Chapter 6

Applied aspects of fish endocrinology

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Chapter Outline

Endocrine systems are regulators of physiological responses to environmental conditions, acting as key transmitters of external and internal cues, and can therefore provide valuable insights to help address pressing issues in fish conservation biology. In this review, after a brief overview of the endocrine systems involved in regulating stress, growth, and reproduction, we examine how fish endocrinologists are developing and applying new tools to monitor, conserve, and assist threatened and endangered wild fish populations. Specifically, we provide examples of how endocrine signals are used to guide the development of conservation hatcheries, to reveal how exposure to environmental stressors can affect development and growth, to enable assisted reproduction, to mitigate the impacts of climate change and endocrine-disrupting chemicals on fish reproduction, and to facilitate the management of invasive species. We also examine how non-invasive sampling techniques, profiling of steroid hormones, and the

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integration of endocrinology with emerging fields such as ecotoxicogenomics and host-microbiome interactions will have impacts on future conservation efforts. Finally, we identify limitations for the broader application of endocrinology in fish conservation and opportunities for fish endocrinologists to make meaningful contributions to the most urgent conservation challenges of our time.

1 Introduction

The ongoing and accelerating loss of fish biodiversity in freshwater and marine ecosystems has brought about an urgent need to develop and apply new tools to monitor, conserve, and assist wild fish populations that are threatened and endangered. As a messenger system involved in the regulation and coordination of all biological processes, the endocrine system can provide key insights into the threats posed by anthropogenic and environmental stressors, as well as the mechanisms by which animals cope. Our understanding of fish endocrine systems continues to grow from its early promise in fisheries management (Schreck and Scanlon, 1977) as novel technologies, model species, and applications are studied, including the identification of key endocrine-related endpoints that can be used to guide the management and conservation of species at risk. In this review, after a brief overview of the endocrine systems involved in regulating stress, growth, and reproduction, we examine how endocrine signals can be used in the development of conservation hatcheries, to monitor the development and growth of wild fish, to control and assist the reproduction of threatened species, to assess the impact of climate change and endocrine-disrupting chemicals on fish reproduction, and to manage invasive species. Finally, looking into the future, we discuss how non-invasive sampling techniques, hormonal profiling, and the integration of endocrine systems in multidisciplinary approaches can benefit and advance the field of fish conservation physiology.

2 Overview of endocrine systems with applications to conservation physiology

The following section is a primer in fish endocrinology focused specifically on the stress, reproductive, and growth-regulating hormones, i.e., the endocrine signals that are more commonly measured and used in fish conservation. As such, for reviews on the hormonal systems involved in ionic regulation, drinking, food intake, digestion, metabolism, and cardiovascular control, we refer the reader to recent volumes of the *Fish Physiology* series (Bernier et al., 2009a; Gamperl et al., 2017; Grosell et al., 2010; McCormick et al., 2012).

2.1 Hormonal control of stress

Fish, like all vertebrates, respond to stressors by initiating the primary stress response which culminates in elevated levels of catecholamines and corticosteroids in the blood. Together, these hormones coordinate a multisystem

physiological response that helps the fish meet and overcome a challenge to homeostasis (Barton, 2002; Barton and Iwama, 1991; Gorissen and Flik, 2016). Because this integrated response includes energetic and behavioral changes, as well as the potential for immune (Khansari et al., 2018) and reproductive inhibition (Pankhurst, 2016), assessing and monitoring the stress status of wild animals, including fish, is a recognized and valued tool in conservation physiology (McCormick and Romero, 2017; Madliger and Love, 2014). Moreover, the conserved and generalized nature of the primary stress response dictates a prescribed physiological response that is largely independent of stressor type, but that varies predictably with stressor magnitude and duration; thus, quantifying stress-related endpoints in wild fish populations can be used in broad contexts, some of which are described in this chapter.

The catecholamine (CA) hormones, epinephrine and norepinephrine, are synthesized from tyrosine in head kidney chromaffin cells of teleost fish and then released from secretory vesicles into the circulation following stimulation by the sympathetic nervous system (Fabbri and Moon, 2016; Reid et al., 1998); although it should be noted that the localization of peripheral catecholaminergic cells and their regulation by neurotransmitters and various blood borne factors differs across fish groups (Fabbri et al., 1998; Nilsson, 1983; Perry and Bernier, 1999). Once in the circulation, CAs initiate a suite of physiological changes, colloquially called the "fight or flight" response, that increase the availability and transport of metabolic fuels (Fig. 1). In the liver, for example, CAs bind to G-protein-coupled α- and β-adrenergic receptors and stimulate glycogenolysis through activation of glycogen phosphorylase (Fabbri et al., 1998). At the same time, increased plasma CAs can have a profound effect on hemoglobin oxygen affinity in some fish groups (Harter and Brauner, 2017). The appearance of CAs in the blood after a stressor is, necessarily, incredibly fast (seconds to minutes), which challenges attempts to collect meaningful baseline values, and therefore limits their usefulness as bioindicators of stress in wild populations (Sopinka et al., 2016). Nevertheless, the mechanisms of action and downstream effects of elevated CAs are relevant to conservation physiology due to the increasing opportunity for this system to be perturbed by pharmaceuticals in the aquatic environment. Drugs that target the highly conserved vertebrate adrenergic receptors (i.e., the β-blockers propranolol, atenolol, metoprolol, and sotalol that are widely prescribed in humans as a treatment for hypertension) continually enter the aquatic environment in bioactive forms that reach concentrations capable of eliciting biological responses in fish (e.g., Ings et al., 2012).

In contrast to CAs, a stress-induced increase in plasma corticosteroids occurs with some time lag from stressor onset (minutes to hours). This important difference means that accurate species-specific baseline values can be acquired, and as a result corticosteroids are a standard and widely used bioindicator of stress in both laboratory and field studies (Sopinka et al., 2016). The time lag is due to the hierarchical hormone cascade, the hypothalamic-pituitary-interrenal (HPI) axis, that regulates on-demand synthesis from

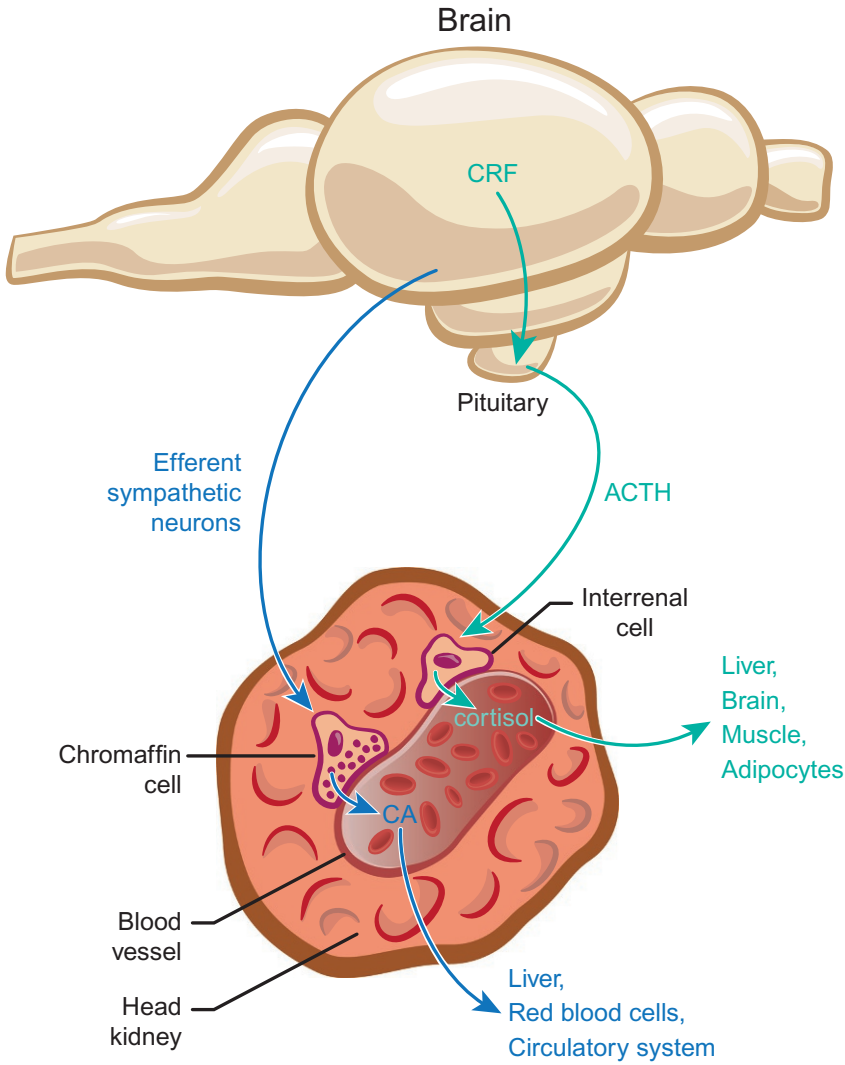

FIG. 1 Schematic representation of the neuroendocrine control of stress in fish. The brain-sympathetic-chromaffin cell pathway (blue) culminates in a release of the catecholamines (CA), epinephrine and norepinephrine, from the chromaffin cells of the head kidney into the circulation. The hypothalamic-pituitary-interrenal (HPI) axis (green) culminates in the release of glucocorticoids (e.g., cortisol) from the head kidney into the circulation. Together, CA and glucocorticoids initiate energy mobilization and other homeostatic responses by interacting with specific receptors that are widely expressed throughout the body, including in the indicated target tissues. Not shown is the cortisol-mediated negative feedback that occurs across the HPI axis to inhibit corticotropin-releasing factor (CRF), adrenocorticotropic hormone (ACTH), and cortisol release. Artwork generated by Ian Smith (University of Guelph).

cholesterol (Fig. 1). Corticosteroids are then distributed via the circulation to target tissues, where their primarily genomic actions are mediated by intracellular receptors. The activation, regulation, and outcome of HPI axis activation and corticosteroid signaling involves the integrated actions of numerous players (neuropeptides, receptors, enzymes, accessory proteins; see Bernier et al., 2009b; Faught et al., 2016 for reviews). For the purpose of this chapter, what is important to note is that this inherent complexity contributes to within and between individual differences in the endocrine stress response (Romero and Beattie, 2022), and that the involvement of so many protein components underscores the heritability of the endocrine stress response (Heath et al., 1993; Øverli et al., 2005; Pottinger and Carrick, 1999) and species-specific differences in maximal stress-induced corticosteroid levels (Barton, 2002; Barton and Iwama, 1991).

Cortisol is the dominant corticosteroid hormone produced in fishes, with the notable exceptions of 1α-hydroxycorticosterone in elasmobranchs and 11-deoxycortisol in cyclostomes. Importantly, fish lack aldosterone synthase, which in tetrapods converts cortisol to aldosterone, and therefore the corticosteroids synthesized by the head kidney interrenal cells have dual function as both glucocorticoids (energy homeostasis) and mineralocorticoids (osmotic homeostasis). As glucocorticoids, a primary function of corticosteroids in fish is to stimulate gluconeogenesis in the liver via upregulation of the major enzymes in this pathway, and glucocorticoid signaling is further implicated in the regulation of glycogen, lipid, and protein stores (Mommsen et al., 1999). Moreover, sustained elevations in circulating corticosteroid levels facilitates the redirection of energy utilization toward essential life-sustaining functions by inhibiting the digestive (Barton et al., 1987; Pfalzgraff et al., 2021), immune (Fabbri and Moon, 2016; Philip and Vijayan, 2015; Pickering and, Pottinger, 1989), and reproductive systems (Pankhurst, 2016; Pankhurst and Van Der Kraak, 1997). As mineralocorticoids, corticosteroids contribute to the maintenance of ion and water homeostasis by regulating ion transporter expression in ionocytes such as the chloride cells of the gills (McCormick et al., 2008). This is especially relevant in euryhaline fish species (Young et al., 1989), and variation in baseline cortisol predicts the timing and success of migrations (Birnie-Gauvin et al., 2019). An appreciation for the breadth of physiological functions under the regulatory control of corticosteroids emphasizes why measuring other known correlates of stress (e.g., growth, immune response, reproduction) will provide more comprehensive information on the stress status of fish (Baker et al., 2013; MacDougall-Shackleton et al., 2019; Romero and Beattie, 2022). This is relevant to management and conservation initiatives including best practices in conservation hatcheries (see Section 3.1) and population monitoring via non-invasive hormone measurements (see Section 4.1).

Given the strong integration of the HPI axis with other physiological systems, repeated or chronic stress exposure may pose a multi-pronged fitness challenge to wild fish populations by reducing growth and body condition (O'Connor et al., 2011; Sadoul and Vijayan, 2016; Vargas-Chacoff et al., 2021), increasing susceptibility to disease (Maule et al., 1987), and limiting reproductive success (Algera et al., 2017; McConnachie et al., 2012; O'Connor et al., 2009).

2.2 Hormonal control of reproduction

Neuroendocrine regulation of fish reproduction is governed by the hypothalamic-pituitary-gonadal (HPG) axis and is a critical component of conservation initiatives given its direct link to individual fitness and population dynamics. For example, manipulation of the HPG axis can be used to support fish culture and restocking programs of threatened species (Kim et al., 2020; Peñaranda et al., 2018; Zadmajid et al., 2018; see Section 3.3). Moreover, disruption of normal HPG axis activity through environmental contamination can be a driving factor in population decline (Abdel-Moneim et al., 2015; Kidd et al., 2007; see Section 3.5). The fact that the maturation and function of the HPG axis is influenced by growth, metabolism, stress, and other physiological attributes (Fuzzen et al., 2011; Zohar et al., 2010) further underscores the need for comprehensive understanding of HPG axis regulation in fish conservation.

The HPG axis in fish, as in all vertebrates, involves a cascade of hormones that govern the development, maturation, and function of the reproductive system (Fig. 2). Stimulatory and inhibitory signals from hypothalamic neurons control the release of the gonadotropic hormones, follicle-stimulating hormone (FSH) and luteinizing hormone (LH), from pituitary gonadotropes. Among the many neuropeptides and neurotransmitters involved in this process, stimulation by gonadotropin-releasing hormones (GnRH) and inhibition by dopamine are considered the primary hypothalamic regulators of gonadotropes (Zohar et al., 2010). Dopamine also inhibits GnRH secretion (Bryant et al., 2016) and is therefore a potent inhibitory signal of the HPG axis. In turn, the activities of gonadotropic and dopaminergic neurons are influenced by other neuromodulators (e.g., kisspeptin, neuropeptide Y, gonadotropin-inhibitory hormone) and hormones (e.g., cortisol, sex steroids) to integrate the reproductive system with other physiological systems (Dufour et al., 2020; Fuzzen et al., 2011; Zohar et al., 2010). Once in circulation gonadotropic hormones induce changes in gonadal tissue to support gamete development and sexual maturation. While FSH stimulates the early stages of gamete development, LH specifically, stimulates ovulation in females and spermiation in males. Both gonadotropic hormones also stimulate the production of sex hormones. In males, the predominant steroids produced are the androgens testosterone (T) and its more biologically active metabolite 11-ketotestosterone (11-KT). In females, testosterone is also produced but it

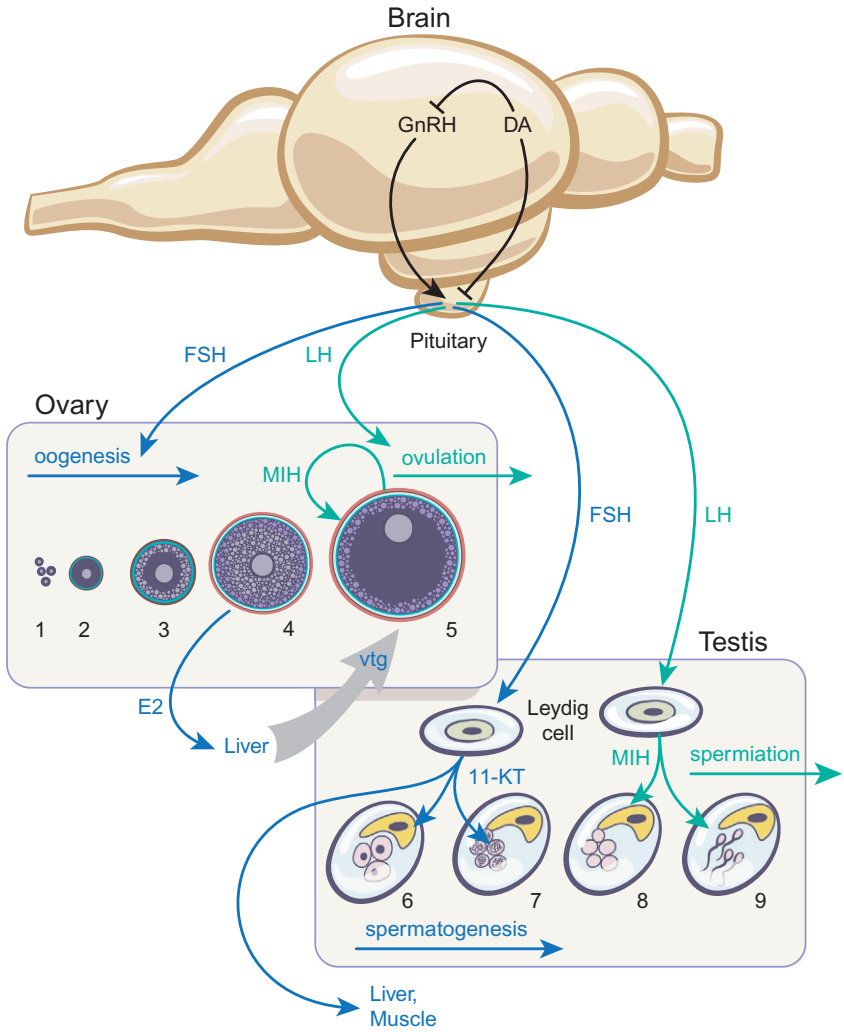

FIG. 2 Schematic representation of the hypothalamic-pituitary-gonadal (HPG) axis that regulates multiple aspects of sexual maturation and reproductive success in fish. The secretion of follicle-stimulating hormone (FSH) and luteinizing hormone (LH) from the pituitary is regulated by multiple stimulatory (arrow) and inhibitory (blunt-end) hypothalamic signals, including gonadotropin-releasing hormone (GnRH) and dopamine (DA). Inhibition of GnRH neurons by DA occurs in most fishes. FSH and LH stimulate gametogenesis and the production of estrogens (e.g., estradiol, E2), androgens (e.g., 11-ketotestosterone, 11-KT), and progestins (e.g., maturation-inducing hormone, MIH) from target cells in the gonads. In the ovary, oogenesis defines the successive maturation of an oogonium (1) to a primary oocyte (2), pre-vitellogenic oocyte (3), vitellogenic oocyte (4), and mature oocyte (5) ready for LH-mediated ovulation. The increased yolk deposition in later growth stages is driven by E2-mediated production of vitellogenin (Vtg) in the liver, one of many E2 targets. In the testis, spermatogenesis defines the successive maturation of spermatogonia (6) to spermatocytes (7), spermatids (8), and spermatozoa (9), which occurs within the seminiferous tubules and is supported by the Sertoli cells (yellow cell alongside developing sperm). The rise in circulating 11-KT also drives the development of a male-specific phenotype via interactions with widely expressed androgen receptors, including in the liver and muscle. Gonad schematics inspired by Alix et al. (2020). Artwork generated by Ian Smith (University of Guelph).

is converted to 17β-estradiol (E2) by the enzyme aromatase (Tokarz et al., 2015). Increased circulating levels of E2 and 11-KT are critical for sexual maturation, including proliferation of oogonia and spermatogonia, respectively, as well as the development of sex-specific phenotypes and behaviors. In females, for example, E2 promotes in hepatocytes the synthesis of the egg yolk protein, vitellogenin (Vtg). In males, increased muscle growth, aggression, and secondary sex characteristics are mediated by 11-KT. Unlike other vertebrates, teleosts also produce maturation-inducing hormones (MIH) in response to gonadal stimulation by LH, either 17α,20β-dihydroxy-4-pregnen-3-one (17,20βP) or 17α,20β,21-trihydroxy-4-pregnen-3-one (20βS). These progesterone-like steroids induce final oocyte maturation and spermiation, enhance sperm motility, and act as male pheromones in some species (Scott et al., 2010; Tokarz et al., 2015).

