



**QUEEN'S  
UNIVERSITY  
BELFAST**

## **Transcriptomic analysis of short-term 17A-ethynylestradiol exposure in two Californian sentinel fish species sardine (*Sardinops sagax*) and mackerel (*Scomber japonicus*)**

Renaud, L., Agarwal, N., Richards, D. J., Falcinelli, S., Hazard, E. S., Carnevali, O., Hyde, J., & Hardiman, G. (2019). Transcriptomic analysis of short-term 17A-ethynylestradiol exposure in two Californian sentinel fish species sardine (*Sardinops sagax*) and mackerel (*Scomber japonicus*). *Environmental Pollution*, 926-937. <https://doi.org/10.1016/j.envpol.2018.10.058>

**Published in:**  
Environmental Pollution

**Document Version:**  
Peer reviewed version

**Queen's University Belfast - Research Portal:**  
[Link to publication record in Queen's University Belfast Research Portal](#)

### **Publisher rights**

Copyright 2018 Elsevier.

This manuscript is distributed under a Creative Commons Attribution-NonCommercial-NoDerivs License (<https://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

### **General rights**

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### **Take down policy**

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact [openaccess@qub.ac.uk](mailto:openaccess@qub.ac.uk).

### **Open Access**

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. – Share your feedback with us: <http://go.qub.ac.uk/oa-feedback>

1 ***Transcriptomic analysis of short-term 17 $\alpha$ -ethynylestradiol exposure in two***  
2 ***Californian sentinel fish species sardine (*Sardinops sagax*) and mackerel***  
3 ***(*Scomber japonicus*)***

4  
5 Ludivine Renaud<sup>1§</sup>, Nisha Agarwal<sup>2§</sup>, Dylan J. Richards<sup>3</sup>, Silvia Falcinelli<sup>4</sup>, E. Starr Hazard<sup>5</sup>,  
6 Oliana Carnevali<sup>4</sup>, John Hyde<sup>6</sup> and Gary Hardiman<sup>1,2,5,7,8\*</sup>.

7  
8 <sup>1</sup>Department of Medicine, Nephrology, Medical University of South Carolina, Charleston, SC, USA

9 <sup>2</sup>Biomedical Informatics Research Center, San Diego State University, San Diego, CA, USA

10 <sup>3</sup>Bioengineering Department, Clemson University, Clemson, SC, USA

11 <sup>4</sup>Dipartimento di Scienze della Vita e dell'Ambiente, Università Politecnica delle Marche, 60131, Ancona,  
12 Italy

13 <sup>5</sup>MUSC Bioinformatics, Center for Genomics Medicine, Medical University of South Carolina, Charleston,  
14 SC, USA

15 <sup>6</sup>NOAA Fisheries, Southwest Fisheries Science Center, La Jolla, CA, USA

16 <sup>7</sup>Department of Public Health Sciences, Medical University of South Carolina, Charleston, SC, USA

17 <sup>8</sup>Laboratory for Marine Systems Biology, Hollings Marine Laboratory, Charleston, SC, USA

18  
19 <sup>§</sup>Joint first authors

20 <sup>\*</sup>Correspondence should be addressed to Gary Hardiman: [hardiman@musc.edu](mailto:hardiman@musc.edu)

21  
22  
23  
24 **Key words:** Endocrine disrupting chemicals; Sardine; Mackerel; RNA sequencing; Xenobiotics;  
25 17 $\alpha$ -ethynylestradiol; Genomic biomarkers  
26

27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50

**ABSTRACT**

Endocrine disrupting chemicals (EDCs) are substances which disrupt normal functioning of the endocrine system by interfering with hormone regulated physiological pathways. Aquatic environments provide the ultimate reservoir for many EDCs as they enter rivers and the ocean via effluent discharges and accumulate in sediments. One EDC widely dispersed in municipal wastewater effluent discharges is 17 $\alpha$ -ethynylestradiol (EE2), an orally bio-active estrogen used in almost all modern formulations of combined oral contraceptive pills and one of the most commonly prescribed medicines. As evidence of the health risks posed by EDCs mount, there is an urgent need to improve diagnostic tools for monitoring the effects of pollutants. As the cost of high throughput sequencing (HTS) diminishes, transcriptional profiling of an organism in response to EDC perturbation presents a cost-effective way of screening a wide range of endocrine responses. Coastal pelagic filter feeding fish species analyzed using HTS provide an excellent tool for EDC risk assessment in the marine environment. Unfortunately, there are limited genome sequence data and annotation for many of these species including Pacific sardine (*Sardinops sagax*) and chub mackerel (*Scomber japonicus*), which limits the utility of molecular tools such as HTS to study disruption of the endocrine system. In this study, we carried out RNA sequencing (RNAseq) of liver RNA harvested from wild sardine and mackerel exposed under laboratory conditions to EE2 and developed an analytical framework for transcriptomic analyses of species with limited genomic information. EE2 exposure altered expression patterns of key genes involved in important metabolic and physiological processes. The systems approach presented here provides a powerful tool for obtaining a comprehensive picture of endocrine disruption in aquatic organisms.

## 51 1. INTRODUCTION

52  
53 The coast of Southern California is home to more than 20 million people. Servicing this  
54 high density urban strip are a series of wastewater treatment plants (WWTPs), which discharge  
55 more than a billion gallons of treated wastewater into the coastal marine environment on a daily  
56 basis [1]. Unfortunately, many contaminants are not filtered at the WWTPs and end up in the  
57 marine environment. These contaminants include a broad suite of compounds collectively referred  
58 to as endocrine disruptors (EDs) in concentrations that have been shown to disrupt the endocrine  
59 system. The derivative of estradiol 17 $\alpha$ -ethynylestradiol (EE2) has been a primary component of  
60 most modern formulations of combined oral contraceptive pills since the 1960s and qualifies as an  
61 ED due to its ability to bind and activate estrogen receptors (ERs) [2]. EE2 is a bio-active estrogen  
62 that is minimally metabolized and subsequently released into the environment via the urine and  
63 feces from individuals who take it as a medication. It has been detected in effluents from three  
64 WWTPs in Southern California at concentrations ranging from 31 to 43 ng/L (100 - 150 pM) [3]  
65 and is also detectable in surface waters in the USA (4 - 40 pM) [4] and in Europe (0.3 – 15 pM)  
66 [5, 6].

67 Active at very low concentration, EE2 has been shown to decrease reproductive potential  
68 by inhibiting gonad development in both male and female vertebrates, increasing ovarian follicle  
69 atresia and inducing complete sex reversal at concentrations ranging from 0.1 to 100 ng/L (0.3 -  
70 340 pM) [7-11]. There is increasing global evidence that exposure to low levels of EDs can lead  
71 to disruption of hormone-mediated responses in fish [12-15].

72 The Pacific sardine (*Sardinops sagax*) and Pacific chub mackerel (*Scomber japonicus*) are  
73 coastal pelagic fishes that are major components of commercial fisheries as well as forage base for  
74 marine mammals and fishes in California [16, 17]. Sardines (*Sardinops spp.*) are found in most  
75 temperate upwelling systems of the world and have supported large commercial fisheries, though  
76 their populations are known to historically go through boom and bust periods of abundance, likely  
77 due to climatic oscillations and to a lesser degree by industrialized fishing in the past century [18-  
78 20]. Along the west coast of North America, Pacific sardines occur across gradients of temperature,  
79 salinity, and anthropogenic pollution from southern Canada into the Gulf of California. As filter  
80 feeders in a coastal environment, sardines can readily accumulate toxins from the environment and  
81 food they eat [21]. Mackerels (*Scomber spp.*) are found in warm and temperate coastal areas  
82 throughout the Atlantic, Pacific and Indian oceans. The Pacific chub mackerel is found throughout  
83 the Pacific and largely overlaps in distribution with the Pacific sardine where both species school  
84 together near the coast and interact with other schooling coastal pelagic species such as northern  
85 anchovy (*Engraulis mordax*) and jack mackerel (*Trachurus symmetricus*) [22]. These species are  
86 widely consumed by humans, owing to their rich omega-3 fatty acids composition [23] imparting  
87 both a distinct flavor profile as well as health benefits. Due to their low trophic diet, cosmopolitan  
88 distribution, affinity for coastal habitats, and importance as forage, they serve as ideal sentinel  
89 species to monitor the health of the coastal marine environment.

90 Management of coastal pelagic fish species requires a detailed understanding of the effects  
91 of pollutants on the physiology of these species. This need motivated our study to characterize the  
92 effect of environmentally relevant levels of EE2 on sardine and mackerel liver transcriptome, the  
93 primary organ impacted by pollution and main site of detoxification [24]. Despite their commercial  
94 and ecological importance, little is known about the sardine and mackerel genomes, a limiting  
95 factor for the use of conventional genomics tools (e.g. microarrays and Q-RT PCR) to study

96 endocrine disruption in these species. However, recent advances in DNA sequencing technologies  
97 have enabled rapid production of transcriptomic data, which has enabled characterization of the  
98 expression of specific genes in these species [25, 26]. Furthermore, these new technologies allow  
99 for the development of biomarker fingerprints in sentinel species for different chemicals, such as  
100 EE2.

101 In this manuscript, we describe **(1)** a novel RNA sequencing (RNAseq) pipeline using  
102 scaffold transcriptomes from related species (**Supplemental Figure S1**) to streamline the data  
103 analysis of HTS for sardine and mackerel exposed to EE2, and **(2)** examine the effects of EE2  
104 exposure on these two sentinel species by performing a systems level analysis of their hepatic  
105 transcriptome and provide common biomarkers to use as possible end points to predict the  
106 estrogen-like contamination in environmental monitoring providing the most relevant Adverse  
107 Outcome Pathways (AOP). This knowledge can help improve tests such as the USA EPA Office  
108 of Prevention, Pesticides and Toxic Substances (OPPTS) Fish Acute Toxicity Test, Freshwater  
109 and Marine and the Organization for Economic Co-operation and Development (OECD) Acute  
110 Toxicity Test for Estuarine and Marine Organisms.

