, we will use two strategies, one
118 based on the reduction of local variability using Run of Homozygosity (ROH) metrics and the
119 second one relying on allele frequencies and the extent of LD based on Extended Haplotype
120 Homozygosity (EHH). ROH is a large homozygous stretch in the genome of an individual
121 inherited from a common ancestor to his parents (McQuillan et al., 2008; Purfield et al., 2012),
122 while EHH measures the extent of shared haplotypes through the association between a single
123 core haplotype and multiple loci at various distances from the core region (Sabeti et al., 2002).
124 In our study, we considered four populations: one INRAE experimental line (with no intentional
125 selection), two French selected lines from two different breeding companies, and a pooled
126 American population gathering samples from one wild river and four hatchery populations, all
127 coming from the North-West of the USA and closely genetically linked (Gao et al., 2018). Our
128 work aimed to discover the main genomic regions sharing strong homozygosity (positive
129 selection) or heterozygosity (balancing selection) across the four rainbow trout populations and
130 to get further insights into the nature of genes spanning these regions.

131

132

133 **2 | Material and methods**

134 2.1 | Populations

135 Three French populations were considered: 14 breeding females from the INRAE synthetic line
136 SY and, 90 and 72 females from two selected lines LB and LC from the breeding companies
137 “Bretagne Truite” (Plouigneau, France) and “Viviers de Sarrance” (Sarrance, France)

138 respectively. The SY was developed by intercrossing several domesticated lines of rainbow
139 trout, in order to create a population with a large diversity (D'Ambrosio et al., 2019).
140 In addition, we considered an American pooled population, hereafter named HA, using the
141 whole genome sequence data of 20 fishes obtained by Gao et al. (2018). The sampling strategy
142 consisted in collecting DNA from 4 individuals in each of five locations from the North-West
143 of the USA: wild fish from Elwha River, and farmed fish from Dworshak, L. Quinault,
144 Quinault, and Shamina hatcheries. We pooled together the 20 individuals, as these five
145 populations were genetically close to each other (Supplementary Figure 1; Gao et al., 2018) and
146 greatly distant from the three French populations (Figure 1).

147

148 2.2 | Genotyping and quality control

149 High-density genotypes were obtained at the INRAE genotyping Platform Gentyane
150 (Clermont-Ferrand, France) for all the 176 French samples using the Affymetrix 665K SNP
151 array recently developed for rainbow trout (Bernard et al., 2022). We only considered the
152 genotypes for the 576,118 SNPs of the Rainbow Trout Axiom® 665K SNP array that were
153 positioned on the Arlee genome (GCA_013265735.3, Gao et al., 2021; Bernard et al., 2022).
154 From the whole-genome sequence information of the 20 American samples (Gao et al., 2018),
155 we extracted the genotypes for the same 576,118 SNPs of the HD chip.

156 Among the 177 French genotyped fish, 19 individuals with more than 30% identity-by-state
157 (IBS) with other individuals were removed from the dataset. We thus kept for the analysis 76,
158 67, 20, and 14 fish sampled from LB, LC, HA, and SY populations, respectively.

159 Then, SNP quality control was performed using PLINK v1.9 software (Chang et al., 2015).

160 Note that, to avoid limitations due to the low number of individuals in SY, quality filters were
161 made considering LC and SY together, as both populations were genotyped on the same SNP

162 plate and are close genetically (D'Ambrosio et al., 2019). About 4,000 SNPs randomly
163 distributed over all the genome were removed for all populations due to extreme deviation from
164 Hardy-Weinberg equilibrium (p -value $< 10^{-7}$). It allowed us to discarded SNPs with high risk of
165 wrong genotyping, in addition to the edit for SNP call rate lower than 97%. We retained 571,319
166 SNPs, 569,030 SNPs, and 573,793 SNPs on LB, 'LC- SY', and HA populations, respectively.
167 Finally, crossing the three SNP lists, we kept the 546,903 common SNPs for the analysis.

168

169 2.3 | Genetic structure of the populations

170 Genetic differentiation between populations was measured with a pairwise F_{st} estimate using
171 the VCFtools v0.1.13 software (Danecek et al., 2011). In addition, a principal component
172 analysis (PCA) was performed with the R package *Adegenet* (function *glPca*) (Jombart &
173 Ahmed, 2011) to visualize the genetic structure of the populations.

174

175 2.4 | Runs of homozygosity

176 Runs of homozygosity (ROH) were identified for each fish using the PLINK v1.9 *homozyg*
177 function (Chang et al., 2015) with the following options '*--homozyg-kb 500 --homozyg-window-*
178 *snp 40 --homozyg-snp 40 --homozyg-gap 500 --homozyg-density 40 --homozyg-het 1*'. ROH was
179 defined by a sliding window with a minimum length of 500 kb containing at least 40
180 homozygous SNPs. This minimum number of homozygous SNPs was chosen using the formula
181 described by Purfield et al. (2012) in order to limit the number of ROHs that might only occur
182 by chance.

183

184 2.4.1 | Estimation of inbreeding coefficients

185 The individual inbreeding coefficients (F_{ROH}) were calculated according McQuillan et al
186 (2008) as $F_{i,ROH} = \frac{\sum length(ROH_i)}{LGenome}$

187 With $\sum length(ROH_i)$ the sum of ROH length in an individual i and $LGenome$ the total length
188 of the autosomal genome covered by SNPs.

189

190 2.4.2 | Identification of ROH islands

191 For each SNP, the number of individuals with this SNP included in a ROH was calculated in
192 order to identify the regions of the genome that were frequently homozygous in each
193 population, i.e. constituting ROH islands (Nothnagel et al., 2010). These ROH hotspots may
194 then be considered as signatures of positive selection (Saravanan et al., 2021).

195 To allow the comparison of ROH islands across populations, we implemented population-
196 specific thresholds based on the ROH occurrence to define ROH islands, as proposed in many
197 studies (Purfield et al., 2017; Mastrangelo et al., 2017; Zhang et al., 2018; Peripolli et al., 2018;
198 Grilz-Seger et al., 2018; Gorssen et al., 2021; Illa et al., 2022). The number of individuals
199 corresponding to the top 5% of SNPs most often found in a ROH within each population was
200 chosen as a threshold to define a ROH island.

201 These top 5% values were equivalent to 35, 27, 5, and 10 individuals for LB, LC, SY, and HA,
202 respectively. Values chosen within each population corresponded to 48.6%, 40.3%, 35.7%, and
203 50% of individuals with a ROH in LB, LC, SY, and HA, respectively. In addition, two close
204 SNPs in the top 5% were considered in the same ROH island if there were separated by a
205 distance lower than 500 kb with less than 40 SNPs in the gap stretch. The ROH island was
206 delimited by a number of individuals, with ROH falling below the top 10% of the SNPs, which
207 correspond to 30, 22, 3, and 7 individuals for LB, LC, SY, and HA populations, respectively.

208 2.4.3 | Detection of balancing selection signals based on regions without ROH

209 We used the ROH occurrence information per SNP to detect extreme heterozygous regions, i.e.
210 without ROH. In these regions, we have an enrichment of heterozygous SNP relative to the
211 genome-wide prevalence that may be due to balancing selection phenomena (Szpiech et al.,
212 2013).

213 Applying the same criteria as for defining ROH, the minimal size and number of SNPs to define
214 a heterozygous region were fixed to 500 kb and 40 SNPs, respectively. Moreover, two
215 successive SNPs were considered in the same region if they were separated by a distance lower
216 than 50 kb. A region was detected in extreme heterozygosity if less than 5% of individuals (per
217 population) have SNPs in ROH in the region, corresponding to a maximum of respectively 4
218 and 3 individuals with a ROH in LB and LC populations, and to 0 individual with a ROH in
219 SY and HA.

220

221 2.5 | Detection of signatures of selection based on Extended Haplotype Homozygosity (EHH)

222 For a given core allele, the EHH is defined as ‘the probability that two randomly chosen
223 chromosomes carrying the core haplotype of interest are identical by descent for the entire
224 interval from the core region to the point x’ (Sabeti et al., 2002). EHH measures the association
225 between a single allele from the study locus (the core region) with multiple loci at various
226 distances x (Sabeti et al., 2002). The iHS (Integrated Haplotype Homozygosity Score) proposed
227 by Voight et al. (2006) aims to compare the integrated EHH profiles obtained for a SNP in the
228 ancestral versus derived states. An extreme value of iHS corresponds to a positive selection
229 because a core haplotype with unusually high EHH and high frequency in the population

230 indicates the presence of a mutation that has spread through the population faster than the
231 haplotype broke down.

232 EHH methodology requires haplotype information. Thus, genotype data must be phased before
233 their calculation. We used FImpute3 (Sargolzaei et al., 2014) to phase the genotypes of the
234 study females, considering all parents (including our study females) and offspring genotyped
235 in LB, LC, and SY populations for different purposes (see respectively Prchal et al., 2022,
236 Lagarde et al., 2022 and Paul et al., 2022). All parents (except 8 SY sires) were genotyped with
237 the HD chip (Bernard et al., 2022), while offsprings (and 8 SY sires) were genotyped with a
238 57K chip only (Palti et al., 2015). Information used for phasing is given in Table 1. Due to the
239 lack of genotyped offsprings, only the HD genotypes information was used to phase the
240 genotypes of the HA population.

241 Once phasing was performed, the *rehh* R package (Gautier & Vitalis, 2012; Gautier et al., 2017)
242 was used to conduct EHH-based analyses. EHH detection was stopped when the EHH value
243 declined under 0.1 or when the gap between two consecutive SNPs was higher than 20 kb
244 (*scan_hh* function with the following options: *limehh* = 0.1; *maxgap*=20 kb).