2.3 Hormonal control of growth and metabolism

As an integrated response of external environmental conditions and internal physiological status, growth in fish can be an important measure of population health and habitat quality. Among the multiple hormones that contribute to regulating the indeterminate growth of fish, the growth hormone (GH)-insulin-like growth factor-I (IGFI) axis and thyroid hormones play prominent roles across all life stages (Fuentes et al., 2013; Power et al., 2001) (Fig. 3). Previous laboratory studies established that components of the GH-IGFI axis can be used as indices of growth and increasingly these biomarkers are being used to monitor the growth of wild fish (Beckman, 2011; Duguid et al., 2018; Picha et al., 2008; see Section 3.2). In contrast, the thyroid axis in fish is particularly sensitive to environmental and anthropogenic stressors and components of this axis may be suitable biomarkers of endocrine disruption (Carr and Patiño, 2011; Deal and Volkoff, 2020; Jarque and Piña, 2014; Nugegoda and Kibria, 2017).

The GH-IGFI axis plays a key role in regulating somatic growth across fishes (Picha et al., 2008; Reinecke et al., 2005). Stored in the pituitary somatotropes, GH is secreted via a multifactorial control system of hypothalamic, pituitary, and peripheral origins which integrates information related to energy metabolism, feeding, and food availability (Chang and Wong, 2009). In fed fish, the growth-stimulating effects of GH are primarily via the stimulation of IGFI from the liver and other tissues, and to a lesser degree from the direct muscle protein synthesizing actions of GH (Nordgarden et al., 2006). In contrast, in fasted fish, plasma GH levels rise and promote lipolysis (Bergan et al., 2015). These nutrient status-dependent effects of GH are explained by the differential expression of GH receptor subtypes linked to signaling cascades that either stimulate the production and release of IGFI or lipolysis (Bergan-Roller and Sheridan, 2018). At the tissue level, activation of IGF receptors by circulating or locally produced IGFI can

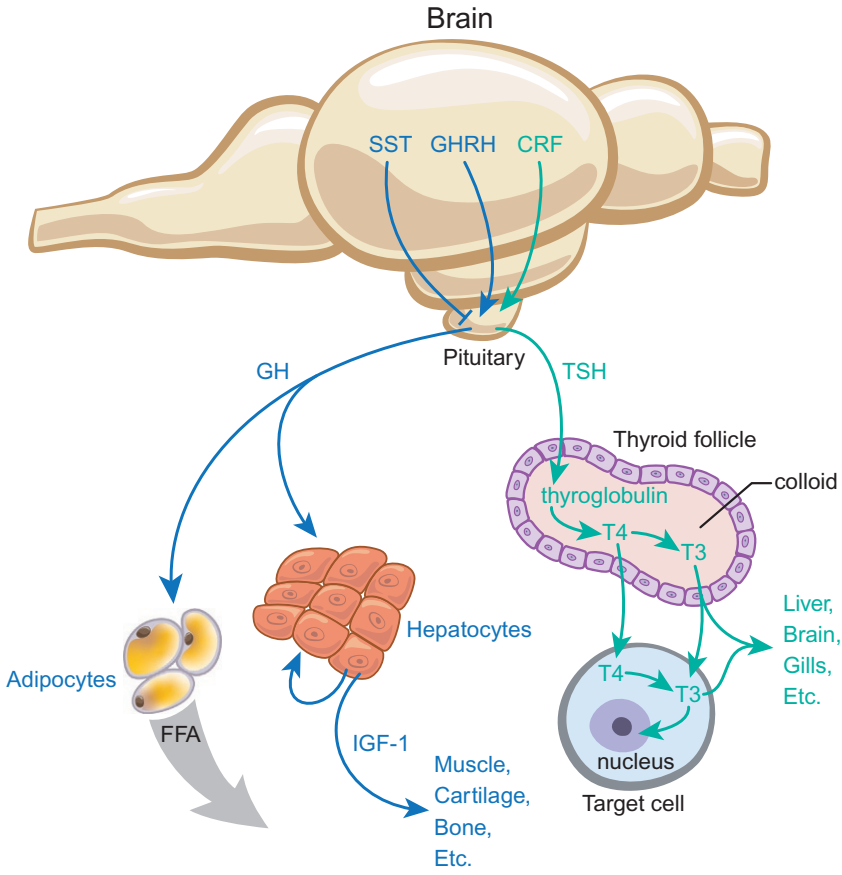

FIG. 3 Schematic representation of the endocrine control of growth and metabolism in fish. The growth hormone (GH)—insulin-like growth factor-1 (IGF-1) axis (left) and the thyroid axis (right) work independently and synergistically (not shown) throughout the lifespan of a fish. Both axes are regulated by complex stimulatory (arrows; e.g., GH-releasing hormone, GHRH; corticotropin-releasing factor, CRF) and inhibitory (blunt-end; e.g., somatostatin, SST) signals from the hypothalamus. Depending on nutritional status, pituitary secretion of GH can signal either catabolic (e.g., lipolysis to release free fatty acids, FFA) or anabolic (e.g., hyperplasia) effects directly on target tissues, or indirectly via IGF-1. Receptors for both GH and IGF-1 are broadly distributed and therefore similar effects occur in multiple cell types beyond those shown here. The release of pituitary thyroid-stimulating hormone (TSH) signals the production and release of thyroid hormones (thyroxine, T4; triiodothyronine, T3) from thyroid follicles, the distribution of which is species dependent. The biologically active T3 regulates gene transcription via thyroid receptors that are widespread in fish tissues. Artwork generated by Ian Smith (University of Guelph).

stimulate protein synthesis as well as cellular proliferation, differentiation, and survival (Reindl and Sheridan, 2012). While multiple IGF binding proteins (IGFBPs) regulate the availability of free IGFI in fish, and IGFBPs can potentiate and/or inhibit IGFI actions (Allard and Duan, 2018), under

various physiological conditions plasma IGFI levels are positively correlated with specific growth rate (Beckman, 2011; Picha et al., 2008).

Thyroid hormones directly contribute to the regulation of growth in fish via their actions on differentiation and organogenesis during embryonic development and post-embryonic life history transitions, and indirectly by stimulating the GH-IGFI axis (Deal and Volkoff, 2020; McMenamin and Parichy, 2013). Thyroid hormones also stimulate metabolism in fish in response to cold, an essential function of the thyroid axis to maintain performance during cold acclimation (Little and Seebacher, 2014). As in other vertebrates, the synthesis and metabolism of thyroid hormones in fishes is regulated by the hypothalamic-pituitary-thyroid (HPT) axis. Under the control of multiple hypothalamic factors, the pituitary thyrotropes release thyroid-stimulating hormone (TSH) into the circulation (Bernier et al., 2009b). In return, TSH stimulates the synthesis and release of pro-hormone thyroxine (T4) from subpharyngeal and renal thyroid follicles (Geven et al., 2007). Circulating T4 is converted in target tissues by type 1 and type 2 deiodinase enzymes into bioactive 3,5,3′-triiodo-L-thyronine (T3) (Jarque and Piña, 2014). T3 binds to two broadly expressed nuclear receptors that mediate the diverse actions of the thyroid axis by promoting or repressing gene transcription (Nelson and Habibi, 2009). Finally, both T3 and T4 have negative feedback effects on the hypothalamic and pituitary levels of the HPT axis and are inactivated by a type 3 deiodinase (Bernier et al., 2009b; Jarque and Piña, 2014).

3 Applied aspects of endocrine systems

3.1 Fish culture

Fish culture can play an important role in the management and protection of endangered species. According to the 2021 version of the International Union for Conservation of Nature's red list, 3210 fish species are threatened, or ~9% of the estimated number of fish species. Among those endangered, hundreds now depend on hatcheries to provide juveniles produced for species protection or restoration (Flagg and Nash, 1999; Froehlich et al., 2017; Taylor et al., 2017). While the use of hatcheries to recover wild populations can contribute to conservation efforts, it may also have unintended consequences. The juvenile fish produced by hatcheries differ from their wild counterparts and can therefore have negative effects on wild fish populations (Araki et al., 2008; Brown and Day, 2002; Flagg et al., 2000; Rand et al., 2012). Still, research in the field of fish endocrinology has played an important role in the development of conversation hatcheries and in their on-going efforts at optimizing the fitness of released fish. For example, fundamental and translational research in fish reproductive endocrinology has been key to the success of conservation hatcheries in reliably producing juveniles from wild fish (Zohar, 2021) (see Section 3.3 for more details). Similarly, research on stress

and growth-regulating hormones is playing an important role in identifying the physiological and behavioral differences between hatchery and wild fish and is guiding the development of novel conservation hatchery strategies.

Numerous studies have compared the endocrine stress response between hatchery and wild fish. In general, cultured fish have a reduced cortisol response to an acute stressor relative to their wild counterparts. For example, hatchery rainbow trout (*Oncorhynchus mykiss*; Woodward and Strange, 1987), chinook salmon (*Oncorhynchus tshawytscha*; Mazur and Iwama, 1993; Salonius and Iwama, 1993), ayu (*Plecoglossus altivelis*; Awata et al., 2011), rainbowfish (*Melanoteania duboulayi*; Zuberi et al., 2011), Eurasian perch (*Perca fluviatilis*; Douxfils et al., 2011) and fighting fish (*Betta splendens*; Verbeek et al., 2008) have lower cortisol levels following acute stress relative to wild fish. Since the cortisol response to stressors in fish has a heritable component (Heath et al., 1993; Øverli et al., 2005; Pottinger and Carrick, 1999), artificial selection for fish with a higher tolerance to the frequent episodes of stress encountered in hatcheries (e.g., netting, air exposure, chasing, crowding, grading) may result in the production of fish with muted stress responses. However, environmental conditions can also affect the responsiveness and sensitivity of fish to stressors. For example, among three groups of coho salmon (*Oncorhynchus kisutch*) sharing a similar genetic background and acclimated to common garden hatchery conditions for 7 months, the wild and colonized groups (i.e., hatchery fish previously transported into a natural environment as fry and re-captured as smolts) had higher cortisol levels following acute air exposure relative to hatchery fish (Salonius and Iwama, 1993). In the same coho salmon stock, wild and colonized smolts consistently had a larger springtime increase in plasma cortisol and a greater saltwater tolerance than hatchery fish (Shrimpton et al., 1994a,b). These results suggest that natural rearing environments favor the survival of fish with a heightened response to stressors and environmental cues, and that colonization of hatchery fish into natural environments may be needed to improve the success of conservation hatcheries.

Several studies have also evaluated alternative rearing practices to reduce the effects of stressors in conservation hatcheries. Relative to a barren environment, hatchery tank enrichments (e.g., the addition of substrate, plants, or shelter) have been shown to reduce resting plasma cortisol levels (Cogliati et al., 2019; Näslund et al., 2013; Rosengren et al., 2017) and the endocrine stress response to simulated hatchery disturbances (Barcellos et al., 2009; Braithwaite and Salvanes, 2005; Cogliati et al., 2019; Marcon et al., 2018; Rosengren et al., 2017). In contrast, enriched tank environment either had no effect (Näslund et al., 2013; Pounder et al., 2016; Wilkes et al., 2012) or were associated with larger post-stress plasma cortisol levels in other studies (Batzina et al., 2014; Boerrigter et al., 2016; Zubair et al., 2012). Among the factors that are known to contribute to the varying effects of tank enrichment (Näslund and Johnsson, 2016), the capacity of

environmental complexity to reduce the endocrine stress response may require lower rearing densities (Cogliati et al., 2019; Rosengren et al., 2017). Interestingly, whether environmental enrichment is provided in hatchery tanks or in a more natural setting also appears to have a differential effect on the endocrine stress response of fish. In juvenile chinook salmon, relative to fish reared in barren hatchery tanks, early rearing in seminatural channels resulted in fish with higher plasma cortisol levels in response diverse stressors (Garner et al., 2011; Madison et al., 2015a), suggesting that the stress responsiveness of channel-reared fish is more akin to those of wild fish. While the above studies suggest that environmental enrichment can affect HPI axis regulation of hatchery fish, it remains to be determined whether these alternative rearing practices translate into improved survival in the wild. In general, while fish reared in semi-natural environments usually perform and survive better in the wild than tank-reared fish, the benefits of hatchery tank enrichment to post-release performance and survival have been mixed (for review, see Näslund and Johnsson, 2016). Future work is needed to assess the relationships between rearing practices, stress responsiveness, and the capacity of hatchery fish to survive in natural environments.

Identifying the neuroendocrine basis of the behavioral differences between hatchery and wild fish may also help conservation hatcheries increase post-release survival rates and minimize the impact of stock supplementation on wild fish populations. The behavioral effects of hatchery selection are well known (for reviews, see Huntingford, 2004; Milla et al., 2021; Olla et al., 1998). Domestication in fish leads to a reduction in predator avoidance (Berejikian, 1995), to decreased foraging abilities (Brown et al., 2003), and promotes aggression and boldness (Rhodes and Quinn, 1998; Riley et al., 2005; Sundström et al., 2003). These behavioral effects of domestication may be at least partially mediated by alterations in brain monoaminergic activity (i.e., dopamine, norepinephrine, and serotonin) involved in the control of behavioral and endocrine stress response in fish (Winberg et al., 2016). For example, in response to standardized stressors, hatchery brown trout (*Salmo trutta*) have lower brain serotonergic and dopaminergic activity than their wild counterparts (Lepage et al., 2000). Similarly, the unpredictable chronic stress of hatchery environments leads to lower hypothalamic catecholaminergic and brain stem serotonergic responses to an acute stressor in Atlantic salmon (*Salmo salar*; Vindas et al., 2016). Although still poorly understood, comparison of hatchery- and wild-reared Atlantic salmon also suggests that the stimulus-deprived hatchery environment can lead to a reduction in neuroplasticity (Mes et al., 2018). In contrast, environmental enrichments can enhance neural plasticity, promote survival-related behaviors, and alter both basal and stress-induced levels of brain monoamines (Arechavala-Lopez et al., 2020; Batzina et al., 2014; Höglund et al., 2005; Mes et al., 2019; Salvanes et al., 2013; Ullah et al., 2020). As such, we suggest that conservation programs may benefit from the study of neurohormones involved in the

regulation of behavioral flexibility, and from research efforts directed toward a greater understanding of the role of environmental complexity in shaping these neuronal circuits.

Hormonal bioindicators of early sexual maturation and growth are also contributing to the development of novel conservation hatchery strategies. Historically, based on the observation that fish size and growth rate are positively correlated with higher post-release smolt survival, juvenile salmonid conservation hatcheries produced fish that were larger and with higher body condition than their wild counterparts (Beckman et al., 1999; Tipping, 1997). However, higher post-release smolt survival rates do not necessarily translate into higher smolt-to-adult return rates (Beamish et al., 2008; Morita et al., 2006). Factors predicted to contribute to this lower overall return of hatchery fish include early sexual maturation of males and reduced propensity to migrate. The faster growth rates and higher energy reserves of hatchery salmonids are associated with increased rates of precocious male maturation (Larsen et al., 2006; Shearer et al., 2006; Vainikka et al., 2012). Recent studies have shown that non-lethal measurement of springtime plasma levels of 11-KT can be used to predict the proportion of chinook salmon and steelhead trout males maturing at the time of smolt release (Medeiros et al., 2018; Middleton et al., 2019), a measure that may prove beneficial for reducing the impact of hatchery programs on precocious sexual maturation. The faster growth rates of hatchery-reared juvenile salmonids are also associated with freshwater residualism, i.e., the failure to out-migrate as smolts, relative to wild fish populations (Chittenden et al., 2010; Davidsen et al., 2014; Vainikka et al., 2012). In chinook salmon, the seasonal growth pattern of wild juveniles is characterized by a marked anabolic to catabolic shift in the autumn that results in a depletion of body lipids and a cessation of growth through the winter, followed by a spring anabolic phase that promotes smolt development and the deposition of energy reserves prior to smolting (Beckman et al., 2000). This dynamic seasonal shift in growth is paralleled by changes in plasma IGFI, with levels dropping throughout the fall, reaching a low in the winter, and increasing again in the spring (Beckman et al., 2000). Importantly, salmon hatcheries that best mimic the above wild fish seasonal growth pattern have higher smolt-to-adult return rates (Beckman et al., 2017; Harbicht et al., 2020; Harstad et al., 2018). In chinook salmon hatcheries, fish with the highest summer and autumn growth rates have higher plasma IGFI and adiposity levels and produce fish with the highest rates of precocious male maturation. In contrast, time-matched wild fish are significantly smaller, leaner, have much lower plasma IGFI levels, and greatly reduced rates of precocious maturation (Larsen et al., 2006). Therefore, further evaluation of plasma IGFI levels may be useful in the assessment of smolt quality and fitness, and for the management of salmonid conservation hatcheries.

The above examples highlight how the integration of endocrinology with physiology and behavior can help guide the refinement of conservation

hatcheries practices to produce fish with more natural hormonal cycles prior to release and to improve post-release survival. Similarly, comparing the endocrine profile of hatchery fish to their wild counterpart post-release may provide a benchmark of successful fish culture conditions and contribute to reintroduction and restoration efforts.

3.2 Development and growth monitoring

Hormones are key regulators of development and life history transitions in fishes. Through their pleiotropic actions, hormones integrate internal and external cues to coordinate the complex physiological and behavioral changes that characterize early development and the larval to juvenile transition (Holzer and Laudet, 2015; McMenamin and Parichy, 2013). Key among these signals for proper embryonic development are maternal thyroid hormones and cortisol (Deal and Volkoff, 2020; Nesan and Vijayan, 2013). For example, in zebrafish embryos, while maternal thyroid hormones play essential roles in neuron differentiation and survival in the brain and spinal cord (Campinho et al., 2014), the knockdown of maternal glucocorticoid receptors prevents mesoderm formation (Nesan et al., 2012) and broadly disrupts organogenesis (Pikulkaew et al., 2011). As such, environmental conditions or endocrine disrupting compounds that interfere with the maternal transfer or actions of thyroid hormones and glucocorticoids during embryonic development may induce developmental defects and compromise larval viability.

Thyroid hormones also play crucial roles in orchestrating the morphological changes associated with the larval to juvenile transition in teleosts, and disruption to the thyroid axis during this sensitive life history transition can have marked effects on larval recruitment (McMenamin and Parichy, 2013). In coral reef fishes, metamorphosis from a pelagic plankton-eating dispersal larval stage to a grazing reef-associated juvenile fish involves a surge in thyroid axis activity, and dramatic changes in pigmentation, digestive tract morphology, and behavior (McCormick et al., 2002). In the convict surgeonfish (*Acanthurus triostegus*), consistent with the notion that thyroid hormones control metamorphosis, algal grazing, and remodeling of the digestive tract for herbivory are stimulated by T3 injections and repressed by thyroid receptor blockade (Holzer et al., 2017). Similarly, manipulation of thyroid hormone signaling in *A. triostegus* demonstrated that thyroid hormones control the development of sensory structures and modulate the behavioral responses and vulnerability to predation (Besson et al., 2020). The fact that exposure of *A. triostegus* larvae to the pesticide chlopyrifos, a common reef pollutant, reduces T3 levels, impairs metamorphosis, and leads to a T3-reversible increase in predation, highlights the sensitivity of coral reef fish larval recruitment to thyroid disruption (Besson et al., 2020; Holzer et al., 2017). Moreover, given the importance of algal grazing by coral reef fishes to maintain coral health (Hughes et al., 2007), thyroid disruption during larval recruitment may have larger consequences for the conservation of coral reef ecosystems (Holzer et al., 2017).