## 112 **2. MATERIALS & METHODS**

### 113 **2.1. Sampling of sardines and mackerels from Southern California coastal locations**

114 Sardine and mackerel were obtained from the live bait receiver operated by Everingham  
115 Bros Inc. in Mission Bay, San Diego, California. Fish were allowed to acclimate to research tanks  
116 at the NOAA Southwest Fisheries Science Center Experimental Aquarium facility under ambient  
117 temperature (~17°C) flow through seawater conditions and fed a pelleted feed (Bio-Oregon) to  
118 satiation. For exposure experiments (for both species), five males were exposed to 12.5 pM EE2  
119 for five hours (environmentally relevant concentration in the range of surface water levels) and an  
120 additional unexposed five males served as controls. Fish were euthanized with an overdose of  
121 Tricaine Methanesulfonate (250mg/L) dissolved in seawater. Livers were harvested and flash-  
122 frozen in liquid nitrogen at -196°C. These procedures followed an approved institutional IACUC  
123 protocol and all animals were treated humanely. RNA was extracted from liver samples using  
124 TRIzol reagent (Invitrogen, CA) and further purified using the RNeasy Mini kit with DNase to  
125 remove DNA (Qiagen, Valencia, CA). RNA concentrations were determined at 260 nm using a  
126 ND1000 (Nanodrop, Wilmington, DE). RNA was tested for structural integrity with the 6000 Nano  
127 LabChip assay from Agilent, (Santa Clara, CA, USA). Only RNA samples with RIN scores > 7.0  
128 were used for RNA-seq.  
129

### 130 **2.2. High Throughput Sequencing (HTS)**

131 Libraries for RNA sequencing (RNAseq) were generated using Illumina TruSeq™ RNA  
132 Sample Preparation Kit (Illumina, USA) in accordance with the manufacturer's recommendations  
133 (**Figure 1A**). The library fragments were purified with AMPure XP system (Beckman Coulter,  
134 USA) to select cDNA fragments of approximately 300 bp in length. DNA fragments with ligated  
135 adaptor molecules on both ends were selectively enriched using Illumina PCR Primer Cocktail in  
136 a 10-cycle PCR reaction. Products were purified using AMPure XP system and quantified using  
137 the Agilent high sensitivity DNA assay on the Agilent Bioanalyzer 2100 system. Clustering was  
138 performed on a cBot Cluster Generation System using TruSeq PE Cluster Kit v3-cBot-HS  
139 (Illumina, USA). After cluster generation, the libraries were sequenced on an Illumina GAIIX  
140

141 sequencer to a depth of approximately 5 million reads per sample and 101-bp single-end reads  
142 were generated. Data was formatted to FASTQ format (with sequences and their associated Phred  
143 quality scores) using CASAVA v1.8 (Illumina). RNA sequencing data has been submitted to the  
144 Gene expression Omnibus with the accession number **GSE113780**.

145

### 146 **2.3. Transcript Level Analysis and Mapping to Reference Transcriptomes**

147 Low quality reads were filtered to exclude those most likely to represent sequencing errors.  
148 Adaptor sequences were subsequently trimmed to generate clean full length reads. Only sequences  
149 which had a Phred quality score of Q30 (which indicated 99.9% base call accuracy) were used for  
150 downstream analysis.

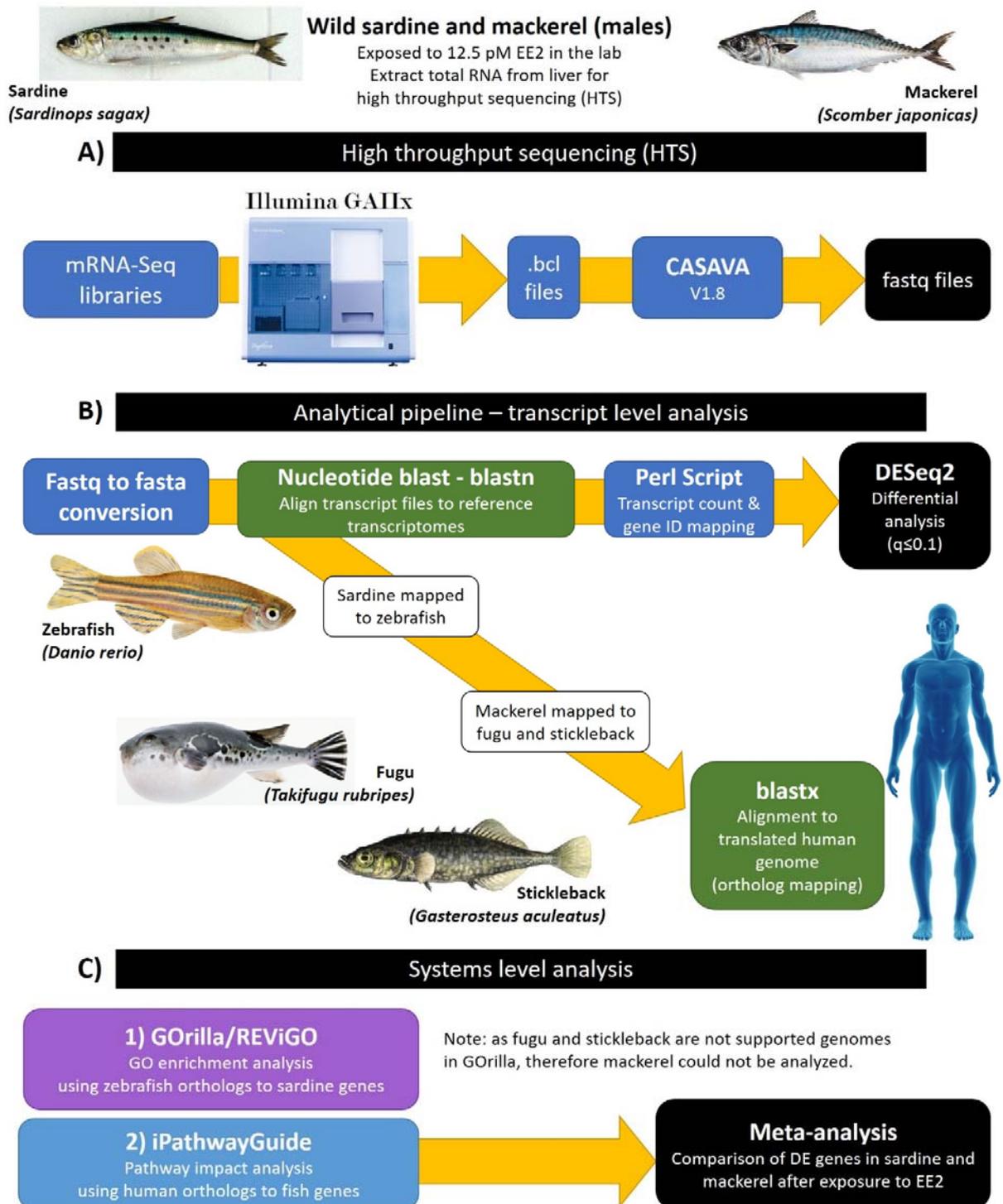
151 To analyze the mackerel and sardine RNAseq data, an analytical pipeline was developed  
152 (**Figure 1B**) that starts with the conversion of fastq files to fasta format via a custom PERL script.  
153 As comprehensive genomic sequence data for both sardine and mackerel are presently not  
154 available, we exploited the phylogenetic similarity of sardine and zebrafish (**Supplemental Figure**  
155 **S1**), and mapped sardine reads to the zebrafish (*Danio rerio*) Genome Reference Consortium  
156 Zebrafish Build 10 (GRCz10) transcriptome using the Nucleotide-Nucleotide Basic Local  
157 Alignment Search Tool (BLAST) nucleotide to nucleotide option (blastn) [27]. For mackerel, we  
158 mapped reads to two reference transcriptomes, fugu (*Takifugu rubripes*) FUGU 4.0 and  
159 stickleback (*Gasterosteus aculeatus*) *Gasterosteus aculeatus* BROAD S1. Fastq files were  
160 converted to fasta files and blastn alignment was carried out against the reference transcriptomes  
161 of interest formatted as fasta files.

162 After determining the threshold alignment length (see below), the reads were assembled  
163 into transcript level expression summaries; the number of reads mapped to each gene or transcript,  
164 with alignment length greater than the threshold alignment length, were summed, yielding a count  
165 as a measure of transcript expression [28].

166 Each sample yielded a vector of counts or summed mapped reads, with length  $p$  equal to  
167 the number of transcripts present. Combining the results from  $n$  samples, the data were formatted  
168 as an  $(n \times p)$  matrix of  $n$  transcripts and  $p$  samples. Log-log and square root plots were generated  
169 from the data using custom R scripts [29]. The base of the logarithm was arbitrarily selected as 2  
170 as the choice facilitated convenient preliminary data QC (**Supplemental Figure S2**).

171 In parallel, human ortholog refseq IDs were appended to the fish sequence reads. This was  
172 achieved by aligning the reference fish transcriptome with the human proteome using blastx.  
173 Utilizing the NCBI gene2refseq function, each human protein ID was linked with its corresponding  
174 gene ID, such that the  $(n \times p)$  matrix of transcript counts, with  $n$  number of reference transcriptome  
175 genes contained the corresponding human gene IDs.

176 In order to infer differential gene expression with robust statistical power, we utilized  
177 DESeq2, a method which tests for differential expression based on a model using negative binomial  
178 distribution [30]. Transcript count data from DESeq2 analysis was ranked according to adjusted  
179 p-value (or q-value), the smallest false discovery rate (FDR) at which a transcript is called  
180 significant. FDR was calculated using the Benjamini-Hochberg multiple testing adjustment  
181 procedure and the cut-off was set at  $q \leq 0.1$ .



182  
183  
184  
185

**Figure 1:** Workflow followed in this study starting with A) high throughput sequencing (HTS), B) transcript level analysis using a novel analytical pipeline, and C) systems level analysis of the GO enrichment and pathway impact.