245

246 2.5.1 | Cross population Extended Haplotype Homozygosity (XP-EHH)

247 From EHH information, we used the XP-EHH statistic (*ies2xpehh* function) to compared the
248 integrated EHH profiles (iES), two by two, between a French (popA) and the HA (popB)
249 populations at the same focal SNP (Sabeti et al., 2007) as:

$$250 \quad XP_EHH = \frac{\ln\left(\frac{iES_{popA}}{iES_{popB}}\right) - Med\left[\ln\left(\frac{iES_{popA}}{iES_{popB}}\right)\right]}{SD\left[\ln\left(\frac{iES_{popA}}{iES_{popB}}\right)\right]}$$

251 The median (*Med*) and standard deviation (*SD*) of $\ln(iES_A/iES_B)$ were computed over all the
252 analysed SNPs.

253

254 2.5.2 | Integrated Haplotype Homozygosity Score (iHS)

255 In the same way, we used the iHS test (Voight et al., 2006) to evaluate the evidence of positive
256 selection based on haplotype frequencies in a single population, using the *ihh2ihs* function of
257 the package *rehh*. This statistic was based on the log-ratio of the integrated EHH (iHH) for
258 haplotypes with the ancestral (A) *versus* the derived (D) alleles and was computed for each

259 autosomal SNP as $iHS = \frac{\ln\left(\frac{iHH_A}{iHH_D}\right) - Mean_p\left[\ln\left(\frac{iHH_A}{iHH_D}\right)\right]}{SD_p\left[\ln\left(\frac{iHH_A}{iHH_D}\right)\right]}$

260 The average ($Mean_p$) and standard deviation (SD_p) of $\ln(iHH_A/iHH_D)$ were computed over all
261 the SNPs with a derived allele frequency p similar to that of the core SNP. In our study, the
262 ancestral allele state is unknown. Therefore, we assumed that the most frequent allele represents
263 the ancestral state as proposed by Bahbahani et al. (2015).

264

265 2.5.3 | Detection of candidate regions

266 To detect candidate regions for signatures of selection based on the iHS test, we used *the*
267 *calc_candidate_region* function of the R package *rehh* (Gautier & Vitalis, 2012). We
268 considered windows of 500 kb across the genome containing at least 30 SNPs, with 10 kb of
269 overlapping. A region was considered as under positive selection if at least one SNP had a
270 $\log(p\text{-value}) > 4$ and extreme iHS value *i.e.* $|iHS| \geq 2.5$.

271

272 2.6 | Identification of common regions under positive selection

273 ROH islands and regions identified by iHS were pooled within each population. Then, the
274 intersection set of the regions identified by one or another method across the four studied
275 populations was established. We eliminated an intersection from the study if one population
276 does not have at least one SNP with an $|iHS| \geq 2.5$ or enough individuals with an ROH in the
277 intersected region. So, only intersections containing either ROH island or extreme iHS ($|iHS| \geq$
278 2.5) for the four populations were thus further analyzed.

279

280 2.7 | Gene analysis

281 The genes annotated in the regions under positive or balancing selection were identified from
282 the NCBI *Oncorhynchus mykiss* genome assembly (GCA_013265735.3). Gene symbols were
283 checked, and, if necessary, familiar names were added using the information available from
284 GeneCards (<https://www.genecards.org/>).

285 Gene ontology (GO) terms study was performed with 'g:profiler' (Raudvere et al., 2019;
286 <https://biit.cs.ut.ee/gprofiler/gost>) for the list of genes identified in the regions of interest.

287 Percent identity of rainbow trout proteins with nine other vertebrate species (human, mouse,
288 cow, goat, pig, chicken, zebrafish, medaka, and Atlantic salmon) was established using the
289 blastp tool (Basic Local Alignment Search Tool on proteins).

290

291

292

293

294 **3| Results**

295 3.1 | Genetic diversity within and across populations

296 The ROH statistics and inbreeding coefficients are presented in **Table 2** for all the populations.
297 The average number of ROH per individual varied between 141 (SY) and 168 (LB). French
298 selected lines had larger average sizes of ROH than populations SY and HA. The average
299 inbreeding coefficients of HA individuals were between three (compared to SY) and five
300 (compared to LB) times lower than those of the French lines.

301 Based on genome-wide F_{st} values, large differentiation of around 0.28 was observed between
302 HA and any of the French populations (Table 3). In the PCA figure (Figure 1), the three French
303 lines differed strongly from the American pooled populations, and the first two PCA axes
304 explained 29% of the total genetic variation. In addition, F_{st} values indicated that all the French
305 lines were moderately differentiated (0.104 – 0.122).

306 Using the XP-EHH statistic, we identified 93, 105 and, 135 regions that strongly discriminated
307 HA from LB, LC and SY, respectively. Among these regions, 34 regions were shared, spanning
308 about 32 Mb in total over 21 chromosomes, and differentiated any of the French lines from the
309 American HA pooled population (Supplementary information S1).

310 The distribution of the proportion of individuals having a ROH at each SNP position is
311 presented in Figure 2. In average, ROH were more shared between individuals for selected lines
312 (LB and LC, on average, 23.39% and 19.82% of individuals respectively) than for other
313 populations (SY and HA, on average, 13.67% and 8.91% of individuals respectively). Probably
314 linked to the composite nature of the HA population (5 sub-groups of 4 individuals), HA
315 contained the lowest number of shared ROH among the individuals but also showed the most
316 shared ROH among individuals.

317 3.2 | Signatures of positive selection

318 3.2.1 | ROH islands

319 The sharing of ROH among individuals, regardless of the population considered, was presented
320 Figure 3. Eight ROH islands were shared by at least 2 populations, and a minimum of 50% of
321 individuals concerned. However, only three of these regions were defined as ROH island in
322 each of the 4 populations.

323 We listed all ROH islands within each population which resulted in the identification of 270
324 ROH islands distributed among the four populations (Supplementary Informations S2 to S5,
325 for LB, LC, SY, and HA, respectively). The ROH islands were not evenly distributed across
326 populations and chromosomes. The average ROH island size was 2,737 kb, varying from 1,593
327 kb to 4,465 kb, depending on the population. The longest ROH island was observed in SY (21.4
328 Mb), while the shortest one was observed in LC (16.1 kb).

329

330 3.2.2 | Identifying selection signatures using iHS

331 The log(p-values) of iHS calculated along the genome are presented in Figure 4 for each
332 population (all regions identified with *calc-candidate_region* are described in Supplementary
333 Informations S6-S9). While numerous regions have been detected as under positive selection
334 overall, fewer candidate regions were detected for the French lines (LB, LC and, SY) than for
335 the Amercian pooled population (HA). The genome-wide highest estimated values of |iHS| were
336 8.97, 7.24, 5.67, and 9.09 for LB, LC, SY, and HA, respectively (with log(p-values) > 7.8).

337 In total, 72, 68, 76, and 54 ROH islands were identified in LB, LC, SY, and HA populations
338 respectively (Figure 5). Using iHS statistics, 55, 69, 73, and 362 signatures of selection were
339 detected for LB, LC, SY, and HA populations, respectively. Only 10.4%, 8.7%, 8.0%, and 5.6%

340 of the regions were detected by both methods (ROH + iHS) for LB, LC, SY, and HA
341 populations, respectively.

342

343 3.2.3 | Regions under positive selection shared by the four studied populations

344 Among the numerous regions identified for each population by either ROH or iHS methods,
345 only nine regions were shared by the four studied populations (Table 4). The average size of
346 these shared regions was 1135 kb. Five of them were located on chromosome 2, and the four
347 other regions were on chromosomes 12, 15, 16, and 20, respectively.

348 Depending on the population, six regions were identified by either ROH or iHS metrics. Two
349 regions, chr2_c and chr15_a, were only detected by ROH in all four populations, while a single
350 region, chr16_a, was only identified through significant iHS statistics in all the four populations
351 (Supplementary Information S10). The list of genes annotated in the nine shared genomic
352 regions is given in Supplementary Informations S11.

353

354 3.3 | Signatures of balancing selection

355 3.3.1. Regions under balancing selection detected within population

356 In total, 14, 24, 158, and 265 hot spots of polymorphism (i.e. without ROH) were identified in
357 LB, LC, SY, and HA populations, respectively. The numbers of heterozygous regions detected
358 for SY and HA populations were drastically larger than those observed for the LB and LC
359 selected lines. The average size of the detected heterozygous regions was 1,400 kb, varying
360 from 1,086 kb to 1,828 kb, depending on the population.

361 Tables listing all heterozygous regions within each population are presented in Supplementary
362 Informations S12 to S15, for LB, LC, SY, and HA, respectively.

363

364 3.3.2. Regions under balancing selection shared by the four studied populations

365 A substantial lack of ROH was observed in four regions of all studied rainbow trout populations
366 (Table 5). Two of them, chr10_a and chr19_a, were particularly small (53 kb and 70 kb,
367 respectively), but still contained at least 20 SNPs. The region chr10_a only encoded one of the
368 introns of the *ctnna2* (= catenin alpha 2) gene while chr19_a was composed of two genes,
369 *smarca5* (=SWI/SNF-related matrix-associated actin-dependent regulator of chromatin
370 subfamily A member 5) and *frem2* (= FRAS1-related extracellular matrix protein 2). A second
371 heterozygous region on chromosome 19 was larger (163 kb) but contained a single annotated
372 gene, *pou4f2* (= POU domain, class 4, transcription factor 2-like). A last region chr13_a
373 spanned over 1,100 kb) on chromosome 13 and was composed of 25 genes. The list of genes
374 annotated in the four shared genomic regions is given in Supplementary Informations S16.

375

376 3.4 | Identification and roles of genes underlying the regions under selection across all 377 populations

378 3.4.1. Common homozygous regions under positive selection

379 The nine common homozygous regions contained a total of 253 genes (listed in Supplementary
380 Information S11). A gene ontology (GO) study was performed and showed a significant over-
381 representation (p -value < 0.01) among the 253 genes of functions related to the following GO
382 terms: membrane (GO:0016020, CC: Cellular Component, p -value = $1.3e10^{-5}$), intrinsic and
383 integral component of membrane (GO:0031224; GO:0016021, CC, p -value = $0.001/0.005$), ion
384 binding (GO:0043167, MF: Molecular Function, p -value = 0.002), and nuclear speck
385 (GO:0016607, CC, p -value = 0.008).

386 Among the nine studied regions, the three regions chr2_a, chr2_c, and chr15_a, that contain
387 less than ten genes annotated in each, were analyzed in further detail to accurately define the
388 roles of underlying genes. The 17 genes located in these three regions are listed in Table 6 with
389 their associated biological functions. These genes play key roles in protein
390 transduction/maturation, genome stability, embryonic development, growth, energetic function,
391 reproduction, or immune function. In addition to this list of genes, a subset of 15 genes in the
392 six other homozygous regions already identified as signatures of selection in the literature were
393 further studied in terms of their biological functions. Detailed information for these genes is
394 also given in Table 6.