Smoltification in salmon, i.e., the transformation of a freshwater-acclimated parr into a seawater tolerant smolt, provides another example of a hormone-dependent life history transition that is critical for recruitment and population sustainability (Björnsson et al., 2011). Driven by seasonal changes in photoperiod and temperature, increases in cortisol, thyroid hormones, GH, and IGFI, coordinate the changes in morphology, physiology, and behavior that pre-adapt the smolt for entry into seawater (McCormick, 2013). Acting primarily on the gills, intestine, integument, and brain, the individual and synergistic actions of the GH-IGFI, HPI, and HPT axes promote lipid mobilization, growth stimulation, salinity tolerance, imprinting, silvering, downstream migration, and schooling behaviors (McCormick, 2013). While the multi-hormonal regulation of smoltification may provide increased flexibility to respond to variable environmental conditions, it also makes the process more vulnerable to a wide range of endocrine-disrupting compounds (EDCs). For example, exposure to environmentally relevant concentrations of estrogenic compounds and xenobiotics (e.g., flame-retardants, pesticides, persistent organic pollutants, or acid and aluminum) can affect the circulating levels of one or more of the above hormones, and impair the growth, downstream migration, seawater tolerance, and olfactory function of juvenile salmonids (Arkoosh et al., 2017; Bangsgaard et al., 2006; Breves et al., 2018; Duffy et al., 2014; Fairchild et al., 1999; Lerner et al., 2007, 2012; Lower and Moore, 2007; Monette et al., 2008). As a result, the disruptive effects of environmental stressors on the endocrine signals that regulate smolt development have the potential to reduce early marine survival and contribute to variation in adult returns between years and among rivers (McCormick et al., 2009).

Rapid growth during the larval and juvenile stages is a major determinant of recruitment to adult fish populations (Pepin, 2016). Both laboratory and field studies show that larger and faster growing juvenile fish gain a survival advantage over smaller conspecifics (Sogard, 1997). Characterized by better energy reserves, the larger members of a cohort may have an enhanced resistance to starvation, a reduced vulnerability to predators, and a greater tolerance of environmental stressors (Shuter and Post, 1990; Sogard, 1997). Therefore, growth monitoring is an important management tool for the conservation of fish populations, and increasingly endocrine indices of growth are being used to assess the growth of field-captured fish.

Among the components of the GH-IGFI axis, IGFI is the most well-established and validated endocrine biomarker of growth in fish. Plasma IGFI levels are higher in fed than in fasted fish, and positively correlated with growth rate in multiple fish species (Andrews et al., 2011; Beckman, 2011; Beckman et al., 2004a; Hack et al., 2019; Picha et al., 2008; Shimizu et al., 2009). In salmonids, laboratory studies have demonstrated that IGFI provides a robust index of recent relative growth rates (4 days to 2 weeks) (Caldarone et al., 2016; Duguid et al., 2018), and plasma IGFI levels are now used to

assess the growth of field-captured fish and to investigate the factors that influence growth during the early marine residence of juvenile fish (Chamberlin et al., 2017; Ferriss et al., 2014; Kaneko et al., 2015). For example, in wild subyearling Chinook salmon (*O. tschwytscha*), higher plasma IGFI levels are closely associated with faster scale-derived growth rates, fuller stomachs, and stomach contents which demonstrate the early adoption of piscivory, key factors known to contribute to early marine survival (Davis et al., 2020). Similarly, plasma IGFI levels used in combination with otolith microchemistry to identify recent habitat use revealed that estuaries provide heterogeneous but overall greater growth opportunities than lake habitats for diadromous dolly varden (*Salvelinus malma*) (Bond et al., 2014). Interestingly, plasma IGFI concentrations have also been used to identify poor growth environments in the coastal waters of British Columbia across five species of juvenile Pacific salmon (Journey et al., 2018). Overall, while there is good evidence that IGFI is a useful bioindicator of growth in juvenile salmonids, it remains to be determined whether circulating levels of IGFI can also be used to monitor the growth of other fish species in the wild.

Emerging evidence suggests that the plasma levels of specific IGFI binding proteins may also serve as indices of growth in fish. In general, the mRNA and protein levels of IGFBPs with larger molecular weights (e.g., IGFBP-2b) decrease in abundance in response to fasting and are positively related to growth rate (Beckman et al., 2004b; Kelley et al., 2002; Peterson and Waldbieser, 2009; Shimizu and Dickhoff, 2017). In contrast, the expression and circulating levels of smaller molecular weight IGFBPs (e.g., IGFBP-1a and -1b) increase in response to fasting and stress, and are inversely related to growth rate (Hack et al., 2019; Madison et al., 2015b; Peterson and Waldbieser, 2009; Shimizu and Dickhoff, 2017; Shimizu et al., 2009). In wild fish, the utility of IGFBP-1a as an inverse index of growth has recently been demonstrated in out-migrating chum (*Oncorhynchus keta*) (Kaneko et al., 2019a) and coho (*O. kisutch*) (Kaneko et al., 2019b) post-smolts. For example, in coastal British Columbia, plasma IGFBP-1b levels were the highest in juvenile coho salmon from regions with poor ocean conditions and were associated with reduced IGFI levels and stomach contents (Kaneko et al., 2019b). Although more research is needed to understand how environmental conditions and nutritional states differentially regulate the various IGFBPs of fish, results from the above studies suggests that circulating IGFBP levels have the potential to contribute to fish stock assessment and conservation.

In contrast, despite the clear growth stimulatory effects of GH treatment in fish and GH overexpression in GH-transgenic fish (Devlin et al., 2001), plasma GH levels may have limited utility as a bioindicator of instantaneous growth in fish. The discordant relationship between the circulating levels of GH and growth in fish stems in part from the dual role of GH in the regulation of anabolic and catabolic metabolic pathways, and from the context-dependent actions of GH (Bergan-Roller and Sheridan, 2018; see Section 2.3 for more details).

3.3 Reproductive control

Successful reproduction is essential for population viability, yet wild fish face a variety of threats to reproduction. For example, overfishing can reduce the abundance of breeding adults, greatly reduce recruitment, and ultimately cause populations to collapse (Myers et al., 1994). Similarly, spawning habitat loss, barriers to migration and spawning grounds, or competition with invasive species have led to the need for reproductive assistance to reduce the loss of genetic diversity and the risk of extinction (Reid and Hall, 2003; Swanson et al., 2008). Climate change (see Section 3.4) and EDCs (see Section 3.5) can also affect all levels of the reproductive axis in fish and the threats to reproduction from these environmental stressors are well documented (Carnevali et al., 2018; Overturf et al., 2015; Servili et al., 2020). Driven primarily by the need to overcome reproduction-related barriers and close the life cycle of economically desirable species for aquaculture, a variety of techniques have been developed in the field of reproduction biology to enable the predictable reproduction of captive fish (Zohar, 2021). While the breeding programs of aquaculture operations and conservation hatcheries have opposite goals, i.e., select for specific genotypes vs maintain genetic diversity, the techniques developed to facilitate fish reproduction in commercial hatcheries have found a variety of applications for fish conservation. In this section, we provide a few select examples of applications of research in fish reproductive control for the conservation of fish.

Various fish species cannot reproduce in captivity as they lack the required environmental and biological cues of spawning habitats that are needed for the final maturation of gametes. Working on the premise that this inability to reproduce in captivity was caused by a hormonal failure, fish endocrinologists in the 1970s set out to discover the hormones of the HPG axis in fish and to identify ways to manipulate them (Zohar, 2021). Early on, it was shown that human chorionic gonadotropin (hCG) could be used to induce final oocyte maturation, ovulation, and spawning (Donaldson and Hunter, 1983), suggesting that the failure of captive fish to undergo final oocyte maturation may be due to a lack of pituitary gonadotropin (LH) release. Once confirmed, this discovery prompted the identification, characterization, and synthesis of synthetic GnRHs to induce LH release from the pituitary and thereby stimulate spawning in captive fish (Mylonas et al., 2017; Zohar and Mylonas, 2001). Combining these GnRH analogues (GnRHa) with a dopamine receptor antagonist led to the formulation of Ovaprim, a potent ovulating/spermiating agent used to promote and facilitate reproduction in a variety of teleost species (Dufour et al., 2010; Peter et al., 1988; Yanong et al., 2009). Further technical advancements, such as the use of homologous recombinant proteins and gene therapy for *in vivo* gonadotropin delivery, should permit a more targeted use of hormonal treatments to solve species-specific reproductive problems (Molés et al., 2020). In general, hormonal manipulations are now used in

aquaculture and captive broodstock programs to advance and synchronize maturation in both sexes; to enhance fecundity, fertility, and embryo survival; to promote the development of secondary sex characteristics; and to counter the reproductive behavioral deficiencies exhibited by captively-reared fish that are released into natural environments (Berejikian et al., 2003; Mylonas et al., 2010; Zohar and Mylonas, 2001).

The conservation and restoration of various fish species and stocks with rapidly declining populations may also benefit from hormonal treatments. With a single opportunity to reproduce and complex life cycles, semelparous and diadromous fish species, such as Pacific salmon and anguillid eels, are particularly sensitive to reproductive barriers. For example, several freshwater eel populations are now listed as critically endangered, so there is an urgent need to further develop and improve protocols for their artificial propagation (Burgerhout et al., 2019; Jacoby et al., 2015). In captivity, however, anguillid eels fail to spontaneously reach sexual maturity, remaining in the pre-pubertal, or silver, life stage. Injections of hCG can induce testicular development and spermatogenesis in male silver *Anguilla* species (Herranz-Jusdado et al., 2019; Lokman et al., 2016). Similarly, a combination of pituitary extracts and a MIH (i.e., 17,20βP) injected into female silver eels helps induce vitellogenesis, follicular maturation and ovulation (Kottmann et al., 2020). A better understanding of the natural triggers involved in eel gametogenesis and the physiological roles played by hormonal transmitters of external cues, such as melatonin, may further improve the success of these maturation protocols (Burgerhout et al., 2019). Such interventions are likely to help in conservation efforts of other at-risk fish species that do not reproduce well in captive environments. For example, pituitary extracts and GnRHa preparations are widely used to induce spermiation in several species of sturgeon and gar (Alavi et al., 2012; Mendoza Alfaro et al., 2008). Although the specific mechanisms of oocyte maturation have yet to be resolved (Hasegawa et al., 2022), ovulation and spawning can also be induced by treatment with GnRHa in these species (Mendoza Alfaro et al., 2008; Mohammadzadeh et al., 2021). Finally, assisted reproductive techniques are also needed for the conservation of many elasmobranch species that are experiencing rapid declines (Ferretti et al., 2010). With a small litter size, a long gestation period and slow sexual maturation, most shark and skate populations are being depleted by fisheries faster than they can reproduce (Frisk et al., 2001; McPhie and Campana, 2009). Consistent with its effects in numerous teleosts species, Kim et al. (2020) demonstrated for the first time in elasmobranchs that Ovaprim can effectively induce semen release and follicular maturation in mature banded houndshark (*Triakis scyllium*) and whitetip shark (*Carcharhinus longimanus*). Although this study did not assess the quality of the germ cells produced, nor whether the semen can be used for successful internal fertilization of the females, the results are a promising step toward the development of a hormone-induced artificial insemination protocol for endangered elasmobranchs.

3.4 Climate change

Climate change-driven alterations in the abiotic characteristics of aquatic ecosystems can have broad and complex effects on the endocrine systems of fishes. While the effects vary significantly with habitat, latitude and depth, climate change is generally slowly raising seawater temperature and increasing ocean acidification; increasing the frequency of combined low flow, elevated temperature, and hypoxic events in riverine habitats; and warming the surface temperature of lakes which increases thermal stratification and hypolimnetic oxygen depletion (Adrian et al., 2009; Bopp et al., 2013; Butcher et al., 2015). Nutrient enrichment is also a major driver of large scale, seasonal, and expanding hypoxic zones in lakes and coastal marine ecosystems around the world (Diaz and Rosenberg, 2008; Howarth et al., 2011; Jenny et al., 2016). While previous studies in fish have shown that elevated temperatures, hypoxia, and acidification can affect stress (Bernier and Craig, 2005; Chadwick et al., 2015; Goikoetxea et al., 2021; Petochi et al., 2011; Vargas-Chacoff et al., 2018) and growth-regulating (Deal and Volkoff, 2020; Kajimura and Duan, 2007; Kamei, 2020) hormones, far more have characterized the effects of these environmental stressors on the hormones of the HPG axis. In general, elevated temperatures and hypoxia can have serious impacts on several critical reproductive processes (Alix et al., 2020; Pankhurst and Munday, 2011; Servili et al., 2020; Pankhurst and Van Der Kraak, 1997). Therefore, given the relevance of successful recruitment to conservation, here we review the known effects of climate-driven warming, deoxygenation and acidification on reproductive hormones and their consequences for reproduction and sex determination in fish.

Although fish generally benefit reproductively from increases in temperature within their physiological tolerance range, temperatures above species-specific thermal maxima can inhibit reproduction via effects at all levels of the HPG axis. While the magnitude and temporal nature of the temperature change are expected to influence species-specific responses, consistent effects on components of the HPG axis in fish exposed to high or prolonged elevations in temperature have been observed. For example, at the hypothalamic level, high temperatures can inhibit the gene expression of GnRH and kisspeptins (Elisio et al., 2012; Okuzawa and Gen, 2013; Shahjahan et al., 2013, 2017), and stimulate gonadotropin-inhibiting hormone (Bock et al., 2021). Similarly, in the pituitary, exposure to high temperatures can reduce transcript abundance of the GnRH receptor and the gonadotropin subunits FSHβ and LHβ (Elisio et al., 2012; Okuzawa and Gen, 2013; Pérez et al., 2011; Shahjahan et al., 2017; Soria et al., 2008; Taranger et al., 2015). In the ovaries, high temperature inhibits FSH and LH receptor mRNA levels (Anderson et al., 2019; Bock et al., 2021; Elisio et al., 2012; Soria et al., 2008) and suppress the expression of several key genes involved in sex steroid synthesis (Anderson et al., 2012, 2019; Bock et al., 2021; Elisio et al., 2012; Mazzeo et al., 2014). Moreover, multiple studies have shown that

fish reared at high temperatures can have lower levels of plasma E2, T, 11-KT, and MIH (Bock et al., 2021; Elisio et al., 2012; García-López et al., 2006; Mazzeo et al., 2014; Okuzawa and Gen, 2013; Pankhurst et al., 2011; Pérez et al., 2011; Vikingstad et al., 2016). In females, the reduced production of E2 is likely due to a down-regulation of gonadal aromatase expression since exposure to high temperatures increases methylation of the aromatase gene promoter and reduces its expression (Navarro-Martín et al., 2011). In fact, the observation that high temperatures inhibit E2 synthesis in isolated ovarian follicles suggests that the effects of temperature on the HPG axis is primarily via direct effects on gonadal steroidogenesis and indirect effects on the hypothalamic and pituitary levels that are mediated by sex steroid feedback loops (Watts et al., 2004). Reduced circulating levels of E2 also likely explain why temperature-stressed female fish typically have lower circulating levels of Vtg and liver Vtg expression (Bock et al., 2021; Clark et al., 2005; King et al., 2007; Mahanty et al., 2019; Pankhurst et al., 2011; Pérez et al., 2011). Therefore, in thermally challenged female fish, while reduced E2 synthesis and Vtg sequestration may inhibit the progression of oocyte development and egg quality, MIH synthesis inhibition may delay or inhibit oocyte maturation, ovulation, and spawning. Similarly, the reduced circulating levels of androgens and MIH in males that experience high temperatures likely contribute to impaired spermatogenesis and sperm maturation, respectively. Importantly, beyond species differences, factors such as sex, thermal insult severity and duration, sexual maturity, age, nutritional status, and others, are known to modulate the effects of high temperatures on the HPG axis (Alix et al., 2020; Pankhurst and Munday, 2011; Servili et al., 2020). Lastly, while it is known that stressors can inhibit reproduction in fish, the extent to which the HPI axis and cortisol contribute to high temperature-mediated reproductive suppression is uncertain (Fuzzen et al., 2011; Pankhurst, 2016).

Hypoxia is now a common occurrence in coastal waters and lakes worldwide (Breitburg et al., 2018; Tellier et al., 2022) and these abiotic conditions can impair reproduction in fish, especially in species that reproduce during the summer (Pankhurst, 2016; Servili et al., 2020; Wu et al., 2003). Although fish avoid lethal levels of dissolved oxygen, sublethal hypoxia is known to suppress reproduction in wild fish populations (Cheek et al., 2009; Friesen et al., 2012a; Thomas et al., 2007, 2015). Importantly, hypoxic conditions that cause reproductive impairment can also induce DNA methylome modifications that cause transgenerational epigenetic impairment of male and female reproduction (Lai et al., 2018, 2019). However, since hypoxia tolerance varies widely among fish species (Rogers et al., 2016), the hypoxic conditions (severity and duration) required to inhibit reproduction in one species may be tolerated by another. Therefore, care should be exercised in extrapolating how specific dissolved oxygen concentrations may affect reproduction across species. As observed for the effects of high temperature on reproduction, chronic hypoxia appears to have broad effects at all levels of the HPG axis

in fish. For example, chronic hypoxia exposure can reduce hypothalamic GnRH gene expression (Lu et al., 2014; Thomas et al., 2007), suppress pituitary FSHβ, LHβ, and estrogen receptor transcript abundance (Lu et al., 2014), and is associated with reduced plasma LH levels (Thomas et al., 2007; Wang et al., 2008). In the gonads, hypoxia exposure has sex-specific effects on the mRNA levels of the receptors for FSH, LH, and estrogen, and reduces the expression of several key genes involved in steroidogenesis (Lu et al., 2014)—effects which may be regulated through the actions of several miRNAs (Lai et al., 2016). Across several species, studies have consistently observed that fish exposed to chronic hypoxia have lower levels of plasma sex steroids, including E2, T, 11-KT, and MIH (Dabrowski et al., 2003; Landry et al., 2007; Lu et al., 2014; Thomas and Rahman, 2009; Thomas et al., 2007; Wu et al., 2003). In Atlantic croaker (*Micropogonias undulatus*), in addition to reducing circulating levels of 20βS, chronic hypoxia reduces the protein levels of the membrane progestin receptor that mediates the non-genomic actions of this MIH in both oocytes and sperm (Thomas and Rahman, 2009). Interestingly, hypoxia impaired signaling from progestin and E2 membrane receptors, while enhancing signaling from membrane androgen receptors and increasing the proportion of atretic and apoptotic ovarian follicles in this species (Ondricek and Thomas, 2018). Finally, hypoxia can downregulate the gene expression of specific liver estrogen receptors and *vtg*, and reduce plasma Vtg levels (Lu et al., 2014; Thomas et al., 2007). Consequently, as observed in temperature-stressed fish, the widespread endocrine disruption associated with chronic hypoxia exposure in fish inhibits oogenesis and spermatogenesis, impairs gamete maturation and egg fertilization, delays spawning, and reduces hatching success and larval survival.