## 186 **2.4. Systems Level Analysis**

187 Gene ontology (GO) enrichment analysis was performed on the sardine dataset mapped  
 188 onto zebrafish genome as previously described [31, 32]. Briefly, GO terms were obtained using  
 189 the online tool Gene Ontology enRIchment anaLysis and visuaLizAtion (GOrilla) (**Figure 1C-1**)  
 190 [33]. GO terms were summarized using REduce & VISualize Gene Ontology (REViGO) that  
 191 combines redundant terms into a single, representative term based on a simple clustering algorithm  
 192 relying on semantic similarity measures [34]. As fugu and stickleback are not supported genomes  
 193 in GOrilla at this point in time, mackerel mapped onto these references could not be analyzed using  
 194 this tool.

195 Pathway impact analysis (**Figure 1C-2**) was performed using iPathwayGuide (Advaita  
 196 Bioinformatics) [35], an approach that retrieves information from the Kyoto Encyclopedia of  
 197 Genes and Genomes (KEGG) database for pathway analysis and diseases [36], from the Gene  
 198 Ontology Consortium database for GO enrichment analysis [37], and from miRBase and  
 199 TARGETSCAN databases for miRNA analysis [38, 39].

200 Area-proportional Venn diagrams were created using VENNY 2.1 [40].

201

## 202 **3. RESULTS**

203

### 204 **3.1. Cross species transcriptome mapping**

205 Due to the lack of reference genomes for sardine and mackerel, reads were mapped to the  
 206 transcriptomes of phylogenetically similar fish species: sardine to the zebrafish transcriptome and  
 207 mackerel to the fugu and stickleback transcriptomes (**Supplemental Table S1**). The mean of the  
 208 total reads obtained with the sardine and mackerel samples were 4 and 3.7 million reads  
 209 respectively. For sardine, about 1.4 million reads mapped to the zebrafish transcriptome, which  
 210 represents 34% cross species mapping efficiency. For mackerel, about 1.5 and 3.5 million reads  
 211 mapped to fugu and stickleback respectively, representing cross species mapping efficiencies of  
 212 40.5% for fugu and 94% for stickleback.

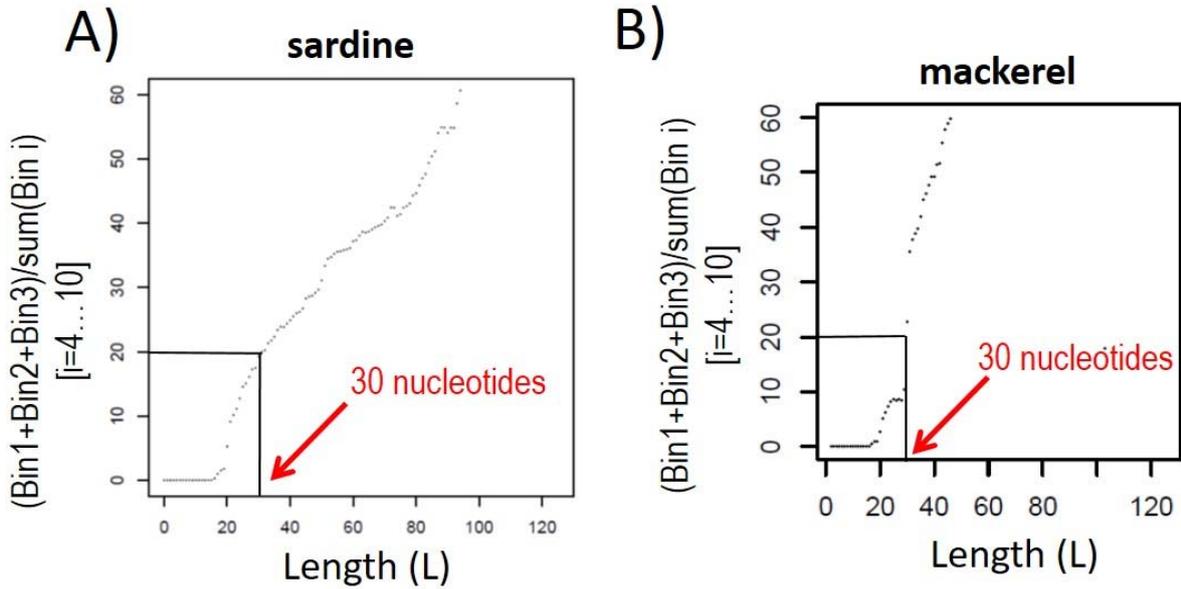
213

### 214 **3.2. Calculation of threshold alignment length to provide maximal alignment stringency**

215 Sequence read lengths were 101bp. In order to determine the minimum alignment length  
 216 that provided the highest number of unique reads, we followed a read binning strategy so that a  
 217 given read was placed in bin 0 if there was no alignment with length  $\geq L$ . When there were  $n$   
 218 alignments  $\geq L$ , the read was placed into bin  $\min(n, 10)$ . Utilizing this binning approach, based on  
 219 alignment lengths a comma-separated values (csv) file was created with row numbers equal to  $L$   
 220 + 1 ( $L$  = threshold alignment length) and columns corresponding to bins 0 to 10. A series of QC  
 221 plots were generated with the alignment length plotted on the x-axis, and the individual and  
 222 fraction of combination of bins on the y-axis. From the plot of  $(\text{bin1} + \text{bin2} + \text{bin3}) / (\text{bin4} + \dots + \text{bin10})$   
 223 on the y-axis and an alignment length  $L$  on the x-axis, which was essentially the fraction of unique  
 224 ( $U$ ) to non-unique ( $1-U$ ) versus alignment length ( $L$ ), it was deduced for sardine and mackerel with  
 225 the  $U/(1-U)$  ratio of 20, that the optimal threshold alignment length was 30 nucleotides (nt), i.e.  
 226 95% of the aligned reads were unique with an alignment length of 30 nt (**Figures 2A and 2B**  
 227 **respectively**).

228

229

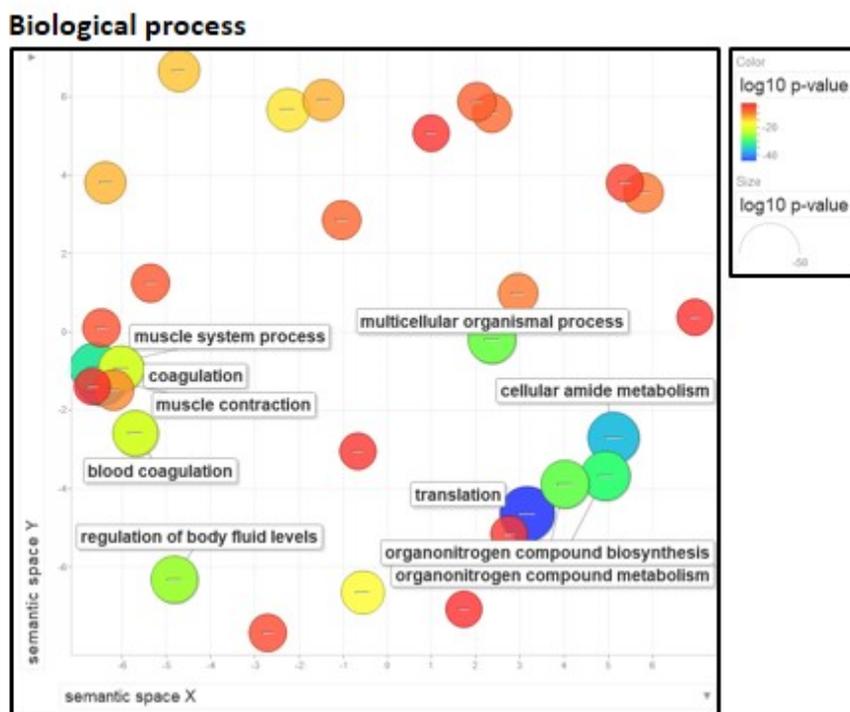


230  
 231 **Figure 2:** Threshold alignment length ( $n=30$ ) for sardine (A) and mackerel (B). Alignment lengths  
 232 plotted on the x-axis (labeled "L"), and the individual and fraction ratio of bin combinations on  
 233 the y-axis. For sardine and mackerel with the  $U/(1-U)$  ratio of 20, the optimal threshold alignment  
 234 length is 30 nucleotides, i.e. 95% of aligned reads are unique (see red arrows).

235

236 **3.3. GO analysis of fish genes**

237 Gene level analysis performed with DESeq2 revealed 4,779 and 2,211 DE hepatic mRNAs  
 238 in sardine and mackerel exposed to EE2 respectively. For systems level analysis, we first entered  
 239 the sardine/zebrafish DE gene list in GOrilla since annotations for zebrafish are available. GOrilla  
 240 GO enrichment analysis showed that translation, muscle contraction, cellular amide metabolism,  
 241 muscle system, organonitrogen compound metabolism and biosynthesis, multicellular organismal  
 242 process, regulation of body fluid levels and blood coagulation were some of the most enriched BP  
 243 terms after exposure to EE2 in the liver of sardines (**Figure 3, deep blue to light green bubbles,**  
 244 **and Supplemental Table S2).**  
 245



246 **Figure 3: EE2 exposed sardine: GOrilla GO enrichment analysis - Biological process.** The  
 247 REViGO scatterplots show cluster members in a 2-dimensional space obtained by applying multi-  
 248 dimensional scaling to a matrix of the GO terms' semantic similarities (the axes have no intrinsic  
 249 meaning). Bubble color indicates the  $-\log_{10} p\text{-value}$  (legend in upper right-hand corner, blue and  
 250 green bubbles are GO terms with greater significant p-values than the orange and red bubbles),  
 251 the size indicates the GO term frequency in the GO database (bubbles of more general terms are  
 252 bigger), and the proximity on the plot reflects the semantic similarity.  
 253

254

### 255 3.4. Pathway impact analysis (*iPathwayGuide*)

256 Since the zebrafish annotations are not as detailed as human annotations [32], we entered  
257 the human orthologs of the sardine/zebrafish and mackerel/fugu DE genes in *iPathwayGuide* for a  
258 content richer GO and pathway impact analysis. Impact analysis uses two types of evidence: i) the  
259 overrepresentation of differentially expressed (DE) genes in a given pathway and ii) the  
260 perturbation of that pathway computed by propagating the measured expression changes across  
261 the pathway topology. Volcano plots revealed a greater dynamic range in the sardine dataset as  
262 compared to mackerel (**Supplemental Figure S3**).