395 We studied the degree of protein identity among 10 vertebrate species for all the 17 genes of
396 regions chr2_a, chr2_c, and chr15_a (Table 7), considering a protein as highly conserved if its
397 identity between rainbow trout and other species was higher than 85%. Except for the proteins
398 linked to *cep162* (centrosomal protein of 162 kDa) and *zp4* (zona pellucida sperm-binding
399 protein 4-like) genes, all other proteins were highly conserved at least between the two studied
400 salmonids. In each of the three regions, one or two genes were highly conserved across the all
401 ten study species: in chr2_a, rainbow trout *cdk14* (cyclin-dependent kinase 14) protein had a
402 percent identity between 86 and 99.6% with the other species; in chr2_c, rainbow trout *brsk2a*
403 (serine/threonine-protein kinase *brsk2*) protein had between 92 and 96.3 % of percent identity
404 with the other species; in chr15_a, two genes, *chn1*(n-chimaerin) and *atp5mc1* (ATP synthase
405 lipid-binding protein, mitochondrial), also had protein percent identity ranging from 85% to
406 98% depending of the species.

407 Some other rainbow trout proteins (*tsnare1*, t-SNARE domain-containing protein 1; *pttg1IP*,
408 pituitary tumor-transforming gene 1 protein-interacting protein) were conserved to a lesser
409 extent (minimum 65% of percent identity) with the three other fish species, some being also

410 conserved at least with chicken (*adgrb1*, adhesion G protein-coupled receptor B1;*b4galnt4a*,
411 N-acetyl-beta-glucosaminyl-glycoprotein 4-beta-N-acetylgalactosaminyltransferase 1) or even
412 with all the nine study species (*zc3h15*, zinc finger CCCH domain-containing protein 15).

413

414 3.4.2. Common heterozygous regions under balancing selection

415 The four common heterozygous regions (Table 5) contained 29 genes (listed in Supplementary
416 Information S16). A gene ontology (GO) terms study showed no significant over-representation
417 of specific GO terms.

418 The degree of protein percent identity among 10 various vertebrate species for these 29 genes
419 are presented in supplementary information S17.

420 Regions chr10_a, chr19_a, and chr19_b contained only a few genes and were then analyzed in
421 further detail to accurately determine the role of underlying genes (Table 8). These genes play
422 key roles in cellular and nuclear organisation and in embryonic development.

423

424

425 **4| Discussion**

426 The objective of our study was to detect signatures of selection into domestic rainbow trout. To
427 reach that goal we studied four genetically distinct populations coming from different locations
428 either in France or in the North-West of the USA. We used two different approaches, ROH and
429 EHH, to detect the genomic regions shared by all populations using a HD SNP. We were able
430 to detect 9 very conserved regions and 4 hotspots of polymorphism, corresponding to 253 and
431 29 annotated genes, respectively.

432

433 4.1 | Genetic structure

434 First, we described the genetic structure of the populations under scrutiny. The three French
435 lines were moderately differentiated with F_{st} ranging from 0.10 to 0.12. These estimations were
436 congruent with those computed by D'Ambrosio et al.'s study (2019) with the same populations
437 that ranged between 0.09 and 0.14, but were estimated using a 38K SNPs array. These moderate
438 differences between the 3 French populations were consistent with the PCA we performed and
439 the history of these populations with a partly common INRAE origin (D'Ambrosio et al.,
440 2019). This trend is shared between European populations with for instance an average F_{st} of
441 0.13 between 12 European rainbow trout strains (Gross et al., 2007) or 0.12 among 9 Norwegian
442 populations (Glover, 2009). Similarly, US farmed populations are also weakly to moderately
443 differentiated with an average F_{st} of about 0.09 (Silverstein et al., 2004) or 0.13 (Liu et al.,
444 2017) and pairwise values ranging from 0.06 and 0.16. We observed a similar pattern in the
445 present study with the HA population that consisted in samples from 5 locations, which all
446 clustered together in the PCA. Reversely, we observed a large differentiation between our
447 French and US populations revealed by large F_{st} values (0.27-0.29). This is likely the result of
448 numerous factors, including selection, genetic drift and absence of gene flow between these
449 very geographically distant populations. In addition, the European farmed populations
450 originated from Californian domesticated strains, that have been shown to differ from strains
451 of North-Western USA (Stanković et al., 2015). We found 34 haplotypes distributed over 21
452 chromosomes that differed between the American pooled population (HA) and all French
453 populations (Supplementary information S1).

454 Due to the moderate to large differentiation between the 4 populations, the conserved regions
455 across all populations are likely to be the result of ancient natural selection traces.

456

457 4.2 | Comparison of methods to detect common signatures of positive selection

458 We used a double check of positive selection traces in the genome by using both ROH and EHH
459 approaches. However, for each population, only a few regions were identified by both methods.
460 These regions detected by more than one method represent stronger evidence of selection
461 signatures since outlier markers detected by various genome scan methods help to uncover true
462 selection signatures by reducing the number of false positives.

463 Even if both methods evaluate the homozygous large stretches in the genome, iHS also
464 considers information based on haplotypic version and linkage disequilibrium from a core SNP.
465 ROH approach detects homozygous regions regardless of their haplotypic versions, contrary to
466 iHS. Thus, it may detect a signature of positive selection even if various haplotypes were
467 present at the homozygous state in the population. In addition, while the ROH approach only
468 detects the homozygous large stretches (at least 500 kb in the present study), iHS can detect
469 small regions under positive selection as the only limitation in EHH region size is based on a
470 threshold value for a minimum LD (0.10). Consequently, the sizes of the detected homozygous
471 region varied between 1,065 kb and 2,857 kb based on ROH metrics and between 1,000 kb and
472 1,600 kb with iHS statistics.

473 The high number of regions (55, 69, 73, and 362) detected by iHS in our study was consistent
474 with numbers detected in either Atlantic salmon (López et al., 2019) or cattle (Saravanan et al.,
475 2021). However, these two previous studies used a lower threshold than ours ($\log(p\text{-value}) = 3$
476 and 2, respectively vs 4 in the present study). Lower numbers of regions were previously
477 detected by iHS in rainbow trout by Cádiz et al. (2021) and in Coho salmon by López et al.
478 (2021). We speculate that these differences in the numbers of detected signals may be linked to
479 the lower density of SNPs they used in both studies (57K or 200K chip versus 665K chip for

480 our study) and the subsequent lower ability to detect LD and haplotypes at fine scale. Indeed,
481 in the Chilean rainbow trout study (Cádiz et al., 2021), only one signal of positive selection was
482 detected by iHS located at 6.398-14.936 Mb on chromosome 20 of the Swanson reference
483 genome, which corresponds to the region 7.488-16.111 Mb on chromosome 20 of the Arlee
484 reference genome. Nevertheless, we also detected by iHS signals of selection in each of our
485 four studied populations, located at 10.5-16.5 Mb for LB, 11.2 – 13.3 Mb for LC, 13.0 – 14.2
486 Mb for SY and 12.3-13.2 Mb for HA (Supplementary Informations S6 to S9 for LB, LC, SY,
487 and HA, respectively). Thus, all these signals were consistent with the larger region identified
488 by Cádiz et al. (2021).

489 A common putative selection signature located at 13.0-13.2Mb could also be shared by all
490 studied populations. In this 200kb-region, we observed at least one iHS value over $|2.5|$ for LB,
491 LC and SY lines, but not for HA population. In this region of 200 kb on chromosome 20, six
492 genes were identified (*lgi1*, *noc3l*, *plce1*, *slc35g1*, *fra10ac1*, *tbc1d12*). Among these genes,
493 Cádiz et al. (2021) identified two candidates genes associated with domestication,
494 *noc3l* (nucleolar complex protein 3 homolog) and *plce1* (1-phosphatidylinositol 4,5-
495 biphosphate phosphodiesterase epsilon-1). Both are related to early development traits in
496 zebrafish (*noc3l*: Walter et al., 2009; *plce1*: Zhou et al., 2009).

497

498 4.3 | Biological functions of genes under positive or balancing selection

499 Among the 282 genes in the 13 regions detected under either positive or balancing selection,
500 most genes seem to play essential roles in fitness as expected with such a dataset comprising
501 both European and US populations. They are related to all main biological functions (genome
502 stability, cell organization, neuronal and embryonic development, energy metabolism, growth,
503 reproduction, and immunity). All identified biological functions were already described in other

504 studies of signatures of selection in farmed rainbow trout (Cádiz et al., 2021) and other
505 domesticated species (López et al., 2018, 2018; Naval-Sanchez et al., 2020; Baesjou &
506 Wellenreuther, 2021; Signer-Hasler et al., 2022).

507

508 4.3.1 Hotspots of heterozygosity and balancing selection for fitness traits

509 In livestock species, many variants under balancing selection are known to improve
510 performance in heterozygote state but cause defect in homozygous state (Hedrick, 2015;
511 Georges et al., 2019). However, in such cases of balancing selection, there is generally only one
512 homozygous state, which is deleterious at a locus level, while the alternative homozygous state
513 is observed in the population. In our study, we highlight four regions potentially involved in
514 balancing selection for which we observed a lack of any kind of long stretches of homozygosity.
515 Even if these regions are extremely heterozygous, the proteins associated with these genes are
516 highly conserved among vertebrates (Supplementary information S17). Many processes may
517 explain these surprising observations at first glance. First of all, these regions may concentrate
518 polymorphism in non-coding parts of the genome. Polymorphism in intronic regions may
519 promote various proteins by allowing alternative splicing. We may also observe an excess of
520 synonymous polymorphism in exons without effects on proteins. Further analyses must be
521 conducted to better understand the mechanisms underlying the maintenance of extreme
522 polymorphism, whether to validate the hypothesis of balancing selection or the existence of
523 high mutation and recombination rates in these specific regions.