In contrast to the detrimental effects of high temperatures and hypoxic conditions, ocean acidification may only have a limited direct impact on fish reproduction. To date, experiments using partial pressures of CO_2 (pCO_2) up to the levels predicted to occur in 100 years (~1000 ppm CO_2) do not support wide-spread impacts on reproductive performance. Overall, the effects of elevated pCO_2 on reproductive output in fishes are equivocal. For example, while exposure to elevated CO_2 reduced the rate of paired spawning in ocellated wrasse (*Symphodus ocellatus*; Milazzo et al., 2016) and the number of egg clutches in spiny damselfish (*Acanthochromis polyacanthus*; Welch and Munday, 2016), it increased reproductive output in orange clownfish (*Amphiprion percula*; Welch and Munday, 2016) and three-spined stickleback (*Gasterosteus aculeatus*; Schade et al., 2014). In cinnamon anemonefish (*Amphiprion melanopus*) high pCO_2 increased breeding activity in one study (Miller et al., 2013) but had no effect in another (Miller et al., 2015). Similarly, high pCO_2 conditions stimulated reproductive output in two-spotted goby (*Gobiusculus flavescens*) in one study (Faria et al., 2018) and had no effect in another (Forsgren et al., 2013). The effects of elevated pCO_2 on gamete quality and survival also appears to be species- and condition-specific. In general, elevated

CO_2 levels do not affect sperm motility in most species of fish examined (Frommel et al., 2010; Inaba et al., 2003). Although high CO_2 can increase egg loss and embryonic abnormalities in some species (Forsgren et al., 2013; Miller et al., 2015) it has no effect in others (Munday et al., 2009, 2011). So far, very few studies have characterized the effects of elevated CO_2 on the HPG axis of fish. While short-term exposure (3–9 days) to elevated CO_2 produced elevated E2 levels in muscle tissue and increased liver E2 receptor gene expression in juvenile Atlantic cod (*Gadus morhua*; Preus-Olsen et al., 2014), long-term exposure (10 months) had no effect on plasma E2 levels in cinnamon anemonefish (Miller et al., 2015). Whether elevated CO_2 levels affect other components of the reproductive endocrine axis in fish remains to be ascertained.

In addition to their effects on reproduction, both elevated temperatures and hypoxic conditions can have marked effects on sex determination in fish. In dozens of species across various families, and in both domesticated and wild fish populations, elevated temperatures during the developmental period of primary sex determination results in the masculinization of genotypic females (for reviews, see Geffroy and Wedekind, 2020; Ospina-Álvarez and Piferrer, 2008). For example, in wild populations of juvenile southern flounder (*Paralichthys lethostigma*) living in North Carolina (USA), where a thermal range of >5 °C naturally occurs across nursery habitats, the cooler northern waters consistently produced a lower proportion of males (37–67%) relative to southern habitats with warmer temperatures (86–94%). Moreover, flounders reared in the laboratory under temperature conditions that mimicked those of natural habitats recapitulated sex ratio differences observed across the wild populations (Honeycutt et al., 2019). Both epigenetic and stress-related mechanisms have been shown to contribute to temperature-dependent sex determination (TSD) in fish. In several species, warm temperature-induced methylation of the *aromatase* gene promoter decreases E2 production and contributes to TSD (Ortega-Recalde et al., 2020). High temperature-induced increases in cortisol production have also been implicated as an important factor influencing TSD in fish (Geffroy and Wedekind, 2020). In brief, while activation of the glucocorticoid response element (GRE) by cortisol and its receptor in the promoter of *aromatase* and the *fsh receptor* results in a down-regulation of these feminizing genes (Hayashi et al., 2010; Yamaguchi et al., 2010), activation of the GRE in the promoter of the *dmrt1a* gene, a transcription factor involved in sex determination, promotes masculinization (Adolfi et al., 2019; Castañeda Cortés et al., 2019). Both field and laboratory studies have also shown that hypoxia exposure can lead to male-biased sex ratios in fish (Cheung et al., 2014; Robertson et al., 2014; Shang et al., 2006; Thomas and Rahman, 2012). Atlantic croakers collected from numerous hypoxic sites in the northern Gulf of Mexico not only had a male-biased sex ratio (>60%), but 19% of the ovaries collected in the hypoxic region contained male germ cells (Thomas and Rahman, 2012). Mechanistically, hypoxia-induced masculinization is due to decreases in brain and ovarian aromatase activity

and an ensuing disruption in the balance of sex steroids (Ivy et al., 2017; Shang et al., 2006; Thomas and Rahman, 2012). In the long-term, male-biased sex ratios may diminish effective population size, thus depleting genetic diversity and reducing the potential of fish populations to adapt to changing environments (Geffroy and Wedekind, 2020). Thus, understanding how climate change disrupts sex steroid production will be important for the future conservation of wild fish populations.

3.5 Endocrine-disrupting chemicals

Endocrine disrupting chemicals (EDCs) pose a pervasive and ubiquitous challenge to aquatic ecosystems. An EDC is defined as any exogenous compound that interferes with the normal activities of hormone systems, including hormone synthesis, cellular action, and bodily elimination (La Merrill et al., 2020). As such, EDCs comprise a large and growing list of chemicals that interfere with endocrine systems through direct (e.g., receptor agonists) or indirect (e.g., cell toxicity) mechanisms, and drive the specific or nonspecific dysfunction of that system (Fig. 4). Examples of EDCs include legacy pollutants (e.g., polychlorinated biphenyls, PCB; dichlorodiphenyltrichloroethane, DDT)

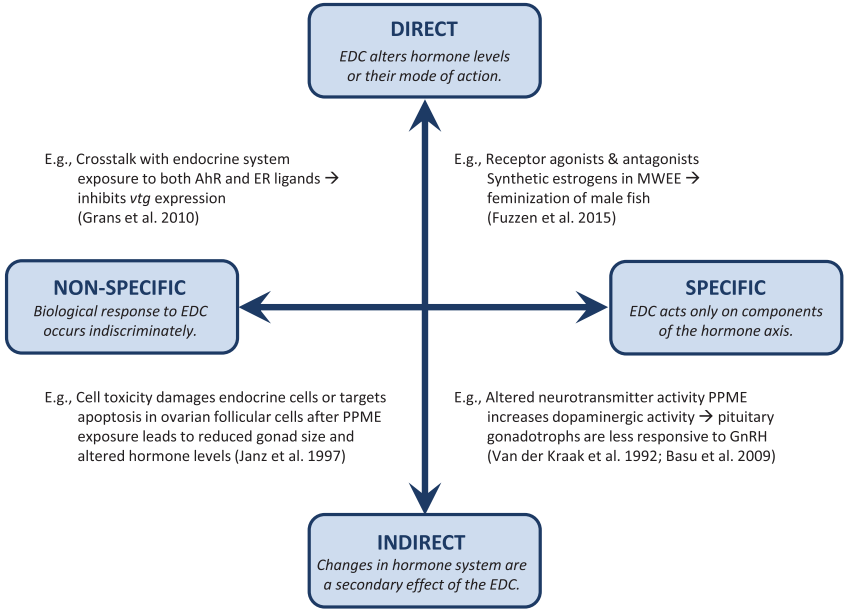

FIG. 4 Endocrine-disrupting chemicals (EDC) affect hormone systems in many ways and may not be mutually exclusive. The vertical axis describes the capacity of EDCs to interact primarily or secondarily with components of endocrine systems. The horizontal axis depicts the degree of specificity by which EDC alters the functionality of endocrine systems. Examples for each quadrant that are discussed in this chapter are provided.

as well as chemicals that are deposited daily into water systems from industrial (e.g., flame retardants, plasticizers), agricultural (e.g., pesticides, herbicides), and other human activities (e.g., hydrocarbons, pharmaceuticals, personal care products). Decades of concerted global efforts to research, assess, monitor, and regulate EDCs have led to established standardized testing protocols for environmental effects monitoring that help to identify and mitigate the risks of EDCs on humans and wildlife (Hecker and Hollert, 2011; Parrott et al., 2006). In fish, for example, the estrogenic potential of aquatic pollutants is defined using *in vitro* or *in vivo* Vtg assays, gonad histopathological assessment, and multigeneration reproductive screening (Hecker and Hollert, 2011).

Conservation concerns are inherent for fish populations exposed to EDCs given the central role of hormone systems in development, growth, life-history transitions, and reproduction. It is well beyond the scope of this chapter to offer a comprehensive review of all categories of EDCs and their various impacts and implications for fish conservation, and many insightful reviews are available for interested readers (Delbes et al., 2022; Goksøyr, 2006; Le Page et al., 2011; Mennigen et al., 2011; Segner, 2011; Söffker and Tyler, 2012; Waye and Trudeau, 2011). Therefore, given that estrogenic effects dominate the literature on EDCs in fish, we highlight three case studies of global relevance that demonstrate some similarities, differences, and challenges posed by EDCs in fish conservation.

3.5.1 Case study 1: Municipal wastewater effluent

Municipal wastewater effluent (MWWE) is a complex mixture of anthropogenic wastes and is the largest contributor of pharmaceuticals and personal care products into the aquatic environment (Aus der Beek et al., 2016). Many of these compounds are found in surface waters at concentrations capable of exerting biological effects, including endocrine disruption, in non-target organisms. Pharmaceuticals, for example, are designed to modify biological systems that are highly conserved across animal taxa, such as E2 receptors. Well-known examples are the synthetic E2 used in oral contraceptives (17α-ethinylestradiol, EE2; Servos et al., 2005), and the E2 receptor antagonist used for hormone therapy in breast cancer patients (tamoxifen; Orias et al., 2015). These and other sex steroid agonists and antagonists are held accountable for the occurrence of mixed gonadal tissue (i.e., both gamete types found in testes or ovaries) in fish populations living downstream of MWWE outfalls around the globe (Abdel-Moneim et al., 2015). Transcriptional responses that promote or inhibit sex-specific phenotypes underpin the development of the intersex condition. Male fathead minnow (*Pimephales promelas*) exposed to EE2, for example, were characterized by decreased gonadal expression of genes involved in testes development (e.g., *anti-Mullerian hormone*) and androgen biosynthesis (e.g., *cytochrome P450 17, cyp17*), and decreased hepatic expression of growth-promoting genes (e.g., *igf1*). At the same time, these same fish showed increased expression of genes

involved in estrogen biosynthesis (e.g., *cyp19a*) and signaling (e.g., *er*, *vtg*) in the testes and liver, respectively (Filby et al., 2007). Over time, these transcriptional responses to environmental EE2 exposure may lead to a feminized phenotype that can include, in severe cases, the presence of full-grown follicles within testicular tissue and reduced fertilization success (Fuzzen et al., 2015; Harris et al., 2011; Jobling et al., 2002a,b).

Despite strong laboratory and field evidence supporting MWWE-induced feminization of male fish, population-level impacts remain challenging to confirm (Matthiessen et al., 2018; Mills and Chichester, 2005). A 3-year dosing study in the Environmental Lakes Area of Ontario, Canada confirmed that chronic exposure to low, environmentally relevant concentrations of EE2 caused feminization of male fish (Vtg production, intersex) and reproductive impairment (adult-skewed age distribution) in a wild population of fathead minnows (Kidd et al., 2007). The population remained collapsed for 2 years after the EE2 dosing ceased in the lake, with only a handful of fathead minnows collected during sampling efforts (Kidd et al., 2007); however, individual and population effects in the lake were species-specific, suggesting that fish with longer generation times, like white sucker (*Catostomus commersonii*) and lake trout (*Salvelinus namaycush*), may be more buffered against chronic EE2 exposure (Kidd et al., 2014; Palace et al., 2009). Moreover, feminization of male fathead minnows was no longer observed for 3 years once the EE2 dosing ceased, and age-class distribution of the population recovered by year 4 (Blanchfield et al., 2015).

3.5.2 Case study 2: Pulp and paper mill effluents

The manufacturing of paper products from raw wood has received international attention for the environmental impacts of mill effluents, including endocrine disruption on fish reproduction. Fish living in the aquatic receiving environments of pulp and paper mills are often characterized by reduced circulating sex hormones (McMaster et al., 1991; Van Der Kraak et al., 1992) and smaller gonads (McMaster et al., 1991; Munkittrick et al., 1991; Sandstrom, 1994), but effects can be species-specific (Chiang et al., 2011; Gibbons et al., 1998; Karels et al., 2001). Importantly, these biological effects are coincident with changes in population sex ratios (Larsson et al., 2000), lower fecundity (McMaster et al., 1991; Munkittrick et al., 1991) and population declines (Sandstrom, 1994). Multiple mechanisms of endocrine disruption are likely to underlie these effects. For example, white sucker exposed to pulp and paper mill effluents (PPME) from a Canadian mill had lower circulating LH levels and a blunted response to GnRH injection (Van Der Kraak et al., 1992). In turn, this impaired pituitary function may be linked to the capacity of some PPME to disrupt neurotransmitter signaling, including dopamine, as shown using *in vitro* competitive binding assays in goldfish (*Carassius auratus*) brain homogenates (Basu et al., 2009). Consistent with the pleiotropic effects of sex steroids and the complex regulation of the HPG axis,

changes in the expression of reproduction-related genes (Costigan et al., 2012), alterations in steroid synthesis and metabolism (Gibbons et al., 1998; Leusch and MacLatchy, 2003; McMaster et al., 1995; Van Der Kraak et al., 1992) and histopathological changes in gonad tissues (Castro et al., 2018; Janz et al., 1997) have all been observed in PPME-exposed fish.

PPME are complex mixtures of chemicals containing many bioactive substances such as wood-derived compounds (e.g., phytosterols, lignin) and organochlorines produced by the bleaching process (e.g., polychlorinated dibenzodioxins and dibenzofurans, PCDD/F) (Hewitt et al., 2007; Lindholm-Lehto et al., 2015; Singh and Chandra, 2019). Given the complexity and mill-to-mill variability in effluent composition (e.g., depending on wood source, pulping process, bleaching agent, effluent treatment infrastructure), efforts to define the causative agents of PPME toxicity and establish regulatory guidelines around them have been challenging (see reviews by Hewitt et al., 2007; McMaster et al., 2006). Moreover, the presence of multiple and as-yet unidentified EDCs in PPME are often reported (Larsson et al., 2006; Martel et al., 2017; Orrego et al., 2017). Nevertheless, altered reproductive endpoints in fish exposed to PPME around the globe highlight the universality of the problem and emphasize the utility of using endocrine metrics to quantify, monitor, and regulate the pulp and paper industry (Barra et al., 2021; Martel et al., 2017; McMaster et al., 2006; Parrott et al., 2006; Ussery et al., 2021).

3.5.3 Case study 3: The aryl hydrocarbon receptor (AhR) and endocrine disruption

Dioxin (2,3,7,8-tetrachlorodibenzo-para-dioxin, TCDD) and dioxin-like chemicals (e.g., PCB; PCDD/F; polycyclic aromatic hydrocarbons, PAH) are well-known and ubiquitous environmental pollutants. These contaminants are found at especially high concentrations in the soils and sediments of industrialized areas and pose a constant challenge to human and animal health, including aquatic organisms, due to continuous inputs (e.g., industrial discharge, atmospheric deposition, oil spills), bioaccumulation and trophic biomagnification, and the staggeringly slow degradation of certain legacy pollutants (Weber et al., 2008). Congeners of dioxin-like chemicals with planar conformations are agonists of the aryl hydrocarbon receptor (AhR), a ligand-activated transcription factor that regulates the expression of thousands of gene targets (Denison and Nagy, 2003). Dysregulation of gene expression mediated by AhR can compromise normal cell function and manifest in a range of toxic responses, including endocrine disruption (Anulacion et al., 2013). For example, studies using fish cell cultures and model species have shown that individual PAH or mixtures containing PAH (e.g., crude oil) alter sex hormone synthesis (Arukwe et al., 2008; Lee et al., 2017; Liu et al., 2018; Monteiro et al., 2000), decrease circulating hormone levels (Arukwe et al., 2008; Booc et al., 2014; Kennedy and Smyth, 2015; Tintos et al., 2007), and reduce fertilization and hatching success (Booc et al., 2014). Consistent

with these indicators of reproductive impairment, *in vitro* studies using fish hepatocytes exposed in combination to ER and AhR agonists (e.g., Gräns et al., 2010; Mortensen and Arukwe, 2007; Yan et al., 2012; but see Mortensen and Arukwe, 2008) support the conclusion of inhibitory crosstalk between the E2 receptor and AhR signaling pathways that disrupts target gene expression, as described in mammalian models (Matthews and Gustafsson, 2006; Fig. 5).

The killifish (*Fundulus heteroclitus*) has been well studied as a model for physiological and multigenerational impacts of exposure to dioxin-like chemicals. Killifish are a small estuarine fish found abundantly along the Atlantic coast of North America, including in some of the most contaminated estuaries on the continent. Plasma Vtg in female killifish and gonadal somatic index (GSI) in male and female killifish were negatively correlated with sediment PAH concentrations throughout Chesapeake Bay, a large estuary and designated Superfund site in the District of Columbia, USA (Pait and Nelson, 2009). Similarly, male and female killifish from the heavily industrialized Newark Bay in New Jersey showed reduced gonadal maturation and GSI relative to fish sampled at a clean reference site, and these results were associated with increased AhR activation in the liver and elevated PAH metabolites in the bile (Bugel et al., 2010). In the New Bedford harbor of Massachusetts, one of the highest ranked PCB-contaminated sites in the

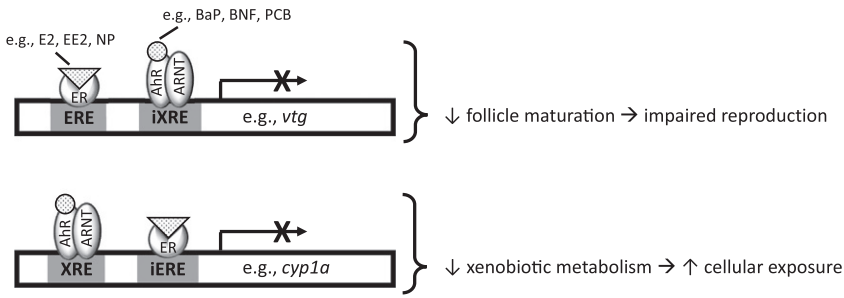

FIG. 5 A proposed mechanism for reciprocal inhibition of estrogen receptor (ER) and aryl hydrocarbon receptor (AhR) gene targets in fish. Both ER and AhR are ligand-activated transcription factors. Activation of ER by endogenous (e.g., 17β-estradiol, E2) or exogenous (e.g., 17α-ethinylestradiol, EE2; nonylphenol, NP) ligands initiates transcription of genes containing estrogen response elements (ERE) in the gene promoter region, such as *vitellogenin* (*vtg*). Activation of AhR by exogenous ligands (e.g., benzo[*a*]pyrene, BaP; β-naphthoflavone, BNF; dioxin-like pentachlorobiphenyls, PCB) promotes the formation of a protein complex with the AhR-nuclear translocator (ARNT) and subsequent transcription of genes containing xenobiotic response elements (XRE), such as *cytochrome P450 type 1a* (*cyp1a*), to facilitate xenobiotic metabolism. Simultaneous exposure to ER- and AhR-agonists inhibits the downstream activation of target genes (see text for references), suggesting the involvement of inhibitory response elements (iERE, iXRE). The outcome of such reciprocal inhibition is a decrease in the typical response to either receptor alone, leading to biological consequences (e.g., impaired reproduction; increased bio-load and cellular exposure to toxicants).

USA, resident female killifish had lower liver *vtg* mRNA levels, decreased circulating sex hormone and lower GSI during the reproductive season compared to females from an uncontaminated site (Greytak et al., 2005). Remarkably, despite clear evidence of endocrine disruption and the assumption of reproductive impairment, killifish populations continue to persist in these polluted areas. Their success has been attributed to genomic adaptations within local populations that have resulted in increased tolerance to industrial pollutants acting via the AhR (Greytak et al., 2005; Whitehead et al., 2012). In contrast to the prolific killifish, and of relevance to conservation, the potential for evolutionary adaptation to dioxin-like chemicals or other pollutants is less likely in fish species with slower generation times, smaller population sizes, and limited genetic variation (Whitehead et al., 2017).