263 DE analysis in sardine exposed to EE2 identified 3,918 DE genes out of a total of 5,321  
264 genes with measured expression (**Supplemental Figure S3A**). Significant differences between the  
265 EE2 exposed and control sardines in metabolic, steroid biosynthesis and cancer pathways emerged  
266 (**Supplemental Table S3 – Biological Pathways**) as well as enrichment in several signaling  
267 pathways such as Fc epsilon RI, cAMP, oxytocin and VEGF. Additionally, complement &  
268 coagulation cascades and focal adhesion biological pathways were also significantly perturbed.

269 The GO analysis revealed that multicellular organismal (**Supplemental Table S3 –**  
270 **Biological Process**), muscle, steroid, metabolic (includes alcohol and cholesterol metabolic  
271 processes) related biological processes were highly enriched after exposure to EE2. Response to  
272 chemical and drug, negative regulation of peptidase and endopeptidase activity as well as positive  
273 regulation of immune system process were also highly represented BP terms in this analysis. Other  
274 general BP GO terms were also listed including regulation of biological quality, ion transport,  
275 developmental process and system process. Together these results suggest that exposure to EE2 in  
276 sardine had a strong impact on transcripts related to metabolism, steroid biosynthesis, several  
277 enzymes and signaling pathways as well as the immune system, response to drug/chemical, and  
278 cancer pathways.

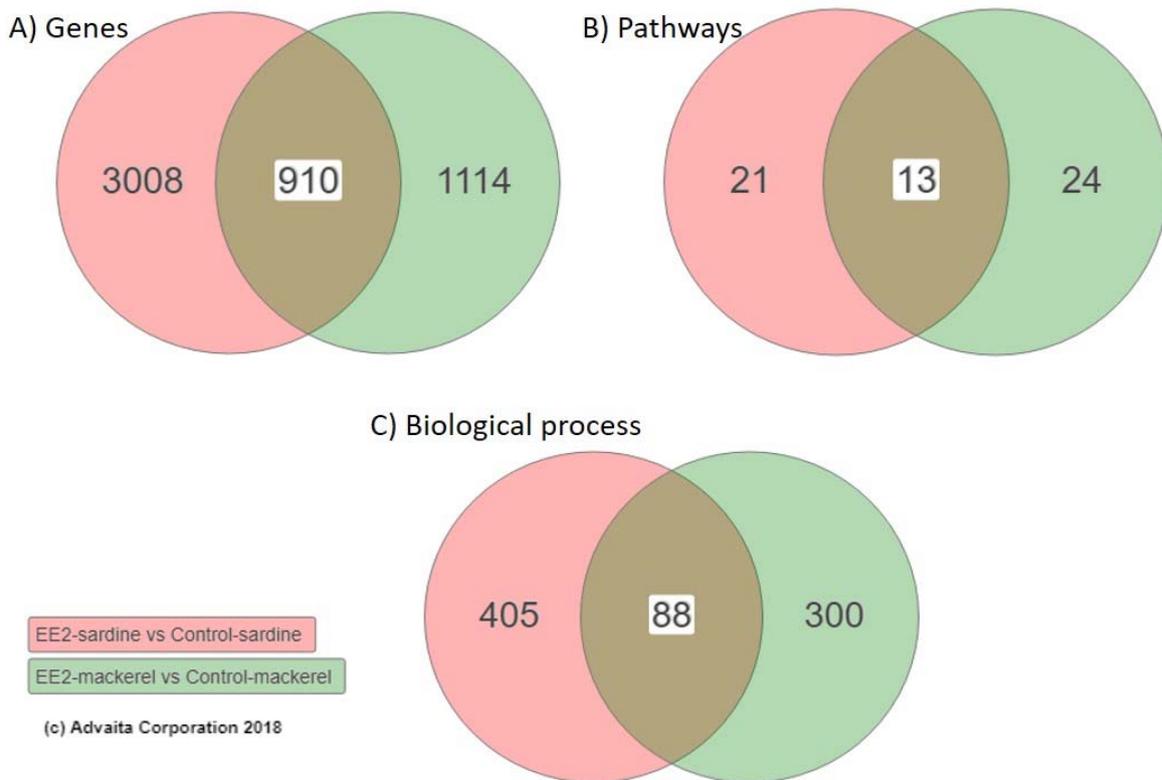
279 Exposure to EE2 in mackerel perturbed 2,024 DE genes out of 5,300 genes with measured  
280 expression (**Supplemental Figure S3B**). The most enriched biological pathways in EE2 exposed  
281 mackerel are fat digestion & absorption, metabolic, steroid biosynthesis and cancer pathways  
282 (**Supplemental Table S4 – Biological Pathways**) as well as enrichment in several signaling  
283 pathways such as PI3K-Akt and Rap1. ECM-receptor interaction, necroptosis, EGFR tyrosine  
284 kinase inhibitor resistance and proteasome pathways were also highly significant in this analysis.

285 Several BP terms related to metabolic (**Supplemental Table S4 – Biological Process**) and  
286 steroid biosynthetic processes were highly enriched in the GO analysis. More specifically,  
287 enriched metabolic processes can be sub-divided into alcohol, cholesterol and lipid related  
288 processes. Together, these results suggest that exposure to EE2 in mackerel disrupts digestion,  
289 steroid biosynthesis, several metabolic processes and signaling pathways, and enhances cancer  
290 pathways.

291  
292  
293

294 **3.5. Meta-analysis (iPathwayGuide)**

295 In order to compare the effects of EE2 exposure on the hepatic transcriptomes of sardine  
 296 and mackerel we carried out a meta-analysis. This revealed that 910 DE genes (**Figure 4A**), 13  
 297 enriched pathways (**Figure 4B and Supplemental Table S5**) and 88 BP (**Figure 4C**) are shared  
 298 by sardine and mackerel. Additionally, this analysis highlighted that each species has a unique  
 299 signature after EE2 exposure; 3,008 DE genes, 21 pathways and 405 BP are unique to sardines  
 300 (**pink in panels A, B, C**) while 1,114 DE genes, 24 pathways and 300 BP are unique to mackerel  
 301 (**green in panels A, B, C**).  
 302



303 **Figure 4:** Venn diagrams from iPathwayGuide. **A)** Intersection between liver DE genes expressed  
 304 in sardine and mackerel in response to EE2 exposure; 910 DE genes are commonly expressed in  
 305 both species while 3,008 and 1,114 DE genes are unique to sardine and mackerel respectively. **B)**  
 306 Intersection between enriched pathways in sardine and mackerel; 13 pathways are common to  
 307 both species while 21 and 24 pathways are unique to sardine and mackerel respectively. **C)**  
 308 Intersection between enriched Biological Process (BP) in sardine and mackerel; 88 BP are  
 309 commonly expressed in both species while 405 and 300 BP are unique to sardine and mackerel  
 310 respectively.  
 311

312

## 313 4. DISCUSSION

314

### 315 *4.1. Development of a novel analytical pipeline for sardine and mackerel*

316 Despite the commercial and ecological importance of sardine and mackerel, very little  
 317 genomic information is available at the present time. The first goal of this study was to develop a  
 318 novel analytical pipeline to facilitate **1)** mapping reads to reference transcriptomes using blastn  
 319 when no reference transcriptome is available for a given species, **2)** calculation of threshold  
 320 alignment length to provide maximal alignment stringency, **3)** assembly of reads with transcript-  
 321 level counts or expression summaries, **4)** sequence quality control, **5)** annotation of sequence reads  
 322 with human GO identifiers, **6)** data normalization (to adjust the read counts for variance in  
 323 sequencing depths between different samples), differential expression analysis and FDR  
 324 estimation using DEseq2, **7)** generation of significant DE transcript lists, and **8)** GO and pathway  
 325 impact analysis.

326 Based on fish phylogenetic relationships and available reference transcriptomes, we  
 327 aligned sardine fasta files to the zebrafish transcriptome using blastn, which provided a cross  
 328 species mapping efficiency of 34%. In the case of mackerel, the fasta files were aligned to both  
 329 the fugu and stickleback transcriptomes (note that a draft genome sequence has been released for  
 330 stickleback which is a closer evolutionary relative of mackerel than fugu). The number of mapped  
 331 sequence tags was considerably higher when stickleback was chosen as the reference (94% cross  
 332 species mapping efficiency) compared with fugu (40.5%). However, fugu was used as the  
 333 reference (for all downstream analyses) as this genome is currently better annotated than  
 334 stickleback [41, 42]. Therefore, zebrafish and fugu transcriptomes served as scaffolds for mapping  
 335 purposes in our study.

336 Analysis of the BLAST data output revealed multiple hits for each single query read of  
 337 varying alignment length to the cognate transcripts. As sequences were being compared across fish  
 338 species, full length alignment was not expected and consequently many of the small alignment  
 339 length hits were not unique or meaningful. It was therefore necessary to parse out smaller  
 340 sequences and determine the optimal alignment length. This was calculated for both fish species  
 341 so that the only transcript retained was the one whose alignment length was the maximum and  
 342 greater than the threshold alignment length for each read.

343

### 344 *4.2. Systems level analysis of transcriptomic changes using zebrafish annotations*

345 Utilizing the online tools GOrilla and REViGO, we performed GO enrichment analysis  
 346 using sardine mapped to zebrafish genes for the sardine dataset. This analysis showed that  
 347 translation (including redundant GO terms peptide and amide biosynthetic process), muscle system  
 348 & contraction, and cellular amide metabolism were some of the most enriched BP terms after  
 349 exposure to EE2 in the liver of sardines, followed by organonitrogen compound metabolism and  
 350 biosynthesis, regulation of body fluid levels and blood coagulation (fibrin clot  
 351 formation/fibrinolysis, negative regulation of wound healing, hemostasis and blood coagulation).  
 352 The enriched BP terms include genes that surprisingly mapped to GO BP terms related to muscle  
 353 system and contraction. This may reflect physiological differences between fish and mammals.  
 354 The histology of the fish liver for example differs from its mammalian counterpart in that there is  
 355 a far less tendency of the hepatocytes to form distinct cords or lobules, and the typical portal triads  
 356 are not obvious [43]. Many of these muscle system & contraction mRNAs are associated with  
 357 disease signatures (e.g. mouse phenotype database MP: 0003141; cardiac fibrosis and MP:

358 0005608; cardiac interstitial fibrosis). EE2 exposure has been linked with hepatotoxicity and  
359 fibrosis [44] so it is conceivable that these mRNA signatures of fibrosis in other tissues are being  
360 detected in this analysis. The liver plays a central role in the clotting process, and acute and chronic  
361 liver diseases have been linked with coagulation disorders [45]. Our GO analysis highlighted that  
362 EE2 exposure impacted “blood coagulation” as mentioned above, reinforcing that the liver plays  
363 a role in the production of clotting factors as well as red blood cell production [46, 47].