524

525 In the heterozygous region chr10_a, the gene *ctnna2* (Table 8) enables actin filament binding
526 activity and is involved in the regulation of neuron migration and neuron projection
527 development. Thus, *ctnna2* plays an essential role in brain development among vertebrates

528 (Uvarov et al., 2014). In yonlong grouper, *ctnna2* seems implicated in vertebral development,
529 because significantly differentially expressed between normal and fish with lordosis (Li et al.,
530 2022). In mice, a homozygous for a mutation of *ctnna2* reduced body weight, male fertility,
531 and induced brain abnormalities (hypoplastic cerebellum, abnormal foliation pattern, ectopic
532 Purkinje cells, and abnormal pyramidal cells in the hippocampus). While the protein associated
533 to this gene is highly conserved among vertebrates (Uvarov et al., 2014; Supplementary
534 information S17), the gene exhibits a strong polymorphism in all the four studied rainbow trout
535 populations. However, a large part of its polymorphism is located in one intronic region (intron
536 6-7) of *ctnna2*. In the zfin database, five transcripts of this gene were identified (three mRNA
537 and two non-coding RNA). We hypothesize that the polymorphism in the intronic region of
538 *ctnna2* is essential for alternative splicing.

539 In the heterozygous region chr13_a (Supplementary information S16), *mmd* and *map2k4* are
540 identified as highly conserved across vertebrates (Supplementary information S17). The
541 gene *mmd* plays an important role in maturing macrophages, which is essential for immune
542 response as observed in mice (Lin et al., 2021). The gene *map2k4* is implicated in a variety of
543 cellular processes (proliferation, differentiation, transcription regulation, development), seems
544 to play a role in liver organogenesis and embryonic development during gastrulation, as
545 demonstrated by morpholino-mediated knockdown in zebrafish (Seo et al., 2010), and
546 implicated in immune response in yellow catfish (Zheng et al., 2022). The inflammatory
547 process in immune response seems linked to the polymorphism of the *map2k4* gene, which is
548 consistent with our hypothesis of balancing selection, and more precisely potential ancestral
549 trans-species polymorphism in this genomic region (Gu et al., 2016; Fijarczyk & Babik, 2015).
550 Trans-species polymorphism is a crucial evolutionary mechanism for sharing adaptative genetic
551 variation across taxa (Klein et al., 1998). The study of this mechanism has primarily

552 concentrated on major histocompatibility complex genes, but a few studies described this
553 process for other immune genes (Ferrer-Admetlla., et al., 2008; Leffler et al., 2013; Těšický &
554 Vinkler, 2015). Maintaining genetic diversity in regions related to the immune system may be
555 essential to resilience against various pathogens. In addition, this region of chromosome 13 has
556 been recently detected as a significant QTL playing a role on resistance to temperature (Lagarde
557 et al., 2022).

558 In the heterozygous region chr19_a (Table 8), the protein encoded by *smarca5* is a component
559 of chromatin remodeling and spacing factor RSF, a facilitator of the transcription of class II
560 genes by RNA polymerase II (zebrafish: Armas et al., 2013; Ding et al., 2021; mice: Limi et
561 al., 2018). The protein is highly conserved among vertebrates (Supplementary information
562 S17), which is consistent with its essential role thought to regulate the transcription of many
563 genes by altering the chromatin structure around those genes. In the same region
564 chr19_a, *frem2* codes for an extracellular matrix protein required for maintenance of the
565 integrity of skin and renal epithelia in zebrafish (Gautier et al., 2008). This protein is moderately
566 conserved across vertebrates (Supplementary information S17). In a study searching for
567 genomic regions with ancestral trans-species polymorphism shared between humans and
568 chimpanzees (Leffler et al., 2013), *frem3*, an important paralog of *frem2*, was identified under
569 balancing selection. However, further studies should test the hypothesis of trans-species
570 conservation of *map2k4* and *frem2* genes that may help to understand the various cellular
571 processes in which the gene is implicated.

572 In the heterozygous region chr19_b (Table 8), *pou4f2* protein is highly conserved among
573 vertebrates (Supplementary information S17) and is a tissue-specific DNA-binding
574 transcription factor involved in the development and differentiation of specific cells. It

575 maintains the visual system neurons in the retina and the lateral line (DeCarvalho et al.,
576 2004) and seems also related to cardiac development in zebrafish (Maskell et al., 2017).

577

578 4.3.2 Hotspots of homozygosity and positive selection for essential biological functions

579 4.3.2.1 | Regions and genes involved in cellular and nuclear organization, and embryonic 580 development

581 In homozygous region chr2_a, three genes plays important roles in embryonic development and
582 then fitness (*cep162*, *tsnare1*, *mrap2*, Table 6). In the homozygous region chr2_b (Table 6), the
583 gene *pbx1* (pre-B-cell leukemia transcription factor 1) is related to early development in
584 zebrafish (Teoh et al., 2010). Mutations in this gene generally cause major malformations,
585 which seem to play an essential role in survival in various species (zebrafish: Teoh et al., 2010;
586 mouse: Selleri et al., 2001; human: Le Tanno et al., 2017). It was detected under positive
587 selection in a Chilean farmed rainbow trout population (Cádiz et al., 2021). However only
588 moderate percent identity (> 65%) is observed between *pbx1* proteins across vertebrates.

589 In the homozygous region chr15_a, many genes (*chn1*, *atp5mc1*, *zc3h15*, *nid2* and *brca2*) were
590 playing essential roles in cell functioning and early development (Table 6). However only two
591 of them were highly conserved among vertebrates (> 85%; *chn1* and *atp5mc1*). The gene
592 *atp5mc1* is a crucial gene for mitochondrial cristae morphology, and plays important roles in
593 metabolic processes associated to growth (Table 6; Palmer et al., 2011; Miller et al., 2019;
594 Wang et al., 2020). In zebrafish, a morpholino knockdown of *chn1* reveals its crucial role in
595 early development, revealing severe abnormalities (development of round somites, lack of yolk
596 extension, and kinkled posterior notochord) (Leskow et al., 2006).

597 Three genes located in close vicinity in region chr16_a (between 46.42 and 46.53 Mb;
598 Supplementary information S11), *samd10* (sterile alpha motif domain-containing protein 10-

599 like), *dnajc5* (dnaJ homolog subfamily C member 5-like), and *tpd54* (tumor protein D54) were
600 also detected in close chromosomal vicinity and under positive selection in ten modern goat
601 breeds and one wild Bezoar goat (Signer-Hasler et al., 2022). This cluster of genes has a
602 significant role in survival and cellular processes (Table 6). In addition, in this region chr16_a,
603 the protein of the gene *magi2* (membrane-associated guanylate kinase, WW and PDZ domain-
604 containing protein 2, Table 6) plays a vital role in embryogenesis in zebrafish (Borah et al.,
605 2016). The gene *magi2* was also identified under positive selection in a domesticated sheep
606 breed compared to the wild Asiatic mouflon (Cumer et al., 2021).

607

608 4.3.2.2 | Regions and genes involved in neural and brain development, and behaviour

609 In total, we identified 7 genes as primarily associated to neural and brain development in both
610 regions detected under positive selection (*tsnare1*, *cdk14*, *brsk2a*, *auts2*, *brd2*,
611 *znf135*, and *grxcr1*). Some genes (*brsk2a*, *znf135*, *grxcr1*, *auts2*; Table 6), related to brain
612 development may induce behavior modifications in farmed animals, that may be related to
613 domestication processes (Pasquet, 2018; Milla et al., 2021; Deng et al., 2022; Liu et al., 2022).
614 This is in line with Źarski et al. (2020) study showing that domestication modulates gene
615 expression involved in neurogenesis.

616 In particular, the gene *auts2* gene was previously identified under positive selection both in
617 cattle (Consortium, bovine Hapmap, 2009) and in domesticated Atlantic salmon populations
618 from Canada and Scotland compared to their wild Atlantic salmon counterpart (López et al.,
619 2018). The gene *znf135* was also detected under positive selection in a farmed population of
620 Atlantic salmon compared to a wild-type population (Gutierrez et al., 2016). The gene *grxcr1*
621 was detected under positive selection in the Tharparkar cattle (Saravanan et al., 2021). It

622 strongly suggests that all these genes play a key role in domestication processes and may act on
623 essential behaviours in both terrestrial and aquatic farmed animals.

624

625 4.3.2.3 | Regions and genes involved in growth metabolism

626 Genes related to growth metabolism were only identified in four regions under positive
627 selection, none of them were detected in high heterozygosity regions.

628 In the homozygous region chr2_a (Table 6), the protein *mrap2* (melanocortin-2 receptor
629 accessory protein 2A) is associated to growth. A lack of this gene exhibit severe obesity in
630 many species (human, zebrafish, rodent: Liu et al., 2013; sea lamprey: Zhu et al., 2019;
631 snakehead: Wang et al., 2021). Yoshida et al. (2017) detected a growth-QTL in Atlantic salmon
632 and considered *mrap2* as a candidate gene for growth up to 25 months. In addition, *mrap2* was
633 identified in the Chilean farmed rainbow trout population as under positive selection (Cádiz et
634 al., 2021). A QTL related to sea lice resistance in rainbow trout (Cáceres et al., 2021) was also
635 detected in the region chr2_a (located from 10.43 Mb to 11.81 Mb of the Swanson reference
636 genome, which corresponds to 26.69 Mb – 28.07 Mb of the Arlee reference genome). Cáceres
637 et al. (2021) explained that having a high potential for growth seem essential for sea lice
638 resistance. Indeed, proteomic investigations allow to establish a link between growth and
639 immune function in salmonids (Causey, 2018).

640 In homozygous region chr2_b (Table 6), the *col9a2* (collagen alpha-2(IX) chain) gene is a
641 component of cartilage and seems also related to growth (Xu et al., 2022).-This gene is detected
642 under positive selection in a Scottish farmed population of Atlantic salmon (López et al.,
643 2018). In addition, the gene *scap* (sterol regulatory element-binding protein cleavage-activating

644 protein) was already identified under positive selection in six farmed Pacific white Shrimp
645 populations (Wang et al., 2022).

646 In the homozygous region chr2_d (Table 6), the gene *igf-1a* (insuline like growth factor receptor
647 1a) plays an important role in growth and transformation events. In salmonids, expressions of
648 *igf-1a* and growth hormone were demonstrated to be modified between domesticated and wild
649 populations of rainbow trout and coho salmon (Tymchuk et al., 2009). The same observation
650 was made with a higher expression of *igf-1a* between larvae from domesticated spawners than
651 larvae from wild spawners of the Eurasian perch (Palińska-Żarska et al., 2021). In addition, *igf-*
652 *I* was also observed as a marker of domestication in dogs (Wayne & vonHoldt, 2012).