3.6 Management of invasive species

Pheromones may have a variety of applications for the management of invasive fish species. Defined as chemicals that mediate behavioral interactions between individuals of the same species, pheromones are broadly used by fish as anti-predator cues, social cues, and reproductive cues (Sorensen and Stacey, 2004; Stacey and Sorensen, 2011). Pheromones in fish are produced and released into the environment by various cell types and glands. In return, they are detected by highly sensitive receptors in the olfactory epithelium of the nares that can activate specific behavioral and physiological responses (Hara, 2011; Laberge and Hara, 2001). For example, derivatives of bile acids, sex steroids and prostaglandins in fish have been implicated in predator avoidance, kin and gender recognition, migration to and aggregation on spawning sites, and the coordination of reproductive processes (Kamio et al., 2022; Stacey and Sorensen, 2002). In general, since they are naturally occurring in the environment, do not persist and can be used at low concentrations because of their high potency and specificity, pheromones are regarded as a relatively safe technique for the control of invasive species (Fredricks et al., 2021). As a result, pheromones have been proposed to facilitate trapping, to disrupt and reduce reproductive success, to promote the success of sterilized fish, to disrupt migration and to repel non-indigenous species from ideal spawning sites or from entering specific waterways (Corkum and Belanger, 2007; Kamio et al., 2022; Sorensen and Johnson, 2016; Sorensen and Stacey, 2004).

Sea lamprey (*Petromyzon marinus*) rely on several complex pheromone mixtures to complete their life cycle, and the use of pheromones may therefore be a useful tool to mitigate the effects of this invasive parasitic species on the native fish of the Laurentian Great Lakes. In brief, larvae residing in streambeds release at least four different migratory pheromones that attract adults upstream during the spawning migration (Fine and Sorensen, 2008; Fissette et al., 2021; Li et al., 2018). Spermiating males in return release at least 12 different sex pheromones that stimulate sexual maturation in both

sexes and elicit mate search and spawning behavior in mature females (Fissette et al., 2021; Li et al., 2017). Although still a work in progress, significant advances have been made toward the incorporation of pheromones into the management of invasive sea lamprey which currently relies primarily on lampricides to kill larvae and barriers to block adults from spawning beds (Fissette et al., 2021; Siefkes, 2017). For example, both synthetic and mixtures of migratory pheromones can elicit electro-olfactogram (EOG) responses and partially mediate stream-finding behaviors in lakes near the mouths of streams (Burns et al., 2011; Meckley et al., 2014). Using a combination of migratory and sex pheromones, both males and females were captured using pheromone-baited traps (Wagner et al., 2006). Specifically, under management scenarios, Johnson et al. (2013) demonstrated that barrier-integrated traps baited with the male sex pheromone, 3-keto petromyzonol sulfate (3kPZS), increased trapping efficiency by 10%. Traps located en route to spawning grounds and baited with a mixture containing all the pheromones from sexually mature males increased trapping efficiency by an additional 10% (Johnson et al., 2015). While ongoing studies are identifying optimal application rates and the specific biological and environmental factors that maximize trapping efficiency with 3kPZS, future research is needed to develop more effective and economical pheromone mixtures (Fissette et al., 2021; Johnson et al., 2020).

Pheromones may also be an effective tool to control the populations of several invasive teleost species such as the round goby (*Neogobius melanostomous*; Corkum et al., 2004). Mature male and female round goby release various pheromones that are detected by conspecifics (Gammon et al., 2005). Screening over 100 steroids and prostaglandins using EOG, Murphy et al. (2001) identified 19 steroids that elicited responses in mature fish. Several of these steroids are synthesized by the testes of sexually mature males (Arbuckle et al., 2005) and have life-stage specific effects on female attraction (Farwell et al., 2017). Moreover, although these pheromones elicit EOG responses in round goby, they do not evoke olfactory sensory responses in various non-target species that share the same habitat, suggesting their specificity for pheromone trapping (Ochs et al., 2013). Reproductive pheromones may also serve for the management of various invasive cyprinid species. Among teleosts, the physiological and behavioral roles of reproductive pheromones is perhaps best understood in goldfish (*C. auratus*) and common carp (*Cyprinus carpio*; Stacey and Sorensen, 2002). For instance, ovulated common carp are known to release a mixture of prostaglandin F2α (PGF2α) and metabolites that attract males and mediate spawning interactions (Lim and Sorensen, 2011). Measurement of PGF2α in natural waters has also been used, together with eDNA, to confirm the presence, infer gender, and assess the relative abundance of common carp induced to aggregate at specific locations using food (Ghosal et al., 2018). In the field, female common carp implanted with PGF2α capsules release a biologically relevant mixture of pheromones

that attract mature males (Lim and Sorensen, 2012). A similar strategy has now been devised to specifically attract silver carp (*Hypophthalmichthys molitrix*; Sorensen et al., 2019), a highly invasive species in the Mississippi River. Finally, pheromone trapping may be a useful technique for controlling populations of invasive largemouth bass (*Micropterus salmoides*). While the specific sex pheromone involved remains to be identified, trapping experiments have shown that the bile from sexually mature largemouth bass males can specifically attract and increase the capture rate of mature females (Fujimoto et al., 2020).

4 Future applications of endocrine systems in conservation physiology

Despite a recognition that hormones play a key role in maintaining homeostasis and regulating reproductive functions, the intrusive and sometimes invasive nature of the traditional methods used to monitor basal circulating levels of hormones in captive and wild animals limit their applicability to conservation physiology. As such, for several decades now, there has been considerable interest in developing non-invasive techniques to monitor hormones (e.g., Monfort, 2002; Scott and Ellis, 2007). The publication of methods to measure corticosteroids in human hair (Bévalot et al., 2000) further spurred the development of innovative approaches to measure steroids in a variety of inert matrices (Aerts et al., 2015; Ellis et al., 2013; Meyer and Novak, 2012; Romero and Fairhurst, 2016). Although the application of non-invasive methods to study fish endocrinology is in its infancy, the validation of these techniques and the development of standard protocols will facilitate the study of fish reproduction, welfare, and conservation. Similarly, since the regulation of most physiological processes involves multiple hormones, the parallel development of techniques to perform hormonal profiling in traditional and novel matrices will provide greater mechanistic insight into the functions of endocrine systems and how these are disrupted by environmental and anthropogenic stressors. Finally, advances in the availability of genomic information for non-model fish species and in genomic technologies are giving researchers new tools to integrate the application of endocrine systems in conservation physiology. Here we highlight the multiomics approach used in ecotoxicogenomics to predict the adverse effects of EDCs on wild fish, and how the use of omics and hormonal measurements can be integrated to provide insight into the emerging field of endocrine-microbiome interactions and to promote its application to conservation measures.

4.1 Non-Invasive monitoring of steroids

Traditionally, studies that measure hormones in fish to gain insight into physiological processes or behaviors quantify hormones in the plasma component

of blood samples. Among the different approaches that can be used to sample blood in fish, the most common technique is caudal puncture (Houston, 1990; Jeffrey et al., 2022). While the invasive nature of blood sampling through the caudal vasculature can be minimized when best practices are followed (Lawrence et al., 2020), several considerations may constrain the use of blood samples for the study of endocrine systems in the field and its application to conservation physiology. For example, since capture and handling stressors are known to affect circulating hormone levels, blood samples must be withdrawn within a few minutes of disturbing the animal (Clark et al., 2011; Gamperl et al., 1994; Pankhurst, 2011; Wendelaar Bonga, 1997)—a challenging prerequisite for a variety of field settings. Blood samples also provide a snapshot of circulating hormone levels at the time of sampling and may therefore have limited value as an integrative long-term measure of stress and welfare. Moreover, blood sampling is impractical for small-bodied fish species and ill-advised for at-risk fish populations. Therefore, taking advantage of the fact that steroids are generally stable chemical substances, lipid-soluble, and excreted via the kidney and gut, endocrinologists have developed several non-invasive techniques to quantify glucocorticoids and sex steroids in alternative matrices. For instance, excreted steroid hormones (i.e., saliva, urine, feces) as well as those deposited in keratinized tissues (i.e., hair, feathers) are now routinely used to quantify steroids and gain insight into the stress and reproductive physiology of various amphibian, avian, and mammalian species (Behringer and Deschner, 2017; Bortolotti et al., 2008; Gormally and Romero, 2020; Heimbürge et al., 2019; Palme, 2019; Romero and Fairhurst, 2016). Similarly, although their development and application lags for fish, several techniques are now available for the quantification of steroids in novel, less invasive matrices. In general, these techniques vary in terms of invasiveness, sample collection practicality and field application. The quantification of steroids in novel matrices may also permit hormone monitoring on different time scales (Fig. 6), thereby broadening the context for integrating this information into conservation initiatives.

The least invasive technique for measuring steroids in fish involves the monitoring of tank water. In fish, free steroids passively diffuse from the bloodstream into the water across the gills (Ellis et al., 2005; Vermeirssen and Scott, 1996). As a result, the rate of steroid release into the surrounding holding water is generally proportional to their concentration in the plasma across multiple steroid classes. For example, the release rate of E2, T, 11-KT, androstenedione, 17,20βP, and cortisol have been shown to be proportional to plasma or whole-body measures (Ellis et al., 2004; Friesen et al., 2012b; Graham et al., 2018; Sebire et al., 2007; Stacey et al., 1989; White et al., 2017). Although the quantification of steroids in fish-holding water requires more planning and validation than typical plasma sampling, this technique has the distinct advantages of eliminating the need to handle and anesthetize fish to collect samples, allowing the simultaneous measurement of

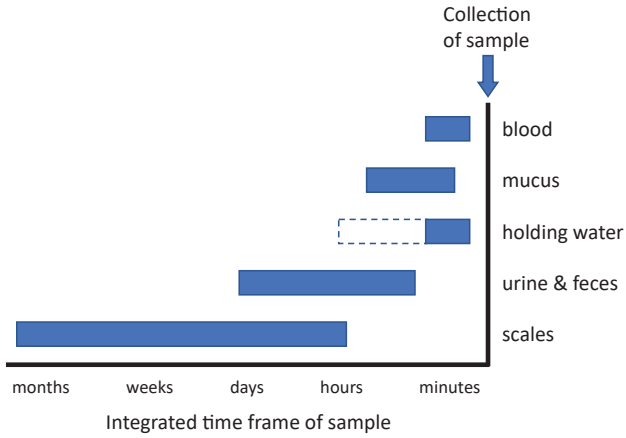

FIG. 6 Alternative matrices may permit cortisol monitoring on different time scales in fish. While blood samples provide a snapshot of circulating cortisol levels at the time of sampling, the general delay in the appearance of peak cortisol in skin mucus relative to peak plasma levels suggest that this matrix may integrate cortisol levels on a slightly longer timeframe than blood. The timeframe integrated by quantifying cortisol in holding water depends on the technique used. Since the rate of cortisol release into the surrounding holding water is generally proportional to its plasma concentration, holding water cortisol levels will integrate over a similar timeframe as blood when using a flow-through holding tank. In contrast, holding water cortisol levels can integrate over a longer time frame when using a static holding tank. Although the factors that affect the lag-time between a stressor and subsequent elevations in free and conjugated urine and fecal corticosteroids in fish are poorly understood, urine and feces may integrate corticosteroid levels on a timeframe of several hours to a few days. Finally, though scales may not show short-lived fluctuations in plasma cortisol, scales may permit cortisol monitoring on a timeframe of hours to months and therefore could serve as an indicator of chronic stress in fish.

multiple steroid hormones from a single sample, and permitting temporal profiling of hormonal responses (Blackwell and Ankley, 2021; Graham et al., 2018; Kidd et al., 2010; Scott and Ellis, 2007; Scott et al., 2008). To date, the quantification of steroids in fish-holding water has been used, among other applications, to study stress and welfare (Ellis et al., 2004, 2007; Fanouraki et al., 2008; Friesen et al., 2012a,b; Leong et al., 2009; White et al., 2017), identify EDCs (Blackwell and Ankley, 2021), assess reproductive stage (Friesen et al., 2012a,b; Graham et al., 2018; Sebire et al., 2007), and detect pheromone communication (Scott and Sorensen, 1994; Stacey et al., 1989). Overall, while the quantification of steroids in holding water is primarily limited to controlled laboratory settings (Ellis et al., 2013), its broad application for the non-invasive study of steroids in various physiological systems and behavioral settings highlight its utility to address important issues in conservation biology.

Whereas free steroids in holding water are primarily derived from the gills, the main excretory routes of conjugated sex steroids, i.e., sulfated and glucoronidated steroids, are the feces and urine (Vermeirssen and Scott, 1996).

Similarly, the main excretory route for clearance of cortisol metabolites and conjugates is the hepato-biliary-fecal route (Mommsen et al., 1999; Scott et al., 2014). Therefore, the quantification of fecal corticosteroid levels may offer an additional method to monitor stress in fish (Cao et al., 2017; Lupica and Turner, 2009; Simontacchi et al., 2008; Turner et al., 2003). Since evacuation of the gastrointestinal (GI) track in fish is protracted, especially in cold-water species (e.g., GI tract evacuation in Atlantic salmon takes up to 48 h at ~13 °C; Aas et al., 2017), fecal corticosteroid levels are unlikely to be influenced by sampling procedures. However, while minimally invasive, the collection of feces from fish tanks by siphon, by manually stripping feces from the abdomen, or by following individuals in the field using scuba may be intrusive and limit the utility of this technique for the collection of repeated samples across time (Ellis et al., 2013). Moreover, to date, it remains unclear how factors known to affect GI evacuation such as water temperature, meal size, feed type, satiety, activity, or metabolic rate affect the lag-time between a stressor and the subsequent elevation in free and conjugated fecal corticosteroids and their metabolites. Similarly, although direct sampling of urine by stripping to quantify sex steroids and their conjugates (Oliveira et al., 1996, 2001) is a minimally invasive technique, the intrusive nature of the procedure may limit its applicability for repeated sampling, and much work remains to determine how such measurements relate to circulating levels (Ellis et al., 2013). Yet, the quantification of conjugated sex steroids of urinary provenance in fish-holding water can provide unique insights into the physiological and behavioral strategies used by fish to communicate social and reproductive cues (Almeida et al., 2005; Hirschenhauser et al., 2008; Keller-Costa et al., 2014; Scott and Sorensen, 1994; Sorensen et al., 2005; Stacey et al., 1989). Therefore, the development of novel sensitive methods for the simultaneous non-invasive quantification of multiple free and conjugated steroids in fish-holding water (e.g., Blackwell and Ankley, 2021) should provide insight into the complex signals used by fish for chemical communication.

Epidermal mucus can also be used to monitor steroids in fish. Mucus collected from the skin contains both sex steroids and cortisol, and the levels are correlated with circulated plasma concentrations (Bertotto et al., 2010; Carbajal et al., 2019a; Schultz et al., 2005; Simontacchi et al., 2008). Although the collection of skin mucus samples requires fish handling and sedation, the technique is minimally invasive, and can readily be used in both laboratory and field settings (Carbajal et al., 2019b; Ellis et al., 2013). As such, the quantification of mucus 11-KT levels has served to determine fish sex, to assess annual reproductive cycles, and to identify whether environmental or hormonal manipulations can stimulate the HPG axis (Barkowski and Haukenes, 2014; Schultz et al., 2007). Mucus cortisol levels have also been used as a physiological indicator of stress in response to various acute disturbances (Bertotto et al., 2010; De Mercado et al., 2018; Guardiola et al., 2016; Khansari et al., 2018; Kroska et al., 2021; Simontacchi et al., 2008). Whether

mucus and plasma cortisol levels provide an opportunity to examine the effects of acute stressors at different time scales remains equivocal. While stressors elicited a similar time course between plasma and mucus cortisol levels in some studies (Carbajal et al., 2019a; Khansari et al., 2018), the appearance of peak cortisol in skin mucous was significantly delayed relative to peak plasma cortisol levels in others (Guardiola et al., 2016; Kroska et al., 2021). In general, several questions remain regarding the potential effects of stressors on mucus production as well as the route and factors that affect the movement of steroids from blood to mucus (Ellis et al., 2013; Pérez-Sánchez et al., 2017; Shephard, 1994).

Recent studies have suggested that fish scales may provide an integrative measure of cortisol production. While acute stressors do not appear to affect scale cortisol content, high and sustained circulating cortisol levels do, and the rates of cortisol accumulation and clearance are much slower in scales than in plasma (Aerts et al., 2015; Carbajal et al., 2019a; Hanke et al., 2019; Laberge et al., 2019). To date, scale cortisol content has been used to assess the effects of unpredictable chronic stress (Laberge et al., 2019), chronic thermal stress (Hanke et al., 2019), sub-optimal aquaculture conditions and impaired welfare (Weirup et al., 2021), and the long-term cortisol dynamics between social group members in a field setting (Culbert et al., 2021). Importantly, despite its utility as an indicator of chronic stress, fish scale cortisol content is unlikely to allow a retrospective historical assessment of stress status as far back in time as feather or hair corticosteroid content (Romero and Fairhurst, 2016; Russell et al., 2012). While specific studies are needed to determine the turnover of steroids in fish scales, the dynamic exchange of cortisol between the circulation and the scale matrix suggest that scale cortisol only allows assessment of the most recent integrated cortisol status of fish (Laberge et al., 2019). The quantity of scale material needed to provide a single determination may also impose limitations on the use of this approach as a non-invasive technique for measuring steroids in fish. Although only a few scales may be needed to determine scale cortisol content in large fish, in smaller fish, most, and in some cases, all scales may be needed to reach current assay thresholds (e.g., Aerts et al., 2015; Culbert et al., 2021; Laberge et al., 2019). Finally, beyond the need to handle and sedate fish to remove scales, sampling procedures should also consider the spatial heterogeneity of scale cortisol content (Laberge et al., 2019).

4.2 Hormonal profiling

Physiological processes are regulated by the actions of multiple endocrine signals, therefore quantifying these hormonal networks (i.e., hormonal profiling) may offer valuable mechanistic insight into animal physiology. While used for the analysis of select hormones since the 1960s, recent technical advances in mass spectrometry have facilitated the simultaneous quantification of

multiple classes of steroids and their metabolites from a single experimental sample (Boggs et al., 2016; Kaabia et al., 2018; Olesti et al., 2021; Son et al., 2020). This technique has been successfully applied to investigations of steroid-related endocrine diseases (Schiffer et al., 2019), and recent initiatives emphasize the suitability of steroid profiling in the field of conservation physiology for reproductive and stress assessment of endangered mammalian species (e.g., Azevedo et al., 2020; Galligan et al., 2018, 2020; Graham et al., 2021; Kumar and Govindhaswamy, 2019; Legacki et al., 2020). In fish, steroid profiling has been used to identify EDCs and their mode of action (Flores-Valverde et al., 2010; Labadie and Budzinski, 2006a,b), to identify novel biomarkers of aging (Dabrowski et al., 2020) and female maturation status (Lokman et al., 1998; Zhou et al., 2017), and to understand the mechanism of action of novel drugs (Kim et al., 2021); however, it has yet to be applied to the conservation of threatened species. Mass spectrometric techniques have also been developed to perform an integrated analysis of peptide hormones and neuropeptides, i.e., for peptidomic analysis (Baggerman et al., 2004; Romanova and Sweedler, 2015). To date, however, these techniques have largely been used to characterize the complement of neuropeptides and peptide hormones of fish brains (Hu et al., 2016; Van Camp et al., 2017) and have yet to find applications in the field of conservation endocrinology. While the simultaneous measurement of multiple classes of hormones is not without significant technical challenges, the study of hormonal profile variation over time in a variety of biological matrices will advance the study of hormone function, accelerate the discovery of novel stress and reproductive biomarkers, and facilitate the incorporation of endocrine measures in conservation management.