### 365 **4.3. Systems level analysis of transcriptomic changes using human orthologs**

366 Another challenge is the fact that zebrafish and fugu have limited gene annotations when  
367 compared to human, further limiting the resolution of the analysis [32]. To remedy this short-  
368 coming, human refseq IDs and GO terms were appended to the fish sequence reads by aligning  
369 the reference fish transcriptomes with the human proteome using blastx. As 69% of zebrafish genes  
370 have at least one human ortholog [48], this approach allows a more sensitive comparative  
371 genomics based analysis of transcriptomic changes in these sentinel species. Utilizing the NCBI  
372 gene2refseq function, each human protein ID was linked with its corresponding gene ID. However,  
373 fish and mammalian species exhibit considerable diversity, each possessing unique biological  
374 characteristics. By “humanizing” the fish dataset, species specific genes are lost, *i.e.* vitellogenin,  
375 and artefactual data may result if the orthologs are not carefully mapped. However, in the absence  
376 of annotated genomes and GO identifiers for the majority fish species, this approach represents a  
377 valid analytical alternative that provides functional characterization of the fish transcriptome.  
378 Additionally, the BLAST program has an internal p-value threshold, ensuring that the homology  
379 between the human and reference fish proteome reported is deemed significant. Furthermore,  
380 information obtained about impacted human pathways also provide insights on the potential effects  
381 to human health of a particular contaminant.

#### 383 **4.3.1. Effects of EE2 on sardine**

384 The most obvious result from our study is that exposure to 12.5 pM EE2 greatly affected  
385 sardine transcripts related to metabolism, including carbon metabolism (KEGG 01200, **Figures**  
386 **S4-S5**), glycolysis and gluconeogenesis (KEGG 00010, **Figures S6-S7**). In particular, the main  
387 metabolic perturbation we observed was on the biosynthesis of steroid hormone (KEGG 00140,  
388 **Figures S8-S9**). This is consistent with previous studies conducted in turbot [49] and zebrafish  
389 [50], and this is the first report to our knowledge of this hormonal disruption induced by EE2 in  
390 sardines. Given that steroid hormones are derived from cholesterol and that our GO analysis  
391 highlighted that cholesterol biosynthetic and metabolic processes were significantly impacted by  
392 exposure to EE2, it is consistent with our previous observation. In rat, EE2 has been shown to  
393 decrease testosterone production via a reduction of the cAMP pathway during steroidogenesis [51].  
394 This is interesting as the cAMP signaling pathway (KEGG 04024, **Figures S10-S11**) was one of  
395 the most enriched Biological Process in our GO analysis. The cAMP pathway regulates pivotal  
396 physiologic processes including metabolism, secretion, calcium homeostasis, muscle contraction,  
397 cell fate and gene transcription [35]. cAMP is one of the most common and universal second  
398 messengers and its formation is promoted by adenylyl cyclase (AC) activation by ligands including  
399 hormones. Estrogenic hormones have been shown to have a non-genomic action that activates  
400 second-messenger signaling systems such as cAMP, explaining how steroid hormones can alter  
401 the expression of genes [52]. To our knowledge, no studies conducted in fish have examined the  
402 impact of EE2 on the cAMP signaling pathway.

403 Several other signaling pathways were enriched upon EE2 exposure, including VEGF,  
404 FcεRI, and oxytocin signaling pathways. The VEGF signaling pathway (KEGG 04370, **Figures**  
405 **S12-S13**) is a crucial signal transducer in both physiologic and pathologic angiogenesis [35]. Its  
406 activation leads to proliferation and migration of endothelial cells. Recent studies in human and  
407 primate have shown that estrogen regulates VEGF expression [53, 54], however the effects of EE2  
408 on VEGF signaling pathway in fish have not been well characterized to date.

409 Activation of the FcεRI signaling pathway (KEGG 04664, **Figures S14-S15**) in mast cells  
410 induces the release of preformed granules containing histamines, proteoglycans (PGs),  
411 prostaglandins and cytokines that contribute to inflammatory responses [35]. Interestingly, many  
412 PGs have been shown to be key macromolecules that contribute to the development of various  
413 types of cancer including proliferation, adhesion, angiogenesis and metastasis [55]. Our analysis  
414 revealed that the pathway “proteoglycans in cancer” was highly enriched in EE2-treated sardines  
415 (KEGG 05205, **Figures S16-S17**), suggesting that exposure to EE2 can disrupt many cancer-  
416 associated pathways, such as FcεRI and proteoglycan pathways. Minimal research has been carried  
417 out on the effects of EE2 on the FcεRI signaling pathway and PGs, highlighting the need for further  
418 examination of this subject.

419 Additionally, the FcεRI signaling pathway plays a role in innate immunity as mast cells  
420 have been shown to play a critical role in defense against bacterial, viral and fungal pathogens [56].  
421 Mast cells are activated during innate immune responses by multiple mechanisms, including well-  
422 established responses to complement components. We showed here that the “complement &  
423 coagulation cascades” pathway (KEGG 04610, **Figures S18-S19**) was highly perturbed by EE2  
424 (consistent with our previous GO analysis with GOrilla using zebrafish annotations), suggesting  
425 that EE2 disrupted the innate immunity of exposed sardines. The effect of combined oral  
426 contraceptive pills containing EE2 on coagulation parameters has been shown in human [57] but  
427 more investigation is needed to understand the effect of EE2 on sardine’s innate immunity.  
428

#### 429 **4.3.2. Effects of EE2 on mackerel**

430 In mackerel, the most enriched biological pathway upon EE2 exposure was “fat digestion  
431 & absorption” (KEGG 04975, **Figures S20-S21**). Given that fat is an important energy source  
432 from food, this emphasizes that EE2 even at low concentration can severely impair major basic  
433 pathways. The second most disturbed pathway in EE2-treated mackerel was “chemical  
434 carcinogenesis” (KEGG 05204, **Figures S22-S23**). In fact, exposure to environmental chemical  
435 carcinogens may account for the majority of human cancers [35] by interacting with a variety of  
436 genotoxic and non-genotoxic mechanisms. Genotoxic mechanisms can generate DNA adducts  
437 (segments of DNA bound to a cancer-causing chemical) either by direct impact on the DNA or  
438 indirectly by affecting metabolism. Non-genotoxic carcinogens induce inflammation,  
439 immunosuppression, formation of reactive oxygen species, activation of receptors and epigenetic  
440 silencing [35]. Our data suggest that EE2 acts as a carcinogen in mackerel potentially by altering  
441 signal-transduction pathways resulting in hypermutability, genomic instability, loss of  
442 proliferation control and resistance to apoptosis. This is consistent with previous studies conducted  
443 in rats [58], in hamsters [59] and zebrafish [60].

444 Moreover, EE2 also perturbed “central carbon metabolism in cancer”, another pathway  
445 that is central to malignant transformation of cells (KEGG 05230, **Figures S24-S25**); as Otto  
446 Warburg discovered, a major shift in cellular metabolism is required in cancer cells in order to  
447 support growth and survival. This shift results in the consumption of large amounts of glucose,

448 maintaining high rates of glycolysis and converting glucose into lactic acid even under normal  
449 oxygen concentrations [61, 62].

450 Several signaling pathways were highly enriched upon EE2 treatment in mackerel,  
451 including PI3K-Akt and Rap1 signaling pathways. The PI3K-Akt signaling pathway (KEGG  
452 04151, **Figures S26-S27**) is activated by many types of cellular stimuli or toxic insults and  
453 regulates fundamental cellular functions such as transcription, translation, proliferation, growth,  
454 and survival [35]. PI3K catalyzes the production of phosphatidylinositol-3,4,5-triphosphate (PIP3)  
455 at the cell membrane, a second messenger that helps to activate Akt. Once active, Akt can control  
456 key cellular processes by phosphorylating substrates involved in apoptosis, protein synthesis,  
457 metabolism, and cell cycle. Our data suggest that exposure to EE2 affects fundamental processes  
458 by regulating second messenger in mackerel, consistent with our previous conclusion that EE2  
459 regulates cAMP and translation in sardines. Interestingly, estrogens have been shown to induce  
460 VEGF-A expression in rat pituitary tumor cells through PI3K-Akt dependent signaling pathway,  
461 independently of activation of estrogen receptors [63]. However, the effects of EE2 on the  
462 mackerel's PI3K-Akt pathway remain undefined.

463 The Rap1 signaling pathway (KEGG 04015, **Figures S28-S29**) controls diverse processes  
464 such as cell adhesion, cell-cell junction formation and cell polarity [35]. Rap1 plays a dominant  
465 role in the control of cell-cell and cell-matrix interactions by regulating the function of integrins  
466 and other adhesion molecules in various cell types. Our analysis also revealed that the “ECM-  
467 receptor interaction” biological pathway was perturbed by EE2 exposure in mackerels (KEGG  
468 04512, **Figures S30-S31**). The ECM serves an important role in the maintenance of cell and tissue  
469 structure and function. Specific interactions between cells and the ECM are mediated by  
470 transmembrane molecules, mainly integrins and also proteoglycans, CD36, or other cell-surface-  
471 associated components [35]. These interactions lead to a direct or indirect control of cellular  
472 activities such as adhesion, migration, differentiation, proliferation, and apoptosis. Together, this  
473 suggests that EE2 disrupted cell-cell and cell-matrix mechanisms by perturbing Rap1 signaling  
474 and ECM-receptor interaction, in agreement with previous *in vitro* studies [64]. *In vivo* data also  
475 suggest that estrogens can exert direct regulatory effects on endothelial cells by increasing surface  
476 expression of integrins and enhancing integrin-mediated signaling [65]. Since integrins have an  
477 important role in mediating endothelial cell attachment, migration and differentiation, the increase  
478 in integrin expression and function induced by estrogens may promote neovascularization and  
479 vessel repair. Moreover, our data show that EE2 diminished the expression of three collagen genes  
480 (*COL1A1*, *COL1A2* and *COL6A3*). This is consistent with Hansen *et al.* [66] who concluded that  
481 administration of EE2 in women suppressed synthesis of collagen in tendon in response to exercise.  
482 Our data also show an increase in expression of *ITGB1* in response to EE2. Castillo-Briceno *et al.*  
483 [67] have previously demonstrated that EE2 induces liver and kidney toxicity and injuries in fish  
484 via upregulation of ECM-related molecules, including *ITGB1*.