653 In the homozygous region chr16_a, the *emilin-3a* gene (elastin microfibril interfacer 3a, Table
654 6) plays a role in extracellular matrix organization and elastic fiber formation. Its gene
655 expression is related to embryonic development and involved in muscle fiber development in
656 zebrafish (Milanetto et al., 2008). *Emilin-3a* had already been identified as under positive
657 selection in one population of F2 Australian snapper farmed population compared to the first
658 generation (F1) of domestication of a wild population (Baesjou & Wellenreuther, 2021). Thus,
659 this signature of selection can be considered as a result of the domestication process.

660 All identified growth-related genes seem associated with domestication. This assertion is
661 confirmed for five genes (*mrp2*, *col9a2*, *scap*, *igf-1a*, *emilin-3*) that were also identified under
662 positive selection in various farmed populations with favorable alleles linked to better growth
663 phenotypes (Table 6).

664

665 4.3.2.4 | Regions and genes involved in reproduction

666 Very few genes directly related to reproduction traits were only identified in highly
667 homozygous regions.

668 In the homozygous region chr2_b, the *brd2* (bromodomain-containing protein 2, Table 6) gene
669 is implicated in several biological process (see section 4.4.1.). It seems related to oogenesis and
670 egg-to-embryo transition in zebrafish (DiBenedetto et al., 2008), which is consistent with a
671 QTL detected for egg size in this region in rainbow trout (D'Ambrosio et al., 2020). Moreover,
672 it seems that *brd2* is involved in spermatogenesis or folliculogenesis, as demonstrated in situ
673 on mice cells (Rhee et al., 1998). Khendek et al. (2017) compared the reproductive
674 performances (egg size, gonadal histology, hormonal levels) between domesticated and F1 with
675 wild broodstock of Eurasian perch populations. They showed that domestication may have
676 increased the oocyte diameter and the level of 17 β -Estradiol, but decreased the embryo survival
677 of domesticated fish. This gene was also identified under positive selection in a selected
678 Canadian population of Atlantic salmon (López et al., 2018).

679 In the homozygous region chr15_a (Table 6), the gene *zp4* has already been identified under
680 positive selection in a farmed Scottish population of Atlantic salmon compared to a wild
681 population (López et al., 2018), and may be related to domestication process.

682

683 4.3.2.5 | Regions and genes involved in immunity

684 Magris et al. (2022) observed that regions under positive selection revealed an enrichment of
685 KEGG terms related to viral infection in farmed brown trout. However, it should be noticed
686 that in our study, few genes related to immune function were identified and no enrichment in
687 immune terms was observed in GO analysis.

688 Genes related to immune function were mainly identified in three different regions detected as
689 putatively under positive selection for two of them and under balancing selection for the last
690 one.

691 In the homozygous region chr2_b (Table 6), genes *tnfaip8l2b* (tumor necrosis factor, alpha-
692 induced protein 8-like protein 2 B) and *atg5* (autophagy protein 5) are related to immune
693 functions. Note that *atg5* is well conserved across vertebrates (> 80%).

694 In the region chr15_a, the gene *zc3h15* (Table 6) seems to have an inhibitory effect on HIV-1
695 replication and then on HIV infection in vitro (mice cells) (Capalbo et al., 2010).

696 A last gene in the region chr16_a, the gene *atp1b3* (sodium/potassium-transporting ATPase
697 subunit beta-1-interacting protein 3) was also identified under positive selection in farmed
698 Atlantic Salmon (Naval-Sanchez et al., 2020). In the Senegalese sole, *atp1b3a* and *atp1b3b*
699 paralogs have been hypothesized to be involved in response to low salinity (Armesto et al.,
700 2015). In addition, this gene is involved in some immune responses. It was shown in cell culture
701 study, that *atp1b3* inhibits hepatitis B virus replication via inducing NF-kappa B activation
702 (human: Zhang et al., 2021) and is involved in numerous viral propagation such as HIV and
703 EV71 (Zheng et al., 2020) in cell culture experiments.

704

705 4.4. Conclusion

706 To sum up, we identified 13 regions under selection with numerous genes strongly involved in
707 essential biological functions. By identifying signatures of selection shared by our four studied
708 populations, we have focused our detection on regions related to ancient evolutionary processes
709 that are essentially important for species survival. We only identified nine homozygous regions
710 presumably under positive selection and four heterozygous regions putatively under balancing

711 selection in four different rainbow populations. While common homozygous regions may be
712 associated with important biological functions underlying both fish fitness and domestication,
713 the heterozygous regions seem mainly linked to fitness functions (cell organization, embryonic
714 development, and immunity) which are involved at different developmental stages or to cope
715 with various pathogens or abiotic stressors. Maintaining genetic diversity in these regions could
716 be essential for the species survival.

717 This study allows us to confirm the importance of a large set of 17 genes already detected as
718 under positive selection in previous studies, among which 10 genes were identified in fishes
719 (*auts2*, *atp1b3*, *zp4*, *znf135*, *igf-1a brd2*, *col9a2*, *mrp2*, *pbx1* and *emilin-3*). We also identify
720 new promising candidate genes as important for rainbow trout fitness. In our opinion, this study
721 substantially increases knowledge of evolutionary processes and helps to determine the
722 genomic location and the nature of the genetic variation that must be maintained in rainbow
723 trout populations for domestication and selection purposes.

724

725 **Acknowledgements**

726 We thank the two breeding companies “Viviers de Sarrance” and “Milin Nevez” that allow us
727 to use their HD genotypes to perform the study. This study was partly supported by the
728 European Maritime and Fisheries Fund and FranceAgrimer (Hypotemp project, n° P
729 FEA470019FA1000016).

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1536 [0193-4](https://doi.org/10.1186/s40170-018-0193-4)

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1539 **Data Accessibility and Benefit-Sharing**

1540 Restrictions applied to the availability of the data that support the findings of this study, which
1541 were used under license and so are not publicly available. The data can be made available for
1542 reproduction of the results from Florence Phocas (florence.phocas@inrae.fr) on request via a
1543 material transfer agreement and with permission of the two breeding companies “Viviers de
1544 Sarrance” (Sarrance, France) and “Milin Nevez” (Plouigneau, France).

1545

1546 **Author contributions**

1547 Katy Paul: Investigations, Methodology, Formal analysis, Writing - Original Draft;

1548 Gwendal Restoux: Conceptualization, Methodology, Draft Reviewing;

1549 Florence Phocas: Supervision, Conceptualization, Methodology, Investigation, Formal
1550 analysis, Resources, Writing - Original Draft.

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1562 **Tables and Figures (with captions)**

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1565 **TABLE 1.** Data information used to phase the HD genotypes of the study females that belong
1566 to the parental cohorts. Number of individuals and SNPs available after quality control

Line	Status of individuals	Number of individuals	Number of SNP used
LB	parents	288	571,319
	offsprings	1,297	29,091
LC	parents	173	569,03
	offsprings	1,350	30,379
SY	parents (dams + 1 sire)	16	569,03
	offsprings (+ 8 sires)	866	32,725

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1569 **TABLE 2.** ROH statistics and inbreeding coefficients of the four studied populations (Standard
1570 deviations are indicated in brackets).

Population	Average number of ROH	Average size of ROH (in kb)	Average F_{ROH}
LB	168 (14.6)	2,770 (270.8)	0.20 (0.02)
LC	157 (15.9)	2,485 (326.8)	0.17 (0.03)
SY	141 (33.5)	1,860 (291.2)	0.12 (0.05)
HA	167 (65.6)	1,433 (145.6)	0.04 (0.03)

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1573 **TABLE 3.** Genome-wide F_{st} statistics derived two-by-two between the four populations.

	LC	LB	HA
SY	0.104	0.122	0.275
LC		0.122	0.275
LB			0.289

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1580 **TABLE 4.** Homozygous regions under positive selection in the four studied populations.

Region	CHR	Start (Mb)	End (Mb)	Size (kb)
chr2_a	2	25.40	26.30	900
chr2_b	2	31.60	34.20	2600
chr2_c	2	46.00	46.66	664
chr2_d	2	69.70	71.20	1500
chr2_e	2	88.46	89.34	878
chr12_a	12	57.97	59.10	1138
chr15_a	15	38.96	39.57	610
chr16_a	16	45.80	47.00	1200
chr20_a	20	19.10	19.83	726

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1582 **TABLE 5.** Highly heterozygous regions shared by the four studied populations.

Region	CHR	Start (Mb)	End (Mb)	Size (kb)	SNP number	SNP density per Mb
chr10_a	10	56.314	56.366	53	20	379
chr13_a	13	46.959	48.071	1,112	446	401
chr19_a	19	10.753	10.823	70	24	342
chr19_b	19	11.354	11.517	163	52	319

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1598 **TABLE 6.** List and functions of the 17 genes annotated in three homozygous regions (chr2_a,
1599 chr2_c and chr15_a) shared by the four rainbow trout populations, and the 15 genes in the six
1600 other regions already identified as signatures of selection in the literature. *SS : Identify by
1601 signature of selection in that study