4.3 Multisystem integration of endocrinology in conservation physiology

4.3.1 Ecotoxicogenomics

Fish are established sentinels of aquatic pollution and are routinely used to screen for endocrine disrupting properties of new chemicals. The advent of genomic technologies has facilitated a deep and comprehensive understanding of tissue-specific biological responses to chemical exposure in model fish species exposed under controlled laboratory conditions, resulting in detailed knowledge on modes of action and adverse outcomes (Caballero-Gallardo et al., 2016; Hook, 2010; Martyniuk et al., 2020; Tyler et al., 2008). In the emerging field of ecotoxicogenomics this mechanistic knowledge is placed into an ecological framework to facilitate interpretation of complex gene-environment interactions for the purposes of risk assessment, site remediation, and ecosystem management. For example, 'omics tools can be used to screen for and predict the impact of contaminant exposure on local fish populations, and to understand species distributions in and around contaminated sites based on the genetic underpinnings of pollutant tolerance (Reid and Whitehead, 2016).

The rapid adoption of ecotoxicogenomics as an interdisciplinary approach to tackle environmental issues is fueled by the increased availability of whole-sequenced genomes for non-model species, technological advances in mass-spectrometry-based proteomics and metabolomics, and the development of bioinformatic tools to facilitate analysis and interpretation of massive datasets. The overall aim is to capitalize on insights from laboratory studies to help define the relationships between water quality and physiological status of resident fish. For example, molecular signatures consistent with HPG axis disruption were detected in the ovarian and hepatic transcriptomes of fathead minnow caged downstream of three WWTP in Minnesota, USA (Berninger et al., 2014; Martinović-Weigelt et al., 2014). Functional analyses of the enriched gene sets indicated dysregulation of E2 signaling pathways, cholesterol biosynthesis and steroid metabolism in the liver (Martinović-Weigelt et al., 2014), and the regulation of oocyte meiosis and gonadotropin signaling pathways in the ovary (Berninger et al., 2014). Importantly, these transcriptional responses were evident after only 4 days of exposure, and varied with site-specific differences in watershed dynamics, land use patterns, and urban population densities that generated unique contaminant profiles and exposure scenarios at each site (Berninger et al., 2014; Martinović-Weigelt et al., 2014). Thus, a measured genomic response can be used as a predictive early indicator of exposure to EDCs where known adverse outcomes of reproductive impairment are expected to impact population recruitment.

Ecotoxicogenomics has a bright future in assessing endocrine disruption for conservation efforts. The holistic nature of 'omics technologies means that multiple endocrine systems can be monitored simultaneously by identifying enriched gene sets or functional pathways in target tissues that are hormonally regulated. This is especially advantageous in the context of complex natural habitats, where wild fish are likely to experience multiple stressors and chemical mixtures of known and unknown endocrine disrupting properties (Hook, 2010). In contrast, targeted approaches that quantify biomarkers of specific endocrine disruption (e.g., circulating vitellogenin or hepatic *vtg* expression in male fish) requires a priori knowledge of causative agents, and a narrow focus on predicted effects may bias interpretation of water quality or even miss underlying issues that are yet to be identified (Hook et al., 2014). An additional strength of ecotoxicogenomics is that it enables early detection of endocrine disruption in advance of adverse organismal outcomes, which may expedite habitat remediation and initiate conservation strategies before critical impacts to populations occur.

4.3.2 Endocrine-microbiome interactions

All animals carry with them a diverse and plentiful community of microorganisms, particularly in the gastrointestinal tract. The gut microbiome has long been known to participate in chemical digestion and thus facilitate nutrient acquisition, but increasingly it is being linked to a seemingly infinite array of host physiological and behavioral processes. A role for the gut microbiome

in health and disease is now widely accepted and is mediated in part by cross-talk with host endocrine systems (Cusick et al., 2021; de Weerth, 2017; Neuman et al., 2015). For example, gut microbes can synthesize bioactive catecholamines *de novo* (Asano et al., 2012), and microbial enzymes (i.e., glucoronidases and sulfatases) can reactivate conjugated hormone metabolites entering the gut lumen from the bile to promote reabsorption over excretion (Ervin et al., 2019, 2020). Comparative physiologists are only beginning to scratch the surface on the mechanisms and outcomes of host-microbiome interactions, but it is clear that many current ecosystem threats can influence the composition of the gut microbiome (Sullam et al., 2012), including increased temperature (Kohl and Yahn, 2016), habitat degradation (San Juan et al., 2020; Watson et al., 2019), and pollutants (Adamovsky et al., 2021; Chen et al., 2018), as well as stress and glucocorticoids in general (Noguera et al., 2018; Stothart et al., 2016).

In fish, studies of gut microbiomes are largely centered on aquaculture applications, but lessons learned here may be transferable to captive breeding and conservation programs. Antibiotic treatments on fish farms are used to prevent and control disease outbreaks and are linked to reduced microbial diversity in the gut and increased representation of opportunistic pathogenic strains (Navarrete et al., 2008). As an alternative approach, supplementation of diets with prebiotics alone, or in combination with probiotics, can improve fish growth and reduce disease outbreaks by fortifying the abundance and diversity of beneficial gut microbes (Clements et al., 2014; Egerton et al., 2018). There is some evidence to suggest an endocrine link to these benefits. For example, great sturgeon (*Huso huso*) fed prebiotic supplements had elevated plasma T4 and TSH along with greater feed conversion efficiency (Adel et al., 2016), suggesting a link between endocrine-controlled growth and the gut microbiome. Complex interactions between stress, immune responses, and the gut microbiome are also likely to contribute to the health of aquaculture species and the success of captive breeding programs. For example, a study in Atlantic salmon (*S. salar*) exposed to a mild, repeated handling stressor showed a strong association between fecal cortisol and the diversity and structure of the gut microbiome, including reduced representation of beneficial strains and increased levels of pathogenic strains in stressed fish relative to controls (Uren Webster et al., 2020). Building fundamental understanding of microbiome-host interactions in fish health, particularly with respect to the endocrine systems, could have considerable impact on conservation efforts. Importantly, the gut microbiome can be qualitatively and quantitatively evaluated via non-lethal fecal sampling and is therefore amenable to long-term monitoring and intervention programs.

5 Conclusions

Fish endocrinologists are making important contributions to the field of conservation physiology, bringing a wealth of laboratory and fundamental

research to applied and emerging challenges. In this chapter, we offer many examples that demonstrate how quantification and manipulation of hormone systems can provide insight into the well-being, growth, and reproductive status of fish, ultimately advancing conservation goals by:

1. Guiding the development of novel conservation hatchery strategies that will minimize the impact of cultured fish on wild populations and help maintain the genetic diversity of wild fish;
2. Revealing how exposure to EDCs and environmental stressors can delay or prevent normal development, result in a mismatch between phenotype and environment, and affect the survival and recruitment of individuals in degrading ecosystems;
3. Identifying habitats and environmental factors that influence growth of wild fish to support life history transitions;
4. Enabling the assisted reproduction of threatened species;
5. Mitigating the impacts of climate change and EDCs on reproduction, sex determination, and population viabilities by establishing mechanistic links between endocrine bioindicators, fish reproduction, and larval recruitment;
6. Facilitating the quantification and removal of invasive species while simultaneously minimizing impacts of such procedures on native species.

Looking ahead, the use of alternative matrices (e.g., holding water, feces, mucus, scales) to simultaneously quantify multiple free and conjugated steroids holds great promise as a non-invasive approach for monitoring the stress and reproductive physiology of captive and wild fish on different time scales. Indeed, the conserved structure of steroid hormones across fish species, their tendency to accumulate in inert matrices, and the commercial availability of tools for steroid quantification favor an increased effort to integrate steroid profiling into conservation practices. Given the pervasive effects of abiotic factors and EDCs on the synthesis of steroid hormones, and the broad physiological consequences of impaired steroidogenesis on fish, we suggest that such efforts could offer valuable insight into fish recruitment mechanisms and help to monitor the impact of anthropogenic and environmental stressors on fish. However, broadscale adoption of such initiatives will first require the development of more sensitive, high-throughput, and cost-effective hormonal analyses, followed by the mobilization of these tools out of researcher's hands and into those of resource managers.

Fish endocrinology has already helped contribute to policy change by providing standardized quantitative endpoints to set water quality standards for certain EDCs around the globe; however, focused attention on a few key limitations and knowledge gaps are needed for fish endocrinology to become ingrained in conservation and restoration initiatives, and to bring about sustained impact on fish conservation. First, fish are the most speciose group of vertebrates, yet most study is carried out in single species or defined groups of fish (e.g., salmonids). Even within the strong evolutionary framework of

vertebrate endocrine systems, important species differences emerge that could skew management decisions without efforts to build a more taxonomically diverse foundation in fish endocrinology. Second, hormone systems function to integrate within and across physiological systems. As such, linking endocrine signals with other biological endpoints, including molecular, biochemical, and physiological biomarkers, will help build a better understanding of chronic sublethal detrimental health effects. Here, approaches using functional genomics and bioinformatics will be essential. Finally, researchers must look beyond biomarker identification to the validation and deployment of feasible tools for specific conservation applications. This will help resource managers use endocrine tools for evidence-based decisions within a regulatory framework.

The greatest environmental challenges of the 21st century include biodiversity loss, the climate crisis, and pollution. Conservation endocrinology is gaining momentum as a dedicated sub-discipline and stands to make meaningful contributions to the conservation problems inherent in these environmental challenges by providing resource managers with tools to assess the impact of natural and anthropogenic factors on the stress, growth, and reproductive status of fish, as well as the means to develop breeding programs for vulnerable populations.

References

Aas, T.S., Sixten, H.J., Hillestad, M., Sveier, H., Ytrestøyl, T., Hatlen, B., Åsgård, T., 2017. Measurement of gastrointestinal passage rate in Atlantic salmon (*Salmo salar*) fed dry or soaked feed. Aquac. Rep. 8, 49–57.

Abdel-Moneim, A., Coulter, D.P., Mahapatra, C.T., Sepúlveda, M.S., 2015. Intersex in fishes and amphibians: population implications, prevalence, mechanisms and molecular biomarkers. J. Appl. Toxicol. 35, 1228–1240.

Adamovsky, O., Bisesi, J.H., Martyniuk, C.J., 2021. Plastics in our water: fish microbiomes at risk? Comp. Biochem. Physiol. Part D Genomics Proteomics 39, 100834.

Adel, M., Nayak, S., Lazado, C.C., Yeganeh, S., 2016. Effects of dietary prebiotic GroBiotic®-A on growth performance, plasma thyroid hormones and mucosal immunity of great sturgeon, *Huso huso* (Linnaeus, 1758). J. Appl. Ichthyol. 32, 825–831.

Adolfi, M.C., Fischer, P., Herpin, A., Regensburger, M., Kikuchi, M., Tanaka, M., Schartl, M., 2019. Increase of cortisol levels after temperature stress activates dmrt1a causing female-to-male sex reversal and reduced germ cell number in medaka. Mol. Reprod. Dev. 86, 1405–1417.

Adrian, R., O'Reilly, C.M., Zagarese, H., Baines, S.B., Hessen, D.O., Keller, W., Livingstone, D.M., Sommaruga, R., Straile, D., Van Donk, E., Weyhenmeyer, G.A., Winder, M., 2009. Lakes as sentinels of climate change. Limnol. Oceanogr. 54, 2283–2297.

Aerts, J., Metz, J.R., Ampe, B., Decostere, A., Flik, G., De Saeger, S., 2015. Scales tell a story on the stress history of fish. PLoS One 10, e0123411.

Alavi, S.M.H., Hatef, A., Pšenička, M., Kašpar, V., Boryshpolets, S., Dzyuba, B., Cosson, J., Bondarenko, V., Rodina, M., Gela, D., Linhart, O., 2012. Sperm biology and control of reproduction in sturgeon: (II) sperm morphology, acrosome reaction, motility and cryopreservation. Rev. Fish Biol. Fish. 22, 861–886.

Algera, D.A., Brownscombe, J.W., Gilmour, K.M., Lawrence, M.J., Zolderdo, A.J., Cooke, S.J., 2017. Cortisol treatment affects locomotor activity and swimming behaviour of male smallmouth bass engaged in paternal care: a field study using acceleration biologgers. Physiol. Behav. 181, 59–68.

Alix, M., Kjesbu, O.S., Anderson, K.C., 2020. From gametogenesis to spawning: how climate-driven warming affects teleost reproductive biology. J. Fish Biol. 97, 607–632.

Allard, J.B., Duan, C., 2018. IGF-binding proteins: why do they exist and why are there so many? Front. Endocrinol. (Lausanne) 9, 1–12.

Almeida, O.G., Miranda, A., Frade, P., Hubbard, P.C., Barata, E.N., Canário, A.V.M., 2005. Urine as a social signal in the Mozambique tilapia (*Oreochromis mossambicus*). Chem. Senses 30, i309–i310.

Anderson, K., Swanson, P., Pankhurst, N., King, H., Elizur, A., 2012. Effect of thermal challenge on plasma gonadotropin levels and ovarian steroidogenesis in female maiden and repeat spawning Tasmanian Atlantic salmon (*Salmo salar*). Aquaculture 334, 205–212.

Anderson, K., Luckenbach, J.A., Yamamoto, Y., Elizur, A., 2019. Impacts of Fsh, Igf1, and high temperature on the expression of genes involved in steroidogenesis, cell communication, and apoptosis in isolated coho salmon previtellogenic ovarian follicles. Aquaculture 506, 60–69.

Andrews, K.S., Beckman, B.R., Beaudreau, A.H., Larsen, D.A., Williams, G.D., Levin, P.S., 2011. Suitability of insulin-like growth factor 1 (IGF1) as a measure of relative growth rates in lingcod. Mar. Coast. Fish. 3, 250–260.

Araki, H., Berejikian, B.A., Ford, M.J., Blouin, M.S., 2008. Fitness of hatchery-reared salmonids in the wild. Evol. Appl. 1, 342–355.

Arbuckle, W.J., Bélanger, A.J., Corkum, L.D., Zielinski, B.S., Li, W., Yun, S.S., Bachynski, S., Scott, A.P., 2005. In vitro biosynthesis of novel 5β-reduced steroids by the testis of the round goby, Neogobius melanostomus. Gen. Comp. Endocrinol. 140, 1–13.

Arechavala-Lopez, P., Caballero-Froilán, J.C., Jiménez-García, M., Capó, X., Tejada, S., Saraiva, J.L., Sureda, A., Moranta, D., 2020. Enriched environments enhance cognition, exploratory behaviour and brain physiological functions of *Sparus aurata*. Sci. Rep. 10, 11252.

Arkoosh, M.R., Van Gaest, A.L., Strickland, S.A., Hutchinson, G.P., Krupkin, A.B., Dietrich, J.P., 2017. Alteration of thyroid hormone concentrations in juvenile Chinook salmon (*Oncorhynchus tshawytscha*) exposed to polybrominated diphenyl ethers, BDE-47 and BDE-99. Chemosphere 171, 1–8.

Arukwe, A., Nordtug, T., Kortner, T.M., Mortensen, A.S., Brakstad, O.G., 2008. Modulation of steroidogenesis and xenobiotic biotransformation responses in zebrafish (*Danio rerio*) exposed to water-soluble fraction of crude oil. Environ. Res. 107, 362–370.

Asano, Y., Hiramoto, T., Nishino, R., Aiba, Y., Kimura, T., Yoshihara, K., Koga, Y., Sudo, N., 2012. Critical role of gut microbiota in the production of biologically active, free catecholamines in the gut lumen of mice. Am. J. Physiol. Gastrointest. Liver Physiol. 303, 1288–1295.

Aus der Beek, T., Weber, F.-A., Bergmann, A., Hickmann, S., Ebert, I., Hein, A., Küster, A., 2016. Pharmaceuticals in the environment—global occurrences and perspectives. Environ. Toxicol. Chem. 35, 823–835.

Awata, S., Tsuruta, T., Yada, T., Iguchi, K., 2011. Effects of suspended sediment on cortisol levels in wild and cultured strains of ayu *Plecoglossus altivelis*. Aquaculture 314, 115–121.

Azevedo, A., Wauters, J., Kirschbaum, C., Serra, R., Rivas, A., Jewgenow, K., 2020. Sex steroids and glucocorticoid ratios in Iberian lynx hair. Conserv. Physiol. 8, coaa075.

Baggerman, G., Verleyen, P., Clynen, E., Huybrechts, J., De Loof, A., Schoofs, L., 2004. Peptidomics. J. Chromatogr. B Analyt. Technol. Biomed. Life Sci. 803, 3–16.

Baker, M.R., Gobush, K.S., Vynne, C.H., 2013. Review of factors influencing stress hormones in fish and wildlife. J. Nat. Conserv. 21, 309–318.

Bangsgaard, K., Madsen, S.S., Korsgaard, B., 2006. Effect of waterborne exposure to 4-tert-octylphenol and 17β-estradiol on smoltification and downstream migration in Atlantic salmon, *Salmo salar*. Aquat. Toxicol. 80, 23–32.

Barcellos, L.J.G., Kreutz, L.C., Quevedo, R.M., da Rosa, J.G.S., Koakoski, G., Centenaro, L., Pottker, E., 2009. Influence of color background and shelter availability on jundiá (*Rhamdia quelen*) stress response. Aquaculture 288, 51–56.

Barkowski, N.A., Haukenes, A.H., 2014. Investigating the utility of measuring 11α-ketotestosterone and vitellogenin in surface mucus as an alternative to plasma samples in assessments of the reproductive axis of white bass. N. Am. J. Aquac. 76, 112–118.

Barra, R.O., Chiang, G., Saavedra, M.F., Orrego, R., Servos, M.R., Hewitt, L.M., McMaster, M.E., Bahamonde, P., Tucca, F., Munkittrick, K.R., 2021. Endocrine disruptor impacts on fish from Chile: the influence of wastewaters. Front. Endocrinol. (Lausanne) 12, 208.

Barton, B.A., 2002. Stress in fishes: a diversity of responses with particular reference to changes in circulating corticosteroids. Integr. Comp. Biol. 42, 517–525.

Barton, B.A., Iwama, G.K., 1991. Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annu. Rev. Fish Dis. 1, 3–26.

Barton, B., Schreck, C., Barton, L., 1987. Effects of chronic cortisol administration and daily acute stress on growth, physiological conditions, and stress responses in juvenile rainbow trout. Dis. Aquat. Organ. 2, 173–185.

Basu, N., Ta, C.A., Waye, A., Mao, J., Hewitt, M., Arnason, J.T., Trudeau, V.L., 2009. Pulp and paper mill effluents contain neuroactive substances that potentially disrupt neuroendocrine control of fish reproduction. Environ. Sci. Technol. 43, 1635–1641.

Batzina, A., Dalla, C., Tsopelakos, A., Papadopoulou-Daifoti, Z., Karakatsouli, N., 2014. Environmental enrichment induces changes in brain monoamine levels in gilthead seabream *Sparus aurata*. Physiol. Behav. 130, 85–90.

Beamish, R.J., Sweeting, R.M., Lange, K.L., Neville, C.M., 2008. Changes in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. Trans. Am. Fish. Soc. 137, 503–520.

Beckman, B.R., 2011. Perspectives on concordant and discordant relations between insulin-like growth factor 1 (IGF1) and growth in fishes. Gen. Comp. Endocrinol. 170, 233–252.

Beckman, B.R., Dickhoff, W.W., Zaugg, W.S., Sharpe, C., Hirtzel, S., Schrock, R., Larsen, D.A., Ewing, R.D., Palmisano, A., Schreck, C.B., Mahnken, C.V.W., 1999. Growth, smoltification, and smolt-to-adult return of spring chinook salmon from hatcheries on the Deschutes River, Oregon. Trans. Am. Fish. Soc. 128, 1125–1150.