485 Our analysis also revealed that the “necroptosis” biological pathway was perturbed in EE2  
486 exposed mackerel (KEGG 04217, **Figures S32-S33**). Necroptosis is a programmed form of  
487 necrosis. It can be initiated by different stimuli, such as tumor necrosis factor (TNF), TNF-related  
488 apoptosis-inducing ligand (TRAIL), Fas ligand (FasL), interferon (IFN), LPS, viral DNA or RNA,  
489 DNA-damage agent and requires the kinase activity of receptor-interacting protein 1 (RIPK1) and  
490 RIPK3 [35]. Its execution involves ROS generation, calcium overload, the opening of the  
491 mitochondrial permeability transition pore, mitochondrial fission, inflammatory response and  
492 chromatinolysis. Necroptosis participates in pathogenesis of many diseases, including

493 neurological diseases, retinal disorders, acute kidney injury, inflammatory diseases and microbial  
494 infections. This cell death process is evolutionarily conserved and a *caspase-3* gene has been  
495 identified in zebrafish [68] and sea bass [69], retaining the motifs that are functionally important,  
496 such as the active site and the cleavage site at the aspartic residue [70]. The examination of the  
497 effects of EE2 exposure on necroptosis in fish is in its infancy and further investigation is needed  
498 to fully understand its impact in mackerel.

499 Exposure to EE2 perturbed the “biosynthesis of amino acids” pathway as well (KEGG  
500 01230, **Figures S34-S35**). This KEGG module is the most conserved one in the KEGG MODULE  
501 database and is found in almost all completely sequenced genomes [35]. Although human  
502 nutritional requirements are well-characterized, little is known of the specific nutrient  
503 (protein/amino acid, lipid, carbohydrate, mineral and vitamin) requirements of cultivated fish  
504 species; even in zebrafish, a commonly used model, this information is almost entirely lacking  
505 [71]. Requirements for amino acids should be delineated in feeding studies with different strains  
506 and life stages before the effect of a given contaminant can fully be assessed on this pathway.  
507 Nevertheless, our data are consistent with a previous study reporting that the most sensitive  
508 biological process to EE2 exposure was amino acid glycosylation [72]; in fact, the authors argued  
509 that the genes relating to amino acid glycosylation may be a more sensitive set of biomarkers than  
510 the current single standard biomarker of vitellogenin.

#### 511 512 **4.4. Meta-analysis (Common pathways and biomarkers in sardine and mackerel and** 513 **extrapolation to humans).**

514 We exploited iPathwayGuide to perform a meta-analysis of the effects of EE2 on the  
515 hepatic transcriptome of the sardine and mackerel. Meta-analysis revealed that several DE genes,  
516 biological pathways and BP are commonly affected in both species whereas others are unique to  
517 sardine or mackerel. “Carbon metabolism (**Figure S36**), steroid hormone biosynthesis (**Figure**  
518 **S37**), glycolysis & gluconeogenesis (**Figure S38**), Rap1 signaling pathway (**Figure S39**) and  
519 chemical carcinogenesis” (**Figure S40**) are amongst the 13 perturbed biological pathways shared  
520 in both species and discussed in the section above. “Glyoxylate & dicarboxylate metabolism, drug  
521 metabolism (other enzymes), retinol metabolism, metabolic pathways, arginine & proline  
522 metabolism, steroid biosynthesis, pathways in cancer and pentose phosphate pathway” are also  
523 commonly disrupted pathways in both species.

524 Taken together, the meta-analysis reveals that exposure to 12.5 pM EE2 has a significant  
525 impact on basic biological responses in both fish species, impacting essential metabolic processes  
526 and biological pathways. These results highlight that EE2 deregulates signaling pathways that are  
527 involved in the development and progression of cancer as well as the endocrine and immune  
528 systems. The literature on estrogen-induced carcinogenesis (and contaminants with estrogenic  
529 properties) is substantial [73-75] yet the exact mechanisms and pathways involved are still under  
530 investigation. One established mechanism involves direct genomic action by activation of  
531 estrogen-receptor signal transduction pathways associated with increased cell proliferation and  
532 inhibition of apoptosis [76-78] via perturbation of genes controlling cell cycle [76] and other  
533 tumor-promoting factors such as VEGF [53, 54, 79]. Our findings are consistent with these studies;  
534 in sardine, the VEGF signaling pathway was significantly perturbed after EE2 exposure and 4  
535 Biological Process GO terms related to cell cycle were enriched, including “regulation of G1/S  
536 transition of mitotic cell cycle and positive regulation of cell cycle G2/M phase transition”  
537 (**Supplemental Figure S41**).

538 Estrogens and estrogenic contaminants can also interfere with cell cycle regulation by  
539 upregulating mitogen-activated protein kinases and secondary messengers, such as cAMP, via  
540 non-genomic action [77, 78, 80]. Accordingly, we determined that the “cAMP and PI3K-Akt  
541 signaling pathways” were significantly impacted in EE2-treated sardines and mackerels  
542 respectively. Estrogen metabolites have been shown to have genotoxic (formation of DNA adducts  
543 and oxidative DNA damage), mutagenic, transforming, and carcinogenic effects [81, 82]. This is  
544 consistent with the enrichment of the “chemical carcinogenesis” pathway in mackerels exposed to  
545 EE2 in our study.

546 Much effort has been expended in search of alternate model for estrogen-related human  
547 cancer research. Lam *et al.* have demonstrated that molecular conservation of estrogen-  
548 responsiveness between zebrafish and human cancer cell lines makes the zebrafish a great model  
549 and established common mechanisms for estrogen-induced carcinogenesis [83]; from an  
550 evolutionary perspective, their findings suggest that estrogen regulation of cell cycle is perhaps  
551 one of the earliest forms of steroidal-receptor controlled cellular processes. Upon further  
552 characterization of the sardine and mackerel transcriptomes, these two species have the potential  
553 for future use as additional cancer research models.

554 In summary the rationale for exploring liver tissue in this study stemmed from the fact that  
555 the liver is the primary organ for metabolism and detoxification. The motivation for carrying out  
556 EE2 exposure experiments was to facilitate extrapolation of toxicological insights from fish  
557 species to human and provide insights into ocean and human health. Our work has uncovered  
558 common biomarkers of low level EE2 exposure which provides a basis for improved risk  
559 assessment practices based on ‘Big Omics Data’. Strategies have been developed by others to  
560 derive AOPs (for example, domoic acid exposure) [84]. Perkins and co-workers employed a  
561 reverse engineering strategy based on network inference to uncover key nodes (i.e., genes, proteins,  
562 metabolites) impacted by chemical perturbation [85, 86]. Kramer and colleagues successfully  
563 demonstrated that models can predict potential population impact, once the data are transformed  
564 into the prediction of an adverse outcome of demographic significance (e.g., reproduction) at the  
565 organism level [87]. Celander *et al.* developed a comparative genomics approach with CYP19  
566 aromatase, and predicted potential aromatase toxicity of new compounds across a multiplicity of  
567 species [88]. Systematic organization of Big Data Science into AOP frameworks likely can  
568 improve regulatory decision-making through greater integration and more meaningful exploitation  
569 of mechanistic data. However, in order to develop a useful knowledgebase that encompasses  
570 toxicological contexts of concern to human health risk assessment, novel approaches such as the  
571 RNAseq pipeline we described must be developed in accordance with AOP core principles.

## 572 573 **5. CONCLUSION**

574 The primary goal of this study was to develop a novel analytical pipeline to elucidate the  
575 effects of environmental levels of EE2 on the hepatic transcriptome in sardine and mackerel, two  
576 species that do not have a well-characterized genome. Using scaffold transcriptomes from related  
577 species (zebrafish for sardine, and fugu for mackerel), we were able to streamline the HTS data  
578 analysis and examine the effects of low dose EE2 exposure on these species by performing a  
579 systems level analysis of their hepatic transcriptome. We determined that even at low doses, EE2  
580 disrupted basic biological processes and pathways, leading to a signature of metabolic, hormonal  
581 and immune dysfunction, as well as carcinogenesis in exposed fish. This work uncovered common  
582 dysregulated genes and biological pathways in both species providing biomarkers for EE2

583 exposure in the marine environment, and facilitating monitoring of ocean environmental health.  
584 As many of these processes and pathways are well conserved from an evolutionary perspective,  
585 and as our analytical pipeline projected the fish genes onto their human orthologs we can infer the  
586 impact that EE2 exposure could have on human-health. Our results call for further examination of  
587 the effects of estrogenic contaminants on fish and human health at concentrations that represent  
588 relevant levels of environmental exposure.  
589  
590

591 **ACKNOWLEDGEMENTS**

592

593 We thank J. Sprague, C. Ludka and E. Ricciardelli at the UCSD Biomedical Genomics  
594 Facility (BIOGEM) for assistance with high throughput sequencing. We thank Drs. Roman Sasik,  
595 Faramarz Valafar, Jienwei Chen, Sean M. Courtney and Jeremy Davis-Turak for bioinformatics  
596 and biostatistical insights. We thank Dr. Michael E. Baker for many useful discussions on steroid  
597 hormones and endocrine disruption. No writing assistance was utilized in the production of this  
598 manuscript.

599

600 **FUNDING SOURCES**

601

602 GH acknowledges funding from SC EPSCoR and start-up funding from College of  
603 Medicine at the Medical University of South Carolina. SF was a recipient of a training grant from  
604 The Campus World Program.