Region	Gene name	Protein name		General functions	References
chr2_a	<i>mrap2</i>	melanocortin-2 receptor accessory protein 2A	Cellular organization and growth	May regulate both receptor trafficking and activation in response to ligands. Link to energy homeostasis control and body weight regulation. Linked to severe obesity in many species	Liu et al., 2013 (human, zebrafish, rodent); Zhu et al., 2019 (sea lamprey); Wang et al., 2021 (snakehead); SS : Cadiz et al., 2021 (rainbow trout), Cumer et al., 2021 (goat)
	<i>cep162</i>	centrosomal protein of 162 kDa	Cellular and nuclear organization	Involved in cilium assembly (promote transition at the cilia base). Acts by specifically recognizing and binding the axonemal microtubule.	Wang et al., 2013
	<i>uncharacterized LOC110539089</i>				
	<i>adgrb1</i>	adhesion G protein-coupled receptor B1	Neuronal and embryonic development	Essential for growth and metastasis of solid tumors (zebrafish). Plays a role during brain/neuron development, associated with autism in mice and human (BAI1 synonymous of <i>adgrb1</i>).	Purcell, 2017 (human); Cazorla-Vázquez & Engel, 2018 (from zebrafish to human); Shiu et al., 2022 (mice)
	<i>tsnare1</i>	t-SNARE domain-containing protein 1	Cellular organization and neuronal development	Predicted to be involved in intracellular protein transport; vesicle docking; vesicle fusion ; and integral component of membrane. Neurodevelopment function.	Fromer et al., 2016 (zebrafish and human)
	<i>pttg1ip</i>	pituitary tumor-transforming gene 1 protein-interacting protein	Cellular organization and growth	Participates in metaphase-anaphase transition of the cell cycle and facilitates translocation of <i>ptg1</i> into the nucleus + allow to predict breast cancer survival + induced transcriptional activation of transcriptional basic fibroblast growth factor (when coexpressing with <i>ptg1</i>).	Repo et al., 2017 (human)
	<i>Cdk14</i>	cyclin-dependent kinase 14	Neuronal and embryonic development	Regulator of cell cycle progression and proliferation + role in meiosis, neuron differentiation/craniofacial development (Wnt signaling pathway)	Margarit et al., 2014 (zebrafish); Yin et al., 2021 (human)
chr2_b	<i>pbx1</i>	pre-B-cell leukemia transcription factor 1	Neuronal and embryonic development	Related to early development in zebrafish. Mutations in this gene generally cause major malformations, which seem to play an essential role in survival in various species.	Teoh et al., 2010 (zebrafish); Selleri et al., 2001 (mouse); Le Tanno et al., 2017 (human); SS: Cadiz et al., 2021 (rainbow trout)
	<i>col9a2</i>	collagen alpha-2(IX) chain	Neuronal and embryonic development	Component of cartilage, implicated in human intervertebral disc degeneration (IVDD) and seems also related to growth. Mutations in this gene may cause diverse syndromes, such as multiple epiphyseal dysplasias and ocular, skeletal, orofacial, and auditory abnormalities in humans.	Muragaki et al., 1996; Baker et al., 2011; Xu et al., 2022 (human); SS: Lopez et al., 2018 (atlantic salmon)
	<i>brd2</i>	bromodomain containing 2	Nuclear and cellular organization, neuronal and embryonic development	Associated with transcription complexes and acetylated chromatin during mitosis. Potential role in oogenesis, egg-to-embryo transition, and proper development of the digestive and central nervous systems (zebrafish). And involved in spermatogenesis or folliculogenesis, as demonstrated in situ on mice cells.	DiBenedetto et al., 2008 (zebrafish); Rhee et al., 1998 (mouse); SS: Lopez et al., 2018 (atlantic salmon)
	<i>scap</i>	sterol regulatory element-binding protein cleavage-activating protein	Cellular organization	Binds to sterol regulatory element binding proteins (SREBPs) and transports them from the ER to the Golgi.	Howarth et al., 2013 (zebrafish); SS: Wang et al., 2022 (Pacific White Shrimp)

Table 6 (continued)

Region	Gene name	Protein name		General functions	References
	<i>tnf-α-ip8l2b</i>	tumor necrosis factor, alpha-induced protein 8-like protein 2 B	Immunity	Predicted to be involved in the negative regulation of T-cell activation, inflammatory response, innate and adaptative immunity by maintaining immune homeostasis.	Umasuthan et al., 2014 (Oplegnathus fasciatus); Sullivan et al., 2017 (vertebrates)
	<i>atg5</i>	autophagy protein 5	Immunity	Involved in several cellular processes linked to the immune response, such as autophagic vesicle formation, innate antiviral immune response, lymphocyte development and proliferation in mice.	Miller et al., 2008; Ye et al., 2018 (mouse)
chr2_c	<i>brsk2a</i>	serine/threonine-protein kinase BRSK2	cellular organization, neuronal and embryonic development	Enable in several functions: ATP/ATPase binding activity, proteine kinase activity. Key role in polarization of neurons and axonogenesis, cell cycle progress (apoptotic signaling pathway) and insulin secretion (metabolic process). This gene is related to autism spectrum disorder (social deficit) and locomotor defects (larval phase and adulthood) in zebrafish	Hiatt et al., 2019 (human); Deng et al., 2022 (human); Liu et al., 2022 (zebrafish)
	<i>abtb2b</i>	Ankyrin Repeat And BTB Domain Containing 2b	Cellular organization	Predicted to be involved in SMAD protein signal transduction., heterodimerization activity. Act upstream of or within cellular response to toxic substance.	
	<i>b4galnt4a</i>	N-acetyl-beta-glucosaminyl-glycoprotein 4-beta-N-acetylgalactosaminyltransferase 1	Cellular organization	Enables acetylgalactosaminyltransferase activity. Predicted to be located in Golgi cisterna membrane. Predicted to be integral component of membrane.	
chr2_d	<i>igf-1a</i>	insulin-like growth factor 1a receptor	Growth	Plays a critical role in transformation events. Cleavage of the precursor generates alpha and beta subunits. It is highly overexpressed in most malignant tissues where it functions as an anti-apoptotic agent by enhancing cell survival.	SS : Wayne & vonHoldt, 2012 (dog); Lopez et al., 2019 (atlantic salmon)
chr2_e	<i>znf135</i>	gastrula zinc finger protein XICGF26.1	Neuronal development and cellular organization	Involved in cytoskeleton organization, regulation of cell morphogenesis, and RNA-binding. A mutation of znf135 is related to neurological symptoms in humans.	Raghuram et al., 2017 (human); SS : Gutierrez et al., 2016 (atlantic salmon)
chr12_a	<i>grxcr1</i>	glutaredoxin domain-containing cysteine-rich protein 1-like	Neuronal development and cellular organization	Involved in actin organization in hair cells and is associated with a non-syndromic hearing impairment and the regulation of hair bundle morphogenesis in mouse. A mutant for this gene was identified in mice and linked to hyperactivity (modifies behaviour).	Liu et al., 2021, Lorente-Cánovas et al., 2022 (mouse); SS: Saravanan et al., 2021 (cattle)
chr15_a	<i>chn1</i>	N-chimaerin	Embryonic development	Encodes GTPase-activating protein. Plays an important role in neuronal signal-transduction mechanisms. Implication during embryonic development: cell polarity and lack of yolk extension. In zebrafish, a morpholino knockdown of chn1 reveals its crucial role in early development, revealing severe abnormalities (development of round somites, lack of yolk extension, and kinked posterior notochord).	Leskow et al., 2006 (zebrafish); Miyake et al., 2008; Ip et al., 2012 (human)
	<i>atp5mc1</i>	ATP synthase lipid-binding protein, mitochondrial	Energetic function	Loss of ATP synthase -> aberrant mitochondria cristae morphology + energy metabolism correlated to immune system	Palmer et al., 2011; Miller et al., 2019 (human); Wang et al., 2020 (chicken)

Table 6 (continued)

Region	Gene name	Protein name		General functions	References
	<i>zc3h15</i>	zinc finger CCCH domain-containing protein 15	Embryonic development and cellular organization	Embryonic development (positive regulation of GTPase activity) / Elongation processivity (high tumor progression in melanoma). In addition, in vitro (mice cells) that <i>zc3h15</i> knockdown had an inhibitory effect on HIV-1 replication and then on HIV infection.	Capalbo et al., 2010 (mice); Li et al 2021 (human)
	<i>zp4</i>	zona pellucida sperm-binding protein 4-like	Reproduction	Extracellular matrix that surrounds the oocytes and early embryo. Plays vital roles during oogenesis, gamete development, fertilization and preimplantation development. Mutation in this gene induces infertility in both males and females in mammals.	Wassarman & Litscher, 2018 (fish); Li et al., 2021 (zebrafish); SS : Lopez et al., 2019 (atlantic salmon)
	<i>uncharacterized protein LOC110490841</i>				
	<i>nid2</i>	nidogen-2-like	Cellular and nuclear organization	Cell-adhesion protein that binds collagens I and IV and laminin and may be involved in maintaining the structure of the basement membrane. Linked to ovarian cancer	Torky et al., 2018 (human); Zhang et al., 2022 (zebrafish, mouse)
	<i>brca2</i>	breast cancer type 2 susceptibility protein	Genome stability and cellular organization	Essential for efficient homology-directed ADN repair. Impaired homology-directed repair caused by <i>brca2</i> deficiency leads to chromosomal instability and tumorigenesis through lack of repair or misrepair of DNA damage. plays an essential role in ovarian development and tumorigenesis of reproductive tissues	Shive et al., 2010 (zebrafish); Rodriguez-Mari et al., 2011 (zebrafish); Moynahan et al., 2001; Chen et al., 2018 (human)
chr16_a	<i>atp1b3</i>	sodium/potassium-transporting ATPase subunit beta-1-interacting protein 3	Cellular and nuclear organization	ATPase responsible for establishing and maintaining the electrochemical gradient of Na ⁺ and K ⁺ ions across the plasma membrane, essential for osmoregulation.	Zhang et al., 2019 (human); SS : Naval-Sanchez et al., 2020 (atlantic salmon)
	<i>Dnajc5</i>	dnaJ homolog subfamily C member 5-like	Cellular and nuclear organization	Regulated the ATPase activity of 70kDa heat shock proteins and plays a role in membrane trafficking and protein folding. This protein has been shown to have also anti-neurodegenerative properties in human with a gene expression study.	Nosková et al., 2011 (human); SS : Signer-Hasler et al., 2022 (goat)
	<i>samD10</i>	sterile alpha motif domain-containing protein 10-like	Cellular and nuclear organization	Linked to binding activity and transmembranaire pathway	SS : Signer-Hasler et al., 2022 (goat)
	<i>nol4</i>	nucleolar protein 4-like	Cellular and nuclear organization	Predicted to enable RNA binding activity	SS : Signer-Hasler et al., 2022 (goat)
	<i>tpd54</i> (= <i>TPD52L2</i>)	tumor protein D54	Cellular and nuclear organization	Related to cellular organization, are characterized by an N-terminal coiled-coil motif that forms homo and heteromeric complexes and affects cell proliferation, adhesion, and invasion.	Mukudai et al., 2013; Zhuang et al., 2019 (human); SS : Signer-Hasler et al., 2022 (goat)
	<i>magi2</i>	membrane-associated guanylate kinase, WW and PDZ domain-containing protein 2	Neuronal and embryonic development	Plays a role in regulating activin-mediated signaling in neuronal cells. In zebrafish, the protein of this gene plays a vital role in embryogenesis.	Borah et al., 2016 (zebrafish); SS : Cumer et al., 2021 (sheep); Hou et al., 2012 (cattle)
	<i>emilin3</i> (= <i>emilin-2</i>)	EMILIN-3	Embryonic development and growth	Played a role in extracellular matrix organization and elastic fiber formation. Its gene expression was related to embryonic development and involved in muscle fiber development in zebrafish.	Milanetto et al., 2008 (zebrafish); SS : Baesjou & Wellenreuther, 2021 (australasian snapper)
chr20_a	<i>auts2</i>	autism susceptibility gene 2 protein homolog	Neuronal development	Related to central nervous system development and is associated with autism in humans.	Oksenberg et al., 2013; Hori et al., 2021 (human); SS : Lopez et al., 2018 (atlantic salmon); Consortium, bovine hapmap, 2009 (cattle)

1602 **TABLE 7.** Percentage of protein identity between rainbow trout and nine other vertebrate
1603 species for all genes annotated in homozygous regions chr2_a, chr2_c and chr15_a.