Beckman, B.R., Larsen, D.A., Sharpe, C., Lee-Pawlak, B., Schreck, C.B., Dickhoff, W.W., 2000. Physiological status of naturally reared juvenile spring chinook salmon in the Yakima River: seasonal dynamics and changes associated with smolting. Trans. Am. Fish. Soc. 129, 727–753.

Beckman, B.R., Fairgrieve, W., Cooper, K.A., Mahnken, C.V.W., Beamish, R.J., 2004a. Evaluation of endocrine indices of growth in individual postsmolt coho salmon. Trans. Am. Fish. Soc. 133, 1057–1067.

Beckman, B.R., Shimizu, M., Gadberry, B.A., Cooper, K.A., 2004b. Response of the somatotropic axis of juvenile coho salmon to alterations in plane of nutrition with an analysis of the relationships among growth rate and circulating IGF-I and 41 kDa IGFBP. Gen. Comp. Endocrinol. 135, 334–344.

Beckman, B.R., Harstad, D.L., Spangenberg, D.K., Gerstenberger, R.S., Brun, C.V., Larsen, D.A., 2017. The impact of different hatchery rearing environments on smolt-to-adult survival of spring chinook salmon. Trans. Am. Fish. Soc. 146, 539–555.

Behringer, V., Deschner, T., 2017. Non-invasive monitoring of physiological markers in primates. Horm. Behav. 91, 3–18.

Berejikian, B.A., 1995. The effects of hatchery and wild ancestry and experience on the relative ability of steelhead trout fry (*Oncorhynchus mykiss*) to avoid a benthic predator. Can. J. Fish. Aquat. Sci. 52, 2476–2482.

Berejikian, B.A., Fairgrieve, W.T., Swanson, P., Tezak, E.P., 2003. Current velocity and injection of GnRHa affect reproductive behavior and body composition of captively reared offspring of wild chinook salmon (*Oncorhynchus tshawytscha*). Can. J. Fish. Aquat. Sci. 60, 690–699.

Bergan, H.E., Kittilson, J.D., Sheridan, M.A., 2015. Nutritional state modulates growth hormone-stimulated lipolysis. Gen. Comp. Endocrinol. 217–218, 1–9.

Bergan-Roller, H.E., Sheridan, M.A., 2018. The growth hormone signaling system: insights into coordinating the anabolic and catabolic actions of growth hormone. Gen. Comp. Endocrinol. 258, 119–133.

Bernier, N.J., Craig, P.M., 2005. CRF-related peptides contribute to stress response and regulation of appetite in hypoxic rainbow trout. Am. J. Physiol. Regul. Integr. Comp. Physiol. 289, 982–990.

Bernier, N.J., Van Der Kraak, G., Farrell, A.P., Brauner, C.J., 2009a. Fish Physiology: Fish Neuroendocrinology. Academic Press, London. vol. 28.

Bernier, N.J., Flik, G., Klaren, P.H.M., 2009b. Regulation and contribution of corticotropic, melanotropic and thyrotropic axes to the stress response in fishes. In: Bernier, N.J., Van Der Kraak, G., Farrell, A.P., Brauner, C.J. (Eds.), Fish Neuroendocrinology, Fish Physiology. vol. 28. Academic Press, London, pp. 235–311.

Berninger, J.P., Martinović-Weigelt, D., Garcia-Reyero, N., Escalon, L., Perkins, E.J., Ankley, G.T., Villeneuve, D.L., 2014. Using transcriptomic tools to evaluate biological effects across effluent gradients at a diverse set of study sites in Minnesota, USA. Environ. Sci. Technol. 48, 2404–2412.

Bertotto, D., Poltronieri, C., Negrato, E., Majolini, D., Radaelli, G., Simontacchi, C., 2010. Alternative matrices for cortisol measurement in fish. Aquacult. Res. 41, 1261–1267.

Besson, M., Feeney, W.E., Moniz, I., François, L., Brooker, R.M., Holzer, G., Metian, M., Roux, N., Laudet, V., Lecchini, D., 2020. Anthropogenic stressors impact fish sensory development and survival via thyroid disruption. Nat. Commun. 11, 3614.

Bévalot, F., Gaillard, Y., Lhermitte, M.A., Pépin, G., 2000. Analysis of corticosteroids in hair by liquid chromatography-electrospray ionization mass spectrometry. J. Chromatogr. B Biomed. Sci. Appl. 740, 227–236.

Birnie-Gauvin, K., Flávio, H., Kristensen, M.L., Walton-Rabideau, S., Cooke, S.J., Willmore, W.G., Koed, A., Aarestrup, K., 2019. Cortisol predicts migration timing and success in both Atlantic salmon and sea trout kelts. Sci. Rep. 9, 2422.

Björnsson, B.T., Stefansson, S.O., McCormick, S.D., 2011. Environmental endocrinology of salmon smoltification. Gen. Comp. Endocrinol. 170, 290–298.

Blackwell, B.R., Ankley, G.T., 2021. Simultaneous determination of a suite of endogenous steroids by LC-APPI-MS: application to the identification of endocrine disruptors in aquatic toxicology. J. Chromatogr. B Analyt. Technol. Biomed. Life Sci. 1163, 122513.

Blanchfield, P.J., Kidd, K.A., Docker, M.F., Palace, V.P., Park, B.J., Postma, L.D., 2015. Recovery of a wild fish population from whole-lake additions of a synthetic estrogen. Environ. Sci. Technol. 49, 3136–3144.

Bock, S.L., Chow, M.I., Forsgren, K.L., Lema, S.C., 2021. Widespread alterations to hypothalamic-pituitary-gonadal (HPG) axis signaling underlie high temperature reproductive inhibition in the eurythermal sheepshead minnow (*Cyprinodon variegatus*). Mol. Cell. Endocrinol. 537, 111447.

Boerrigter, J.G.J., van den Bos, R., van de Vis, H., Spanings, T., Flik, G., 2016. Effects of density, PVC-tubes and feeding time on growth, stress and aggression in African catfish (*Clarias gariepinus*). Aquacult. Res. 47, 2553–2568.

Boggs, A.S.P., Bowden, J.A., Galligan, T.M., Guillette, L.J., Kucklick, J.R., 2016. Development of a multi-class steroid hormone screening method using liquid chromatography/tandem mass spectrometry (LC-MS/MS). Anal. Bioanal. Chem. 408, 4179–4190.

Bond, M.H., Beckman, B.R., Rohrbach, L., Quinn, T.P., 2014. Differential growth in estuarine and freshwater habitats indicated by plasma IGF1 concentrations and otolith chemistry in dolly varden *Salvelinus malma*. J. Fish Biol. 85, 1429–1445.

Booc, F., Thornton, C., Lister, A., MacLatchy, D., Willett, K.L., 2014. Benzo[a]pyrene effects on reproductive endpoints in *Fundulus heteroclitus*. Toxicol. Sci. 140, 73–82.

Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., Vichi, M., 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10, 6225–6245.

Bortolotti, G.R., Marchant, T.A., Blas, J., German, T., 2008. Corticosterone in feathers is a long-term, integrated measure of avian stress physiology. Funct. Ecol. 22, 494–500.

Braithwaite, V.A., Salvanes, A.G.V., 2005. Environmental variability in the early rearing environment generates behaviourally flexible cod: implications for rehabilitating wild populations. Proc. R. Soc. B Biol. Sci. 272, 1107–1113.

Breitburg, D., Levin, L.A., Oschlies, A., Grégoire, M., Chavez, F.P., Conley, D.J., Garçon, V., Gilbert, D., Gutiérrez, D., Isensee, K., Jacinto, G.S., Limburg, K.E., Montes, I., Naqvi, S.W.A., Pitcher, G.C., Rabalais, N.N., Roman, M.R., Rose, K.A., Seibel, B.A., Telszewski, M., Yasuhara, M., Zhang, J., 2018. Declining oxygen in the global ocean and coastal waters. Science 359, eaam7240.

Breves, J.P., Duffy, T.A., Einarsdottir, I.E., Björnsson, B.T., McCormick, S.D., 2018. *In vivo* effects of 17α-ethinylestradiol, 17β-estradiol and 4-nonylphenol on insulin-like growth-factor binding proteins (igfbps) in Atlantic salmon. Aquat. Toxicol. 203, 28–39.

Brown, C., Day, R.L., 2002. The future of stock enhancements: lessons for hatchery practice from conservation biology. Fish Fish. 3, 79–94.

Brown, C., Davidson, T., Laland, K., 2003. Environmental enrichment and prior experience of live prey improve foraging behaviour in hatchery-reared Atlantic salmon. J. Fish Biol. 63, 187–196.

Bryant, A.S., Greenwood, A.K., Juntti, S.A., Byrne, A.E., Fernald, R.D., 2016. Dopaminergic inhibition of gonadotropin-releasing hormone neurons in the cichlid fish *Astatotilapia burtoni*. J. Exp. Biol. 219, 3861–3865.

Bugel, S.M., White, L.A., Cooper, K.R., 2010. Impaired reproductive health of killifish (*Fundulus heteroclitus*) inhabiting Newark Bay, NJ, a chronically contaminated estuary. Aquat. Toxicol. 96, 182–193.

Burgerhout, E., Lokman, P.M., van den Thillart, G.E.E.J.M., Dirks, R.P., 2019. The time-keeping hormone melatonin: a possible key cue for puberty in freshwater eels (*Anguilla* spp.). Rev. Fish Biol. Fish. 29, 1–21.

Burns, A.C., Sorensen, P.W., Hoye, T.R., 2011. Synthesis and olfactory activity of unnatural, sulfated 5β-bile acid derivatives in the sea lamprey (*Petromyzon marinus*). Steroids 76, 291–300.

Butcher, J.B., Nover, D., Johnson, T.E., Clark, C.M., 2015. Sensitivity of lake thermal and mixing dynamics to climate change. Clim. Change 129, 295–305.

Caballero-Gallardo, K., Olivero-Verbel, J., Freeman, J.L., 2016. Toxicogenomics to evaluate endocrine disrupting effects of environmental chemicals using the zebrafish model. Curr. Genomics 17, 515–527.

Caldarone, E.M., MacLean, S.A., Beckman, B.R., 2016. Evaluation of nucleic acids and plasma IGF1 levels for estimating short-term responses of postsmolt Atlantic salmon (*Salmo salar*) to food availability. Fish. Bull. 114, 288–301.

Campinho, M.A., Saraiva, J., Florindo, C., Power, D.M., 2014. Maternal thyroid hormones are essential for neural development in zebrafish. Mol. Endocrinol. 28, 1136–1149.

Cao, Y., Tveten, A.K., Stene, A., 2017. Establishment of a non-invasive method for stress evaluation in farmed salmon based on direct fecal corticoid metabolites measurement. Fish Shellfish Immunol. 66, 317–324.

Carbajal, A., Reyes-López, F.E., Tallo-Parra, O., Lopez-Bejar, M., Tort, L., 2019a. Comparative assessment of cortisol in plasma, skin mucus and scales as a measure of the hypothalamic-pituitary-interrenal axis activity in fish. Aquaculture 506, 410–416.

Carbajal, A., Soler, P., Tallo-Parra, O., Isasa, M., Echevarria, C., Lopez-Bejar, M., Vinyoles, D., 2019b. Towards non-invasive methods in measuring fish welfare: the measurement of cortisol concentrations in fish skin mucus as a biomarker of habitat quality. Animals 9, 939.

Carnevali, O., Santangeli, S., Forner-Piquer, I., Basili, D., Maradonna, F., 2018. Endocrine-disrupting chemicals in aquatic environment: what are the risks for fish gametes? Fish Physiol. Biochem. 44, 1561–1576.

Carr, J.A., Patiño, R., 2011. The hypothalamus-pituitary-thyroid axis in teleosts and amphibians: endocrine disruption and its consequences to natural populations. Gen. Comp. Endocrinol. 170, 299–312.

Castañeda Cortés, D.C., Padilla, L.F.A., Langlois, V.S., Somoza, G.M., Fernandino, J.I., 2019. The central nervous system acts as a transducer of stress-induced masculinization through corticotropin-releasing hormone B. Development 146, dev172866.

Castro, A.J.G., Baptista, I.E., de Moura, K.R.S., Padilha, F., Tonietto, J., de Souza, A.Z.P., Soares, C.H.L., Silva, F.R.M.B., Van Der Kraak, G., 2018. Exposure to a Brazilian pulp mill effluent impacts the testis and liver in the zebrafish. Comp. Biochem. Physiol., Part C: Toxicol. Pharmacol. 206–207, 41–47.

Chadwick, J.G., Nislow, K.H., McCormick, S.D., 2015. Thermal onset of cellular and endocrine stress responses correspond to ecological limits in brook trout, an iconic cold-water fish. Conserv. Physiol. 3, cov017.

Chamberlin, J.W., Beckman, B.R., Greene, C.M., Rice, C.A., Hall, J.E., 2017. How relative size and abundance structures the relationship between size and individual growth in an ontogenetically piscivorous fish. Ecol. Evol. 7, 6981–6995.

Chang, J.P., Wong, A.O.L., 2009. Growth hormone regulation in fish. In: Bernier, N.J., Van Der Kraak, G., Farrell, A.P., Brauner, C.J. (Eds.), Fish Neuroendocrinology, Fish Physiology. vol. 28. Academic Press, London, pp. 151–195.

Cheek, A.O., Landry, C.A., Steele, S.L., Manning, S., 2009. Diel hypoxia in marsh creeks impairs the reproductive capacity of estuarine fish populations. Mar. Ecol. Prog. Ser. 392, 211–221.

Chen, L., Guo, Y., Hu, C., Lam, P.K.S., Lam, J.C.W., Zhou, B., 2018. Dysbiosis of gut microbiota by chronic coexposure to titanium dioxide nanoparticles and bisphenol A: implications for host health in zebrafish. Environ. Pollut. 234, 307–317.

Cheung, C.H.Y., Chiu, J.M.Y., Wu, R.S.S., 2014. Hypoxia turns genotypic female medaka fish into phenotypic males. Ecotoxicology 23, 1260–1269.

Chiang, G., Mcmaster, M.E., Urrutia, R., Saavedra, M.F., Gavilán, J.F., Tucca, F., Barra, R., Munkittrick, K.R., 2011. Health status of native fish (*Percilia gillissi* and *Trichomycterus areolatus*) downstream of the discharge of effluent from a tertiary-treated elemental chlorine-free pulp mill in Chile. Environ. Toxicol. Chem. 30, 1793–1809.

Chittenden, C.M., Biagi, C.A., Davidsen, J.G., Davidsen, A.G., Kondo, H., McKnight, A., Pedersen, O.P., Raven, P.A., Rikardsen, A.H., Mark Shrimpton, J., Zuehlke, B., Scott McKinley, R., Devlin, R.H., 2010. Genetic versus rearing-environment effects on phenotype: hatchery and natural rearing effects on hatchery- and wild-born coho salmon. PLoS One 5, e12261.

Clark, R.W., Henderson-Arzapalo, A., Sullivan, C.V., 2005. Disparate effects of constant and annually-cycling daylength and water temperature on reproductive maturation of striped bass (*Morone saxatilis*). Aquaculture 249, 497–513.

Clark, T.D., Donaldson, M.R., Drenner, S.M., Hinch, S.G., Patterson, D.A., Hills, J., Ives, V., Carter, J.J., Cooke, S.J., Farrell, A.P., 2011. The efficacy of field techniques for obtaining and storing blood samples from fishes. J. Fish Biol. 79, 1322–1333.

Clements, K.D., Angert, E.R., Montgomery, W.L., Choat, J.H., 2014. Intestinal microbiota in fishes: what's known and what's not. Mol. Ecol. 23, 1891–1898.

Cogliati, K.M., Herron, C.L., Noakes, D.L.G., Schreck, C.B., 2019. Reduced stress response in juvenile chinook salmon reared with structure. Aquaculture 504, 96–101.

Collier, T.K., Anulacion, B.F., Arkoosh, M.R., Dietrich, J.P.J.P., Incardona, J.P., Johnson, L.L., Ylitalo, G.M., Myers, M.S., 2013. Effects on fish of polycyclic aromatic hydrocarbons (PAHS) and naphthenic acid exposures. In: Tierney, K.B., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology, Organic Chemical Toxicology of Fishes, vol. 33. Academic Press, London, pp. 195–255.

Corkum, L.D., Belanger, R.M., 2007. Use of chemical communication in the management of freshwater aquatic species that are vectors of human diseases or are invasive. Gen. Comp. Endocrinol. 153, 401–417.

Corkum, L.D., Sapota, M.R., Skora, K.E., 2004. The round goby, *Neogobius melanostomus*, a fish invader on both sides of the Atlantic Ocean. Biol. Invasions 6, 173–181.

Costigan, S.L., Werner, J., Ouellet, J.D., Hill, L.G., Law, R.D., 2012. Expression profiling and gene ontology analysis in fathead minnow (*Pimephales promelas*) liver following exposure to pulp and paper mill effluents. Aquat. Toxicol. 122–123, 44–55.

Culbert, B.M., Ligocki, I.Y., Salena, M.G., Wong, M.Y.L., Hamilton, I.M., Aubin-Horth, N., Bernier, N.J., Balshine, S., 2021. Rank- and sex-specific differences in the neuroendocrine regulation of glucocorticoids in a wild group-living fish. Horm. Behav. 136, 105079.

Cusick, J.A., Wellman, C.L., Demas, G.E., 2021. The call of the wild: using non-model systems to investigate microbiome–behaviour relationships. J. Exp. Biol. 224, jeb224485.

Dabrowski, K., Rinchard, J., Ottobre, J.S., Alcantara, F., Padilla, P., Ciereszko, A., De Jesus, M.J., Kohler, C.C., 2003. Effect of oxygen saturation in water on reproductive performances of pacu *Piaractus brachypomus*. J. World Aquacult. Soc. 34, 441–449.

Dabrowski, R., Ripa, R., Latza, C., Annibal, A., Antebi, A., 2020. Optimization of mass spectrometry settings for steroidomic analysis in young and old killifish. Anal. Bioanal. Chem. 412, 4089–4099.

Davidsen, J.G., Daverdin, M., Sjursen, A.D., Rønning, L., Arnekleiv, J.V., Koksvik, J.I., 2014. Does reduced feeding prior to release improve the marine migration of hatchery brown trout *Salmo trutta* smolts? J. Fish Biol. 85, 1992–2002.

Davis, M.J., Chamberlin, J.W., Gardner, J.R., Connelly, K.A., Gamble, M.M., Beckman, B.R., Beauchamp, D.A., 2020. Variable prey consumption leads to distinct regional differences in

chinook salmon growth during the early marine critical period. Mar. Ecol. Prog. Ser. 640, 147–169.

De Mercado, E., Larrán, A.M., Pinedo, J., Tomás-Almenar, C., 2018. Skin mucous: a new approach to assess stress in rainbow trout. Aquaculture 484, 90–97.

de Weerth, C., 2017. Do bacteria shape our development? Crosstalk between intestinal microbiota and HPA axis. Neurosci. Biobehav. Rev. 83, 458–471.

Deal, C.K., Volkoff, H., 2020. The role of the thyroid axis in fish. Front. Endocrinol. (Lausanne) 11, 1–25.

Delbes, G., Blázquez, M., Fernandino, J.I., Grigorova, P., Hales, B.F., Metcalfe, C., Navarro-Martín, L., Parent, L., Robaire, B., Rwigemera, A., Van Der Kraak, G., Wade, M., Marlatt, V., 2022. Effects of endocrine disrupting chemicals on gonad development: mechanistic insights from fish and mammals. Environ. Res. 204, 112040.