605

606

607

608

609

610

- 611  
612 **REFERENCES**  
613
- 614 1. Baker, M.E.;Vidal-Dorsch, D.E. Molecular analysis of endocrine disruption in hornyhead  
615 turbot at wastewater outfalls in southern california using a second generation multi-species  
616 microarray. *PLoS One* **2013**. 8,e75553.
  - 617 2. Escande, A.;Pillon, A. Evaluation of ligand selectivity using reporter cell lines stably  
618 expressing estrogen receptor alpha or beta. *Biochemical Pharmacology* **2006**. 71,1459-  
619 1469.
  - 620 3. Soliman, M.A.;Pedersen, J.A.Suffet, I.H. Rapid gas chromatography-mass spectrometry  
621 screening method for human pharmaceuticals, hormones, antioxidants and plasticizers in  
622 water. *J Chromatogr A* **2004**. 1029,223-237.
  - 623 4. Filali-Meknassi, Y.;Auriol, M. Quantification of steroid sex hormones using solid-phase  
624 extraction followed by liquid chromatography-mass spectrometry. *Water Environ Res*  
625 **2007**. 79,687-696.
  - 626 5. Belfroid, A.;Van der Horst, A. Analysis and occurrence of estrogenic hormones and their  
627 glucuronides in surface water and waste water in The Netherlands. *Science of the Total*  
628 *Environment* **1999**. 225,101-108.
  - 629 6. Benijts, T.;Dams, R. Analysis of estrogenic contaminants in river water using liquid  
630 chromatography coupled to ion trap based mass spectrometry. *Rapid Communications in*  
631 *Mass Spectrometry* **2002**. 16,1358-1364.
  - 632 7. Hill, R.L.Janz, D.M. Developmental estrogenic exposure in zebrafish (Danio rerio): I.  
633 Effects on sex ratio and breeding success. *Aquatic Toxicology* **2003**. 63,417-429.
  - 634 8. Petersen, G.;Andersen, L. Baseline test studies and development of ELISA. *Zebra Fish for*  
635 *Testing Endocrine Disrupting Chemicals. TemaNord* **2000**. 555,35-46.
  - 636 9. Van den Belt, K.;Verheyen, R.Witters, H. Effects of 17 $\alpha$ -ethynylestradiol in a partial life-  
637 cycle test with zebrafish (Danio rerio): effects on growth, gonads and female reproductive  
638 success. *Science of the Total Environment* **2003**. 309,127-137.
  - 639 10. Van den Belt, K.;Verheyen, R.Witters, H. Comparison of vitellogenin responses in  
640 zebrafish and rainbow trout following exposure to environmental estrogens. *Ecotoxicology*  
641 *and environmental safety* **2003**. 56,271-281.
  - 642 11. Weber, L.P.;Hill, R.L.Janz, D.M. Developmental estrogenic exposure in zebrafish (Danio  
643 rerio): II. Histological evaluation of gametogenesis and organ toxicity. *Aquatic Toxicology*  
644 **2003**. 63,431-446.
  - 645 12. Filby, A.L.;Neuparth, T. Health impacts of estrogens in the environment, considering  
646 complex mixture effects. *Environ Health Perspect* **2007**. 115,1704-1710.
  - 647 13. Jin, Y.;Shu, L. Temperature and photoperiod affect the endocrine disruption effects of  
648 ethinylestradiol, nonylphenol and their binary mixture in zebrafish (Danio rerio). *Comp*  
649 *Biochem Physiol C Toxicol Pharmacol* **2010**. 151,258-263.
  - 650 14. Jobling, S.;Burn, R.W. Statistical modeling suggests that antiandrogens in effluents from  
651 wastewater treatment works contribute to widespread sexual disruption in fish living in  
652 English rivers. *Environ Health Perspect* **2009**. 117,797-802.
  - 653 15. Tyler, C.R.;Lange, A. The roach (*Rutilus rutilus*) as a sentinel for assessing endocrine  
654 disruption. *Environ Sci* **2007**. 14,235-253.

- 655 16. Cardona, L.;Martínez-Iñigo, L. The role of sardine as prey for pelagic predators in the  
656 western Mediterranean Sea assessed using stable isotopes and fatty acids. *Marine Ecology*  
657 *Progress Series* **2015**. 531,1-14.
- 658 17. Trites, A.;Donnelly, C. The decline of Steller sea lions *Eumetopias jubatus* in Alaska: a  
659 review of the nutritional stress hypothesis. *Mammal review* **2003**. 33,3-28.
- 660 18. Baumgartner, T. Reconstruction of the history of the Pacific sardine and northern anchovy  
661 populations over the past two millenia from sediments of the Santa Barbara basin,  
662 California. *CalCOFI Rep* **1992**. 33,24-40.
- 663 19. Hill, K.T.;Crone, P.R.;Zwolinski, J.P. Assessment of the Pacific sardine resource in 2017  
664 for U.S. management in 2017-18. Pacific Fishery Management Council, April 2017  
665 Briefing Book. 2017: Portland, Oregon. p. 146 p.
- 666 20. McClatchie, S.;Hendy, I. Collapse and recovery of forage fish populations prior to  
667 commercial exploitation. *Geophysical Research Letters* **2017**. 44,1877-1885.
- 668 21. Lefebvre, K.;Silver, M. Domoic acid in planktivorous fish in relation to toxic *Pseudo-*  
669 *nitzschia* cell densities. *Marine Biology* **2002**. 140,625-631.
- 670 22. Zeng, L.;Cheng, Q. Thirty novel microsatellite markers for the coastal pelagic fish, *Scomber*  
671 *japonicus* (Scombridae). *J Genet* **2012**. 91,e64-68.
- 672 23. Kris-Etherton, P.M.;Harris, W.S.;Appel, L.J. Fish consumption, fish oil, omega-3 fatty  
673 acids, and cardiovascular disease. *Circulation* **2002**. 106,2747-2757.
- 674 24. Mitra, V.;Metcalf, J. Metabolic functions of the liver. *Anaesthesia & Intensive Care*  
675 *Medicine* **2012**. 13,54-55.
- 676 25. Hardiman, G. Application of ultra-high throughput sequencing and microarray  
677 technologies in pharmacogenomics testing. In: Dasgupta A, editor. *Therapeutic Drug*  
678 *Monitoring*. London: Elsevier; 2012. **2012**144–159.
- 679 26. Fox, S.;Filichkin, S.;Mockler, T.C. Applications of ultra-high-throughput sequencing.  
680 *Methods Mol Biol* **2009**. 553,79-108.
- 681 27. Altschul, S.F.;Gish, W. Basic local alignment search tool. *J Mol Biol* **1990**. 215,403-410.
- 682 28. Li, J.;Tibshirani, R. Finding consistent patterns: A nonparametric approach for identifying  
683 differential expression in RNA-Seq data. *Stat Methods Med Res* **2013**. 22,519-536.
- 684 29. Team, R.C. R: A language and environment for statistical computing [Internet]. Vienna,  
685 Austria: R Foundation for Statistical Computing; 2014. 2015.
- 686 30. Love, M.I.;Huber, W.;Anders, S. *Moderated estimation of fold change and dispersion for*  
687 *RNA-Seq data with DESeq2* Country, 2014.
- 688 31. Huff, M.;da Silveira, W.A. Systems Analysis of the Liver Transcriptome in Adult Male  
689 Zebrafish Exposed to the Plasticizer (2-Ethylhexyl) Phthalate (DEHP). *Sci Rep* **2018**.  
690 8,2118.
- 691 32. Renaud, L.;Silveira, W.A.D. The Plasticizer Bisphenol A Perturbs the Hepatic Epigenome:  
692 A Systems Level Analysis of the miRNome. *Genes (Basel)* **2017**. 8.
- 693 33. Eden, E.;Navon, R. GOrilla: a tool for discovery and visualization of enriched GO terms  
694 in ranked gene lists. *BMC Bioinformatics* **2009**. 10,48.
- 695 34. Supek, F.;Bosnjak, M. REVIGO summarizes and visualizes long lists of gene ontology  
696 terms. *PLoS One* **2011**. 6,e21800.
- 697 35. Draghici, S.;Khatri, P. A systems biology approach for pathway level analysis. *Genome*  
698 *Res* **2007**. 17,1537-1545.