Region	gene_ID	Human	Mouse	Goat	Cattle	Pig	Chicken	Zebrafish	Medaka	Atlantic salmon
chr2_a	<i>mrap2a</i>	45.71	43.52	43.87	44.98	45.45	42.20	56.22	50.45	87.55
	<i>cep162</i>	36.61	37.50	40.95	40.95	50.00	53.73	38.61	62.50	80.66
	<i>adgrb1</i>	62.37	63.44	62.12	61.95	61.74	67.72	84.02	80.94	98.16
	<i>tsnare1</i>	54.78	31.50	56.99	55.79	56.02	60.74	85.62	78.55	98.29
	<i>pttg1IP</i>	60.00	57.89	57.04	57.04	58.82	59.74	70.92	66.03	93.89
	<i>cdk14</i>	87.05	87.05	86.44	86.02	85.99	87.24	88.96	91.08	99.58
chr2_c	<i>brsk2a</i>	92.12	92.50	92.66	92.19	92.66	93.82	96.14	92.05	96.26
	<i>abtb2b</i>	71.54	70.76	71.93	71.74	71.74	72.46	81.05	61.68	97.35
	<i>b4galnt4a</i>	63.35	65.38	57.14	64.63	64.95	66.37	66.06	79.96	96.55
chr15_a	<i>chn1</i>	88.80	86.59	88.04	87.32	88.04	88.10	85.29	85.01	98.04
	<i>atp5mc1</i>	97.37	87.10	91.76	94.44	93.33	86.17	91.30	97.87	94.12
	<i>zc3h15</i>	69.35	68.57	67.55	67.55	67.55	66.90	74.33	71.57	97.30
	<i>zp4</i>	29.67	29.61	31.87	37.47	30.21	31.46	45.60	49.74	74.74
	<i>nid2</i>	52.00	51.16	51.11	51.11	51.22	55.00	58.14	52.78	97.87
	<i>brca2</i>	46.24	43.72	37.12	32.42	45.61	45.85	38.68	54.08	92.05

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1605 **TABLE 8.** List and functions of the 4 genes annotated in three heterozygous regions (chr10_a,
1606 chr19_a, and chr19_b) shared by the four rainbow trout populations.

Region	Gene name	Protein name	General function	References
chr10_a	<i>ctnna2</i>	catenin alpha 2	Enables actin filament binding activity, and involved in negative regulation of Arp2/3 complex-mediated actin nucleation. Regulation of neuron migration and of neuron projection development. Implicated in brain malformations. Seems implicated in vertebral development((deformities) in Yunlong grouper.	Uvarov et al., 2014 (vertebrates); Li et al., 2022 (Yunlong grouper)
chr19_a	<i>smarca5</i>	SWI/SNF-related matrix-associated actin-dependent regulator of chromatin subfamily A member 5	The protein encoded by this gene is a member of the SWI/SNF family of proteins. Members of this family have helicase and ATPase activities and are thought to regulate transcription of certain genes by altering the chromatin structure around those genes. The protein encoded by this gene is a component of the chromatin remodeling and spacing factor RSF, a facilitator of the transcription of class II genes by RNA polymerase II	Ding et al., 2021 (zebrafish); Limi et al., 2018 (mice); Armas et al., 2013 (zebrafish)
	<i>frem2</i>	FRAS1-related extracellular matrix protein 2	Plays a role in epidermal-dermal interactions -> important for the integrity of skin and renal epithelia.	Gautier et al., 2008 (zebrafish)
chr19_b	<i>pou4f2</i>	POU domain, class 4, transcription factor 2-like	May be involved in maintaining visual system neurons in the retina, and in the lateral line. The level of the encoded protein is also elevated in a majority of breast cancers, resulting in accelerated tumor growth. Seems link to cardiac development in zebrafish	DeCarvalho et al., 2004 (zebrafish); Maskell et al. 2017 (zebrafish)

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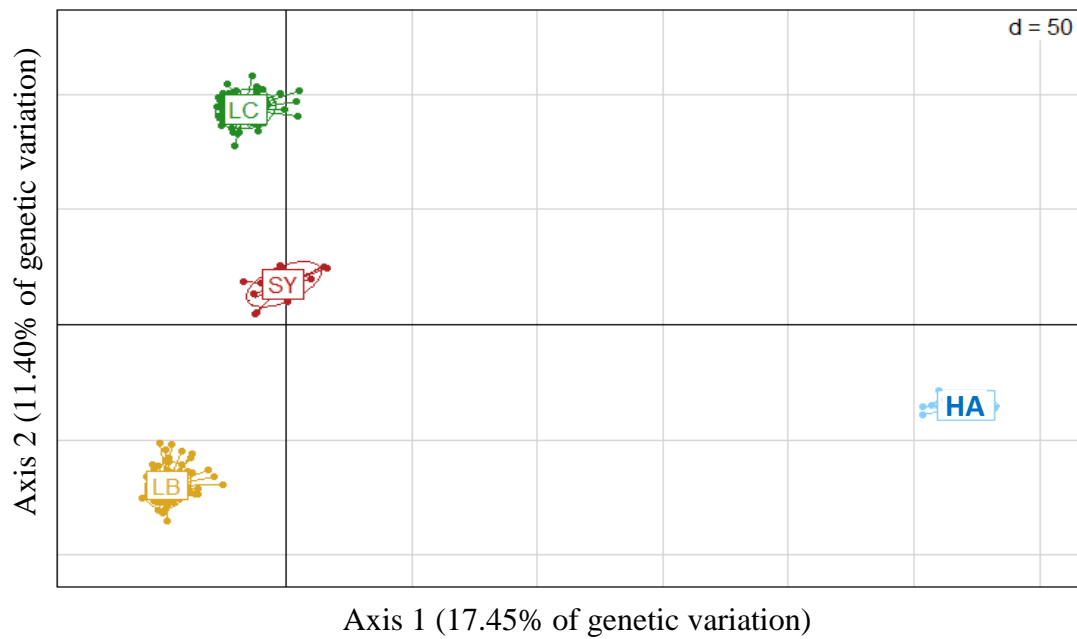


FIGURE 1. Principal component analysis (PCA) of the genetic diversity of the four rainbow trout populations (LB, LC, SY, and HA) based on 546,903 SNPs.

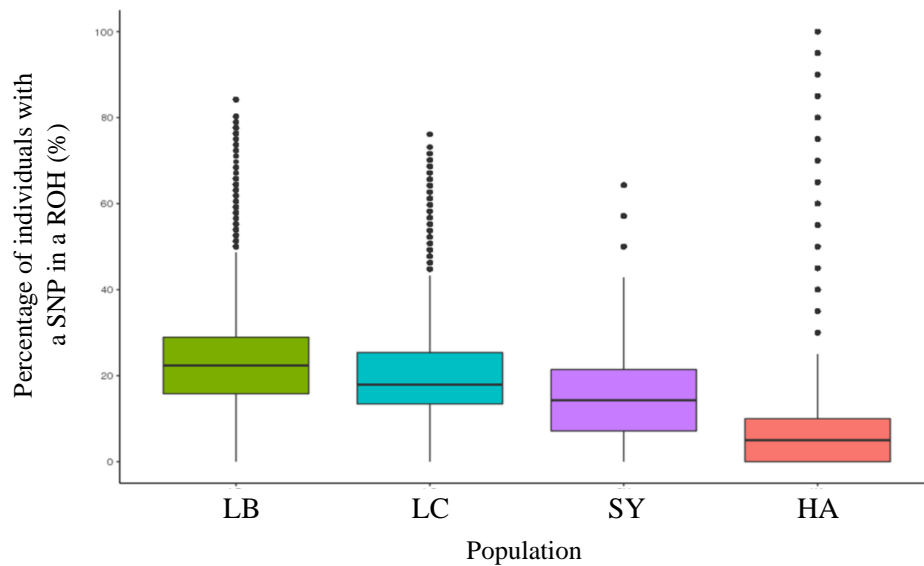


FIGURE 2. Box-plots of the occurrence of ROH (number of individuals having this ROH) per SNP for each rainbow trout population LB, LC, SY, and HA.