Denison, M.S., Nagy, S.R., 2003. Activation of the aryl hydrocarbon receptor by structurally diverse exogenous and endogenous chemicals. Annu. Rev. Pharmacol. Toxicol. 43, 309–334.

Devlin, R.H., Biagi, C.A., Yesaki, T.Y., Smailus, D.E., Byatt, J.C., 2001. Growth of domesticated transgenic fish. Nature 409, 781–782.

Diaz, R.J., Rosenberg, R., 2008. Spreading dead zones and consequences for marine ecosystems. Science 321, 926–929.

Donaldson, E.M., Hunter, G.A., 1983. Induced final maturation, ovulation, and spermiation in cultured fish. Fish Physiol. 9, 351–403.

Douxfils, J., Mandiki, S.N.M., Marotte, G., Wang, N., Silvestre, F., Milla, S., Henrotte, E., Vandecan, M., Rougeot, C., Mélard, C., Kestemont, P., 2011. Does domestication process affect stress response in juvenile Eurasian perch *Perca fluviatilis*? Comp. Biochem. Physiol. A Mol. Integr. Physiol. 159, 92–99.

Duffy, T.A., Iwanowicz, L.R., McCormick, S.D., 2014. Comparative responses to endocrine disrupting compounds in early life stages of Atlantic salmon, *Salmo salar*. Aquat. Toxicol. 152, 1–10.

Dufour, S., Quérat, B., Tostivint, H., Pasqualini, C., Vaudry, H., Rousseau, K., 2020. Origin and evolution of the neuroendocrine control of reproduction in vertebrates, with special focus on genome and gene duplications. Physiol. Rev. 100, 869–943.

Dufour, S., Sebert, M.E., Weltzien, F.A., Rousseau, K., Pasqualini, C., 2010. Neuroendocrine control by dopamine of teleost reproduction. J. Fish Biol. 76, 129–160.

Duguid, W.D.P., Iwanicki, T.W., Journey, M.L., Noel, A.L., Beckman, B.R., Juanes, F., 2018. Assessing indices of growth for field studies of juvenile salmon: an experiment and synthesis. Mar. Coast. Fish. 10, 204–223.

Egerton, S., Culloty, S., Whooley, J., Stanton, C., Ross, R.P., 2018. The gut microbiota of marine fish. Front. Microbiol. 9, 873.

Elisio, M., Chalde, T., Miranda, L.A., 2012. Effects of short periods of warm water fluctuations on reproductive endocrine axis of the pejerrey (*Odontesthes bonariensis*) spawning. Comp. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 163, 47–55.

Ellis, T., James, J.D., Stewart, C., Scott, A.P., 2004. A non-invasive stress assay based upon measurement of free cortisol released into the water by rainbow trout. J. Fish Biol. 65, 1233–1252.

Ellis, T., James, J.D., Scott, A.P., 2005. Branchial release of free cortisol and melatonin by rainbow trout. J. Fish Biol. 67, 535–540.

Ellis, T., James, J.D., Sundh, H., Fridell, F., Sundell, K., Scott, A.P., 2007. Non-invasive measurement of cortisol and melatonin in tanks stocked with seawater Atlantic salmon. Aquaculture 272, 698–706.

Ellis, T., Sanders, M.B., Scott, A.P., 2013. Non-invasive monitoring of steroids in fishes. Wien. Tierarztl. Monatsschr. 100, 255–269.

Ervin, S.M., Li, H., Lim, L., Roberts, L.R., Liang, X., Mani, S., Redinbo, M.R., 2019. Gut microbial β-glucuronidases reactivate estrogens as components of the estrobolome that reactivate estrogens. J. Biol. Chem. 294, 18586–18599.

Ervin, S.M., Simpson, J.B., Gibbs, M.E., Creekmore, B.C., Lim, L., Walton, W.G., Gharaibeh, R.Z., Redinbo, M.R., 2020. Structural insights into endobiotic reactivation by human gut microbiome-encoded sulfatases. Biochemistry 59, 3939–3950.

Fabbri, E., Capuzzo, A., Moon, T.W., 1998. The role of circulating catecholamines in the regulation of fish metabolism: an overview. Comp. Biochem. Physiol. C Pharmacol. Toxicol. Endocrinol. 120, 177–192.

Fabbri, E., Moon, T.W., 2016. Adrenergic signaling in teleost fish liver, a challenging path. Comp. Biochem. Physiol. B Biochem. Mol. Biol. 199, 74–86.

Fairchild, W.L., Swansburg, E.O., Arsenault, J.T., Brown, S.B., 1999. Does an association between pesticide use and subsequent declines in catch of Atlantic salmon (*Salmo salar*) represent a case of endocrine disruption? Environ. Health Perspect. 107, 349–357.

Fanouraki, E., Papandroulakis, N., Ellis, T., Mylonas, C.C., Scott, A.P., Pavlidis, M., 2008. Water cortisol is a reliable indicator of stress in European sea bass, *Dicentrarchus labrax*. Behaviour 145, 1267–1281.

Faria, A.M., Lopes, A.F., Silva, C.S.E., Novais, S.C., Lemos, M.F.L., Gonçalves, E.J., 2018. Reproductive trade-offs in a temperate reef fish under high pCO2 levels. Mar. Environ. Res. 137, 8–15.

Farwell, M., Hughes, G., Smith, J.L., Clelland, E., Loeb, S.J., Semeniuk, C., Scott, A.P., Li, W., Zielinski, B., 2017. Differential female preference for individual components of a reproductive male round goby (*Neogobius melanostomus*) pheromone. J. Great Lakes Res. 43, 379–386.

Faught, E., Aluru, N., Vijayan, M.M., 2016. The molecular stress response. In: Schreck, C.B., Tort, L., Farrell P., A, Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 113–166.

Ferretti, F., Worm, B., Britten, G.L., Heithaus, M.R., Lotze, H.K., 2010. Patterns and ecosystem consequences of shark declines in the ocean. Ecol. Lett. 13, 1055–1071.

Ferriss, B.E., Trudel, M., Beckman, B.R., 2014. Regional and inter-annual trends in marine growth of juvenile salmon in coastal pelagic ecosystems of British Columbia, Canada. Mar. Ecol. Prog. Ser. 503, 247–261.

Filby, A.L., Thorpe, K.L., Maack, G., Tyler, C.R., 2007. Gene expression profiles revealing the mechanisms of anti-androgen- and estrogen-induced feminization in fish. Aquat. Toxicol. 81, 219–231.

Fine, J.M., Sorensen, P.W., 2008. Isolation and biological activity of the multi-component sea lamprey migratory pheromone. J. Chem. Ecol. 34, 1259–1267.

Fissette, S.D., Buchinger, T.J., Wagner, C.M., Johnson, N.S., Scott, A.M., Li, W., 2021. Progress towards integrating an understanding of chemical ecology into sea lamprey control. J. Great Lakes Res. 47, S660–S672.

Flagg, T.A., Nash, C.E., 1999. A Conceptual Framework for Conservation Hatchery Strategies for Pacific Salmonids. NOAA Technical Memorandum.

Flagg, T.A., Berejikian, B.A., Colt, J.E., Dickhoff, W.W., Harrell, L.W., Maynard, D.J., Nash, C.E., Strom, M.S., Iwamoto, R.N., Mahnken, C.V.W., 2000. Ecological and Behavioral Impacts of Artificial Production Strategies on the Abundance of Wild Salmon Populations: A Review of Practices in the Pacific Northwest. NOAA Technical Memorandum.

Flores-Valverde, A.M., Horwood, J., Hill, E.M., 2010. Disruption of the steroid metabolome in fish caused by exposure to the environmental estrogen 17α-ethinylestradiol. Environ. Sci. Technol. 44, 3552–3558.

Forsgren, E., Dupont, S., Jutfelt, F., Amundsen, T., 2013. Elevated CO2 affects embryonic development and larval phototaxis in a temperate marine fish. Ecol. Evol. 3, 3637–3646.

Fredricks, K.T., Hubert, T.D., Amberg, J.J., Cupp, A.R., Dawson, V.K., 2021. Chemical controls for an integrated pest management program. North Am. J. Fish. Manag. 41, 289–300.

Friesen, C.N., Aubin-Horth, N., Chapman, L.J., 2012a. The effect of hypoxia on sex hormones in an African cichlid *Pseudocrenilabrus multicolor victoriae*. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 162, 22–30.

Friesen, C.N., Chapman, L.J., Aubin-Horth, N., 2012b. Holding water steroid hormones in the African cichlid fish *Pseudocrenilabrus multicolor victoriae*. Gen. Comp. Endocrinol. 179, 400–405.

Frisk, M.G., Miller, T.J., Fogarty, M.J., 2001. Estimation and analysis of biological parameters in elasmobranch fishes: a comparative life history study. Can. J. Fish. Aquat. Sci. 58, 969–981.

Froehlich, H.E., Gentry, R.R., Halpern, B.S., 2017. Conservation aquaculture: shifting the narrative and paradigm of aquaculture's role in resource management. Biol. Conserv. 215, 162–168.

Frommel, A.Y., Stiebens, V., Clemmesen, C., Havenhand, J., 2010. Effect of ocean acidification on marine fish sperm (Baltic cod: *Gadus morhua*). Biogeosciences 7, 3915–3919.

Fuentes, E.N., Valdés, J.A., Molina, A., Björnsson, B.T., 2013. Regulation of skeletal muscle growth in fish by the growth hormone—insulin-like growth factor system. Gen. Comp. Endocrinol. 192, 136–148.

Fujimoto, Y., Yambe, H., Takahashi, K., Sato, S., 2020. Bile from reproductively mature male largemouth bass micropterus salmoides attracts conspecific females and offers a practical application to control populations. Manag. Biol. Invasions 11, 415–427.

Fuzzen, M.L.M., Bernier, N.J., Van Der Kraak, G., 2011. Stress and reproduction. In: Norris, D.O., Lopez, K.H. (Eds.), Hormones and Reproduction of Vertebrates. Academic Press, Burlington, pp. 103–117.

Fuzzen, M.L.M., Bennett, C.J., Tetreault, G.R., McMaster, M.E., Servos, M.R., 2015. Severe intersex is predictive of poor fertilization success in populations of rainbow darter (*Etheostoma caeruleum*). Aquat. Toxicol. 160, 106–116.

Galligan, T.M., Schwacke, L.H., Houser, D.S., Wells, R.S., Rowles, T., Boggs, A.S.P., 2018. Characterization of circulating steroid hormone profiles in the bottlenose dolphin (*Tursiops truncatus*) by liquid chromatography–tandem mass spectrometry (LC–MS/MS). Gen. Comp. Endocrinol. 263, 80–91.

Galligan, T.M., Boggs, A.S.P., Balmer, B.C., Rowles, T., Smith, C.R., Townsend, F., Wells, R.S., Kellar, N.M., Zolman, E.S., Schwacke, L.H., 2020. Blubber steroid hormone profiles as indicators of physiological state in free-ranging common bottlenose dolphins (*Tursiops truncatus*). Comp. Biochem. Physiol. A Mol. Integr. Physiol. 239, 110583.

Gammon, D.B., Li, W., Scott, A.P., Zielinski, B.S., Corkum, L.D., 2005. Behavioural responses of female *Neogobius melanostomus* to odours of conspecifics. J. Fish Biol. 67, 615–626.

Gamperl, A.K., Vijayan, M.M., Boutilier, R.G., 1994. Experimental control of stress hormone levels in fishes: techniques and applications. Rev. Fish Biol. Fish. 4, 215–255.

Gamperl, A.K., Gillis, T.E., Farrell, A.P., Brauner, C.J., 2017. Fish Physiology. The Cardiovascular System: Morphology, Control and Function, vol. 36A. Academic Press, London.

García-López, Á., Pascual, E., Sarasquete, C., Martínez-Rodríguez, G., 2006. Disruption of gonadal maturation in cultured Senegalese sole *Solea senegalensis* Kaup by continuous light and/or constant temperature regimes. Aquaculture 261, 789–798.

Garner, S.R., Madison, B.N., Bernier, N.J., Neff, B.D., 2011. Behavioural interactions and hormones in naturally and hatchery-spawned chinook salmon. Ethology 117, 37–48.

Geffroy, B., Wedekind, C., 2020. Effects of global warming on sex ratios in fishes. J. Fish Biol. 97, 596–606.

Geven, E.J.W., Nguyen, N.K., Van Den Boogaart, M., Spanings, F.A.T., Flik, G., Klaren, P.H.M., 2007. Comparative thyroidology: thyroid gland location and iodothyronine dynamics in Mozambique tilapia (*Oreochromis mossambicus* Peters) and common carp (*Cyprinus carpio* L.). J. Exp. Biol. 210, 4005–4015.

Ghosal, R., Eichmiller, J.J., Witthuhn, B.A., Sorensen, P.W., 2018. Attracting common carp to a bait site with food reveals strong positive relationships between fish density, feeding activity, environmental DNA, and sex pheromone release that could be used in invasive fish management. Ecol. Evol. 8, 6714–6727.

Gibbons, W.N., Munkittrick, K.R., McMaster, M.E., Taylor, W.D., 1998. Monitoring aquatic environments receiving industrial effluents using small fish species 2: comparison between responses of trout-perch (*Percopsis omiscomaycus*) and white sucker (*Catostomus commersoni*) downstream of a pulp mill. Environ. Toxicol. Chem. 17, 2238–2245.

Goikoetxea, A., Sadoul, B., Blondeau-Bidet, E., Aerts, J., Blanc, M.O., Parrinello, H., Barrachina, C., Pratlong, M., Geffroy, B., 2021. Genetic pathways underpinning hormonal stress responses in fish exposed to short- and long-term warm ocean temperatures. Ecol. Indic. 120, 106937.

Goksøyr, A., 2006. Endocrine disruptors in the marine environment: mechanisms of toxicity and their influence on reproductive processes in fish. J. Toxicol. Environ. Health, Part A 69, 175–184.

Gorissen, M., Flik, G., 2016. The endocrinology of the stress response in fish: an adaptation-physiological view. In: Schreck, C.B., Tort, L., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 75–111.

Gormally, B.M.G., Romero, L.M., 2020. What are you actually measuring? A review of techniques that integrate the stress response on distinct time-scales. Funct. Ecol. 34, 2030–2044.

Graham, M.A., Earley, R.L., Baker, J.A., Foster, S.A., 2018. Evolution of steroid hormones in reproductive females of the threespine stickleback fish. Gen. Comp. Endocrinol. 268, 71–79.

Graham, K.M., Burgess, E.A., Rolland, R.M., 2021. Stress and reproductive events detected in North Atlantic right whale blubber using a simplified hormone extraction protocol. Conserv. Physiol. 9, coaa133.

Gräns, J., Wassmur, B., Celander, M.C., 2010. One-way inhibiting cross-talk between arylhydrocarbon receptor (AhR) and estrogen receptor (ER) signaling in primary cultures of rainbow trout hepatocytes. Aquat. Toxicol. 100, 263–270.

Greytak, S.R., Champlin, D., Callard, G.V., 2005. Isolation and characterization of two cytochrome P450 aromatase forms in killifish (*Fundulus heteroclitus*): differential expression in fish from polluted and unpolluted environments. Aquat. Toxicol. 71, 371–389.

Grosell, M., Farrell, A.P., Brauner, C.J., 2010. In: Fish Physiology: The Multifunctional Gut of Fish, vol. 30. Academic Press, London.

Guardiola, F.A., Cuesta, A., Esteban, M.Á., 2016. Using skin mucus to evaluate stress in gilthead seabream (*Sparus aurata* L.). Fish Shellfish Immunol. 59, 323–330.

Hack, N.L., Cordova, K.L., Glaser, F.L., Journey, M.L., Resner, E.J., Hardy, K.M., Beckman, B.R., Lema, S.C., 2019. Interactions of long-term food ration variation and

short-term fasting on insulin-like growth factor-1 (IGF-1) pathways in copper rockfish (*Sebastes caurinus*). Gen. Comp. Endocrinol. 280, 168–184.

Hanke, I., Ampe, B., Kunzmann, A., Gärdes, A., Aerts, J., 2019. Thermal stress response of juvenile milkfish (*Chanos chanos*) quantified by ontogenetic and regenerated scale cortisol. Aquaculture 500, 24–30.

Hara, T.J., 2011. Neurophysiology of olfaction. In: Farrell, A.P. (Ed.), Encyclopedia of Fish Physiology: From Genome to Environment. Elsevier Science & Technology, San Diego, pp. 208–217.

Harbicht, A.B., Fraser, D.J., Ardren, W.R., 2020. Minor shifts towards more natural conditions in captivity improve long-term survival among reintroduced Atlantic salmon. Can. J. Fish. Aquat. Sci. 77, 931–942.

Harris, C.A., Hamilton, P.B., Runnalls, T.J., Vinciotti, V., Henshaw, A., Hodgson, D., Coe, T.S., Jobling, S., Tyler, C.R., Sumpter, J.P., 2011. The consequences of feminization in breeding groups of wild fish. Environ. Health Perspect. 119, 306.

Harstad, D.L., Larsen, D.A., Miller, J., Adams, I., Spangenberg, D.K., Nance, S., Rohrbach, L., Murauskas, J.G., Beckman, B.R., 2018. Winter-rearing temperature affects growth profiles, age of maturation, and smolt-to-adult returns for yearling summer Chinook salmon in the upper Columbia River basin. North Am. J. Fish. Manag. 38, 867–885.

Harter, T.S., Brauner, C.J., 2017. The O_2 and CO_2 transport system in teleosts and the specialized mechanisms that enhance Hb–O_2 unloading to tissues. In: Gamperl, A.K., Gillis, T.E., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology, The Cardiovascular System: Development, Plasticity and Physiological Responses, vol. 36B. Academic Press, London, pp. 1–106.

Hasegawa, Y., Surugaya, R., Adachi, S., Ijiri, S., 2022. Regulation of 17α-hydroxyprogesterone production during induced oocyte maturation and ovulation in amur sturgeon (*Acipenser schrenckii*). J. Mar. Sci. Eng. 10, 86.

Hayashi, Y., Kobira, H., Yamaguchi, T., Shiraishi, E., Yazawa, T., Hirai, T., Kamei, Y., Kitano, T., 2010. High temperature causes masculinization of genetically female medaka by elevation of cortisol. Mol. Reprod. Dev. 77, 679–686.

Heath, D.D., Bernier, N.J., Heath, J.W., Iwama, G.K., 1993. Genetic, environmental, and interaction effects on growth and stress response of chinook salmon (*Oncorhynchus tshawytscha*) fry. Can. J. Fish. Aquat. Sci. 50, 435–442.

Hecker, M., Hollert, H., 2011. Endocrine disruptor screening: regulatory perspectives and needs. Environ. Sci. Eur. 23, 1–14.

Heimbürge, S., Kanitz, E., Otten, W., 2019. The use of hair cortisol for the assessment of stress in animals. Gen. Comp. Endocrinol. 270, 10–17.

Herranz-Jusdado, J.G., Rozenfeld, C., Morini, M., Pérez, L., Asturiano, J.F., Gallego, V., 2019. Recombinant vs purified mammal gonadotropins as maturation hormonal treatments of European eel males. Aquaculture 501, 527–536.

Hewitt, L.M., Parrott, J.L., McMaster, M.E., 2007. A decade of research on the environmental impacts of pulp and paper mill effluents in Canada: sources and characteristics of bioactive substances. J. Toxicol. J. Toxicol. Environ. Health B Crit. Rev. 9, 341–356.

Hirschenhauser, K., Canário, A.V.M., Ros, A.F.H., Taborsky, M., Oliveira, R.F., 2008. Social context may affect urinary excretion of 11-ketotestosterone in African cichlids. Behaviour 145, 1367–1388.

Höglund, E., Weltzien, F.A., Schjolden, J., Winberg, S., Ursin, H., Døving, K.B., 2