- 699 36. Kanehisa, M.;Goto, S. KEGG: kyoto encyclopedia of genes and genomes. *Nucleic Acids*  
700 *Res* **2000**. 28,27-30.
- 701 37. Ashburner, M.;Ball, C.A. Gene ontology: tool for the unification of biology. The Gene  
702 Ontology Consortium. *Nat Genet* **2000**. 25,25-29.
- 703 38. Agarwal, V.;Bell, G.W. Predicting effective microRNA target sites in mammalian mRNAs.  
704 *Elife* **2015**. 4.
- 705 39. Kozomara, A.;Griffiths-Jones, S. miRBase: annotating high confidence microRNAs using  
706 deep sequencing data. *Nucleic Acids Research* **2013**. 42,D68-D73.
- 707 40. Oliveros, J.C. VENNY. An interactive tool for comparing lists with Venn Diagrams. **2007**.
- 708 41. Aparicio, S.;Chapman, J. Whole-genome shotgun assembly and analysis of the genome of  
709 *Fugu rubripes*. *Science* **2002**. 297,1301-1310.
- 710 42. Jones, F.C.;Grabherr, M.G. The genomic basis of adaptive evolution in threespine  
711 sticklebacks. *Nature* **2012**. 484,55.
- 712 43. NCTC. Fish Histology and Histopathology Manual. 2014 03/06/2018]; Available from:  
713 <https://training.fws.gov/resources/course-resources/fish-histology/index.html>.
- 714 44. Pandey, G.;Pandey, S.;Sharma, M. Experimental hepatotoxicity produced by ethinyl  
715 estradiol. *Toxicology international* **2011**. 18,160.
- 716 45. Amitrano, L.;Guardascione, M.A. Coagulation disorders in liver disease. *Semin Liver Dis*  
717 **2002**. 22,83-96.
- 718 46. Bourdeau, V.;Deschenes, J. Genome-wide identification of high-affinity estrogen response  
719 elements in human and mouse. *Mol Endocrinol* **2004**. 18,1411-1427.
- 720 47. Cleuren, A.C.;Van der Linden, I.K. 17 $\alpha$ -Ethinylestradiol rapidly alters transcript levels  
721 of murine coagulation genes via estrogen receptor alpha. *J Thromb Haemost* **2010**. 8,1838-  
722 1846.
- 723 48. Howe, K.;Clark, M.D. The zebrafish reference genome sequence and its relationship to the  
724 human genome. *Nature* **2013**. 496,498-503.
- 725 49. Labadie, P.;Budzinski, H. Alteration of steroid hormone profile in juvenile turbot (*Psetta*  
726 *maxima*) as a consequence of short-term exposure to 17 $\alpha$ -ethinylestradiol. *Chemosphere*  
727 **2006**. 64,1274-1286.
- 728 50. Hoffmann, J.;Torontali, S. Hepatic gene expression profiling using Genechips in zebrafish  
729 exposed to 17 $\alpha$ -ethinylestradiol. *Aquatic Toxicology* **2006**. 79,233-246.
- 730 51. Kuo, T.-H.;Wang, K.-L. Inhibitory Effects of 17 Alpha-Ethinylestradiol on the Production  
731 of Testosterone by Rat Leydig Cells. 2012, Oxford University Press.
- 732 52. Aronica, S.M.;Kraus, W.L.;Katzenellenbogen, B.S. Estrogen action via the cAMP signaling  
733 pathway: stimulation of adenylate cyclase and cAMP-regulated gene transcription.  
734 *Proceedings of the National Academy of Sciences* **1994**. 91,8517-8521.
- 735 53. Chennazhi, K.P.;Nayak, N.R. Regulation of angiogenesis in the primate endometrium:  
736 vascular endothelial growth factor. *Semin Reprod Med* **2009**. 27,80-89.
- 737 54. Okada, H.;Tszuzuki, T. Regulation of decidualization and angiogenesis in the human  
738 endometrium: mini review. *J Obstet Gynaecol Res* **2014**. 40,1180-1187.
- 739 55. Theocharis, A.D.;Karamanos, N.K. Proteoglycans remodeling in cancer: Underlying  
740 molecular mechanisms. *Matrix Biol* **2017**.
- 741 56. Marshall, J.S.;Jawdat, D.M. Mast cells in innate immunity. *Journal of Allergy and Clinical*  
742 *Immunology* **2004**. 114,21-27.

- 743 57. Al-Obaidy, M.J.Al-Youzbaki, W.B. Effect of combined oral contraceptive pills on some  
744 coagulation parameters. *Effect of educational level of pregnant women on compliance with*  
745 *antenatal care services in Erbil city* 164.
- 746 58. Yager, J.D.;Roebuck, B.D. Effects of ethinyl estradiol and tamoxifen on liver DNA  
747 turnover and new synthesis and appearance of gamma glutamyl transpeptidase-positive  
748 foci in female rats. *Carcinogenesis* **1986**. 7,2007-2014.
- 749 59. Li, J.J.Li, S.A. Estrogen carcinogenesis in Syrian hamster tissues: role of metabolism.  
750 *Federation proceedings* **1987**. 46,1858-1863.
- 751 60. Notch, E.G.;Miniutti, D.M.Mayer, G.D. 17 $\alpha$ -Ethinylestradiol decreases expression of  
752 multiple hepatic nucleotide excision repair genes in zebrafish (*Danio rerio*). *Aquatic*  
753 *Toxicology* **2007**. 84,301-309.
- 754 61. Diaz-Ruiz, R.;Rigoulet, M.Devin, A. The Warburg and Crabtree effects: On the origin of  
755 cancer cell energy metabolism and of yeast glucose repression. *Biochimica et Biophysica*  
756 *Acta (BBA) - Bioenergetics* **2011**. 1807,568-576.
- 757 62. Warburg, O. On the origin of cancer cells. *Science* **1956**. 123,309-314.
- 758 63. Banerjee, S.;Saxena, N. 17 $\alpha$ -Estradiol-induced VEGF-A expression in rat pituitary tumor  
759 cells is mediated through ER independent but PI3K-Akt dependent signaling pathway.  
760 *Biochemical and Biophysical Research Communications* **2003**. 300,209-215.
- 761 64. Hofbauer, R.;Frass, M. Oral contraceptives that contain ethinyl estradiol (0.035 mg) and  
762 cyproterone acetate (2 mg) inhibit leukocyte transmigration through endothelial cell  
763 monolayers. *Fertility and sterility* **1999**. 72,652-656.
- 764 65. Cid, M.C.;Esparza, J. Estradiol enhances endothelial cell interactions with extracellular  
765 matrix proteins via an increase in integrin expression and function. *Angiogenesis* **1999**.  
766 3,271-280.
- 767 66. Hansen, M.;Koskinen, S.O. Ethinyl oestradiol administration in women suppresses  
768 synthesis of collagen in tendon in response to exercise. *The Journal of physiology* **2008**.  
769 586,3005-3016.
- 770 67. Castillo-Briceño, P.;Arizcun-Arizcun, M. Correlated expression profile of extracellular  
771 matrix-related molecules during the inflammatory response of the teleost fish gilthead  
772 seabream. *Developmental & Comparative Immunology* **2010**. 34,1051-1058.
- 773 68. YABU, T.;KISHI, S. Characterization of zebrafish caspase-3 and induction of apoptosis  
774 through ceramide generation in fish fathead minnow tailbud cells and zebrafish embryo.  
775 *Biochemical Journal* **2001**. 360,39-47.
- 776 69. Reis, M.I.R.;Nascimento, D.S. Molecular cloning and characterisation of sea bass  
777 (*Dicentrarchus labrax* L.) caspase-3 gene. *Molecular Immunology* **2007**. 44,774-783.
- 778 70. Rojas, V.;Guzmán, F. Development of a caspase-3 antibody as a tool for detecting  
779 apoptosis in cells from rainbow trout (*Oncorhynchus mykiss*). *Electronic Journal of*  
780 *Biotechnology* **2012**. 15,12-12.
- 781 71. Lawrence, C. The husbandry of zebrafish (*Danio rerio*): a review. *Aquaculture* **2007**.  
782 269,1-20.
- 783 72. Yang, L.;Allen, B.C.Thomas, R.S. BMDExpress: a software tool for the benchmark dose  
784 analyses of genomic data. *BMC Genomics* **2007**. 8,387.
- 785 73. Paulose, T.;Speroni, L. Estrogens in the wrong place at the wrong time: Fetal BPA  
786 exposure and mammary cancer. *Reproductive Toxicology* **2015**. 54,58-65.

- 787 74. Rutkowska, A.Z.;Szybiak, A. Endocrine disrupting chemicals as potential risk factor for  
788 estrogen-dependent cancers. *Pol Arch Med Wewn* **2016**. 126,562-570.
- 789 75. Trevino, L.S.;Wang, Q.Walker, C.L. Hypothesis: Activation of rapid signaling by  
790 environmental estrogens and epigenetic reprogramming in breast cancer. *Reprod Toxicol*  
791 **2015**. 54,136-140.
- 792 76. Pearce, S.T.Jordan, V.C. The biological role of estrogen receptors  $\alpha$  and  $\beta$  in cancer.  
793 *Critical reviews in oncology/hematology* **2004**. 50,3-22.
- 794 77. Russo, J.Russo, I.H. The role of estrogen in the initiation of breast cancer. *The Journal of*  
795 *steroid biochemistry and molecular biology* **2006**. 102,89-96.
- 796 78. Yager, J.D.Davidson, N.E. Estrogen carcinogenesis in breast cancer. *New England Journal*  
797 *of Medicine* **2006**. 354,270-282.
- 798 79. Mueller, M.D.;Vigne, J.-L. Regulation of vascular endothelial growth factor (VEGF) gene  
799 transcription by estrogen receptors  $\alpha$  and  $\beta$ . *Proceedings of the National Academy of*  
800 *Sciences* **2000**. 97,10972-10977.
- 801 80. Bonkhoff, H. Estrogen receptor signaling in prostate cancer: Implications for  
802 carcinogenesis and tumor progression. *Prostate* **2018**. 78,2-10.
- 803 81. Roy, D.;Cai, Q. Estrogen-induced generation of reactive oxygen and nitrogen species, gene  
804 damage, and estrogen-dependent cancers. *Journal of Toxicology and Environmental*  
805 *Health, Part B* **2007**. 10,235-257.
- 806 82. Russo, J.;Lareef, M.H. Estrogen and its metabolites are carcinogenic agents in human  
807 breast epithelial cells. *The Journal of steroid biochemistry and molecular biology* **2003**.  
808 87,1-25.
- 809 83. Lam, S.H.;Lee, S.G. Molecular conservation of estrogen-response associated with cell  
810 cycle regulation, hormonal carcinogenesis and cancer in zebrafish and human cancer cell  
811 lines. *BMC Medical Genomics* **2011**. 4,41.
- 812 84. Watanabe, K.H.;Andersen, M.E. Defining and modeling known adverse outcome  
813 pathways: Domoic acid and neuronal signaling as a case study. *Environmental toxicology*  
814 *and chemistry* **2011**. 30,9-21.
- 815 85. Perkins, E.J.;Chipman, J.K. Reverse engineering adverse outcome pathways.  
816 *Environmental toxicology and chemistry* **2011**. 30,22-38.
- 817 86. Perkins, E.J.;Antczak, P. Adverse outcome pathways for regulatory applications:  
818 examination of four case studies with different degrees of completeness and scientific  
819 confidence. *Toxicological Sciences* **2015**. 148,14-25.
- 820 87. Kramer, V.J.;Etterson, M.A. Adverse outcome pathways and ecological risk assessment:  
821 Bridging to population - level effects. *Environmental Toxicology and Chemistry* **2011**.  
822 30,64-76.
- 823 88. Celander, M.C.;Goldstone, J.V. Species extrapolation for the 21st century. *Environmental*  
824 *toxicology and chemistry* **2011**. 30,52-63.
- 825  
826  
827  
828  
829