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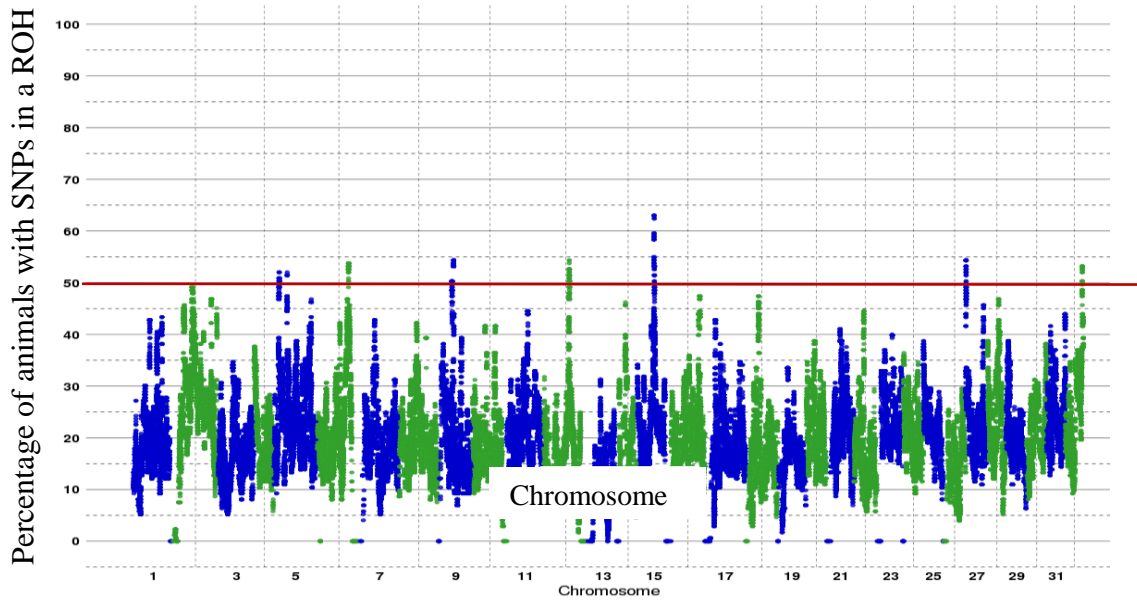
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1652 **FIGURE 3.** Manhattan plot of the occurrence of ROH per SNP across chromosomes (gathering
1653 all rainbow trout populations). The red line highlights the ROH islands.

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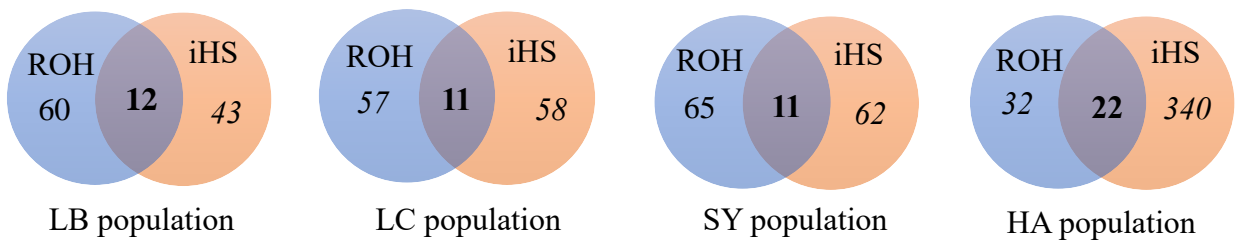
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1664 **FIGURE 5.** Venn Diagram of the number of regions identified as ROH island or iHS signature
1665 of selection for each rainbow trout population.

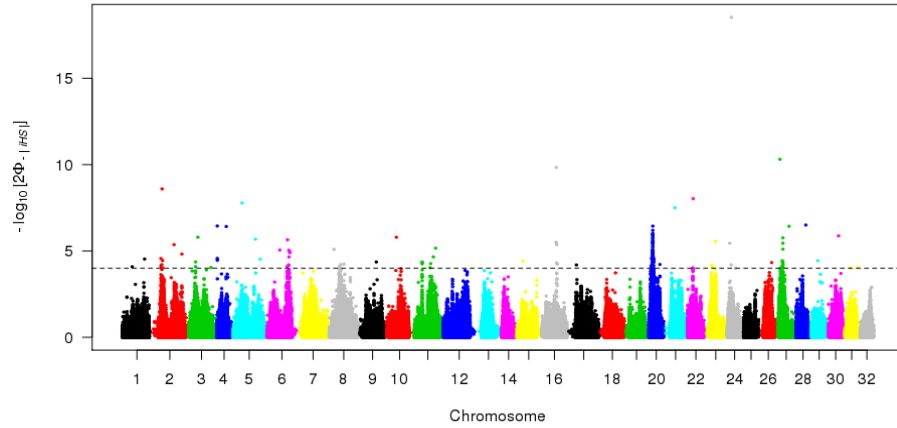
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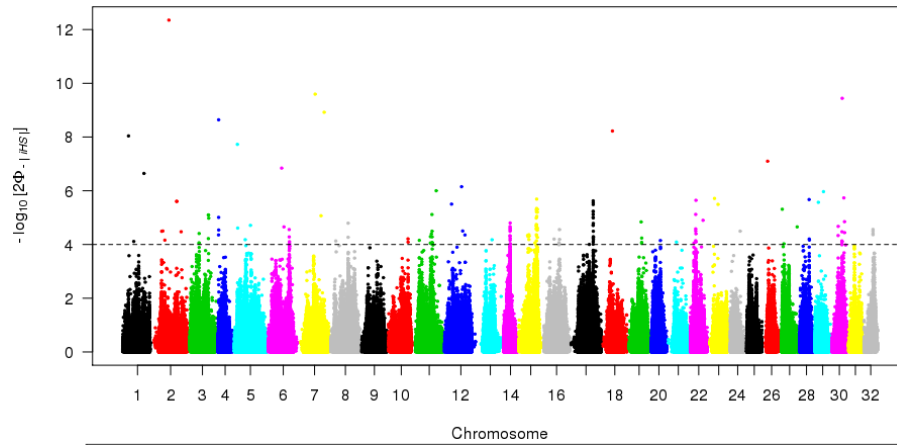
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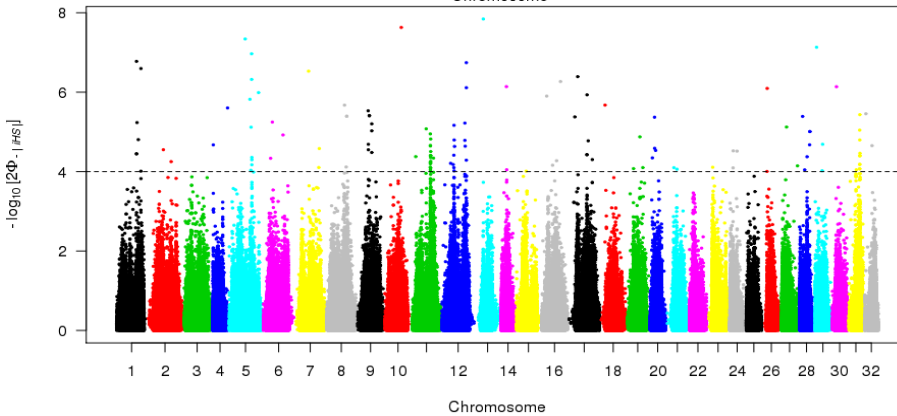
LB.



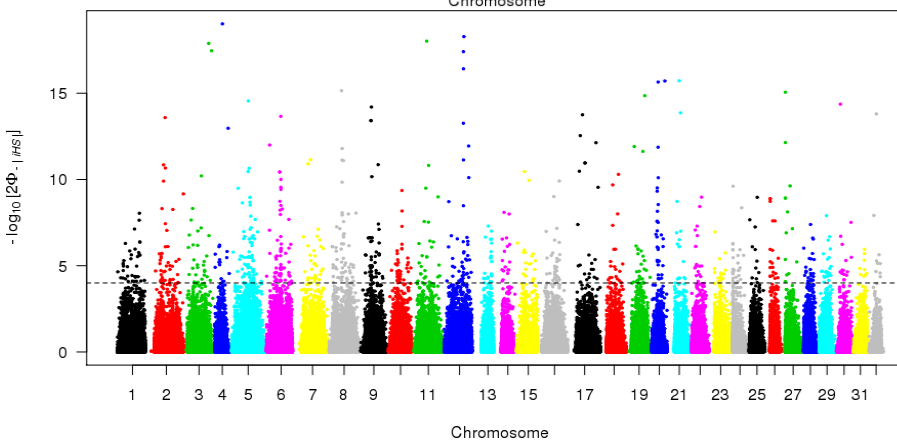
LC.



SY.



HA.



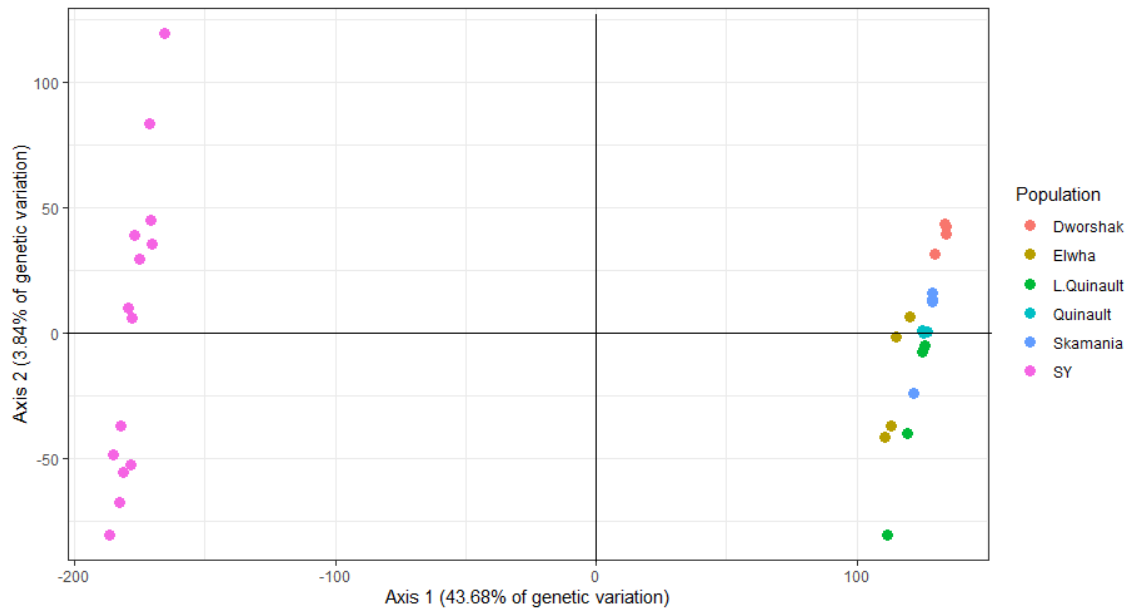
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FIGURE 4. Genome-wide distribution of $\log(p\text{-value})$ for standardized iHS for each population (LB, LC, SY, HA). The dashed line indicates the $\log(p\text{-value})$ significance threshold set to 4 to identify regions under positive selection

1700 **Appendices**

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1715 **Supplementary figure 1.** Principal component analysis (PCA) of the genetic diversity of SY,
1716 and HA sub-populations based on 546,903 SNPs.

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1718 File: *Supplementary_Tables.xlsx*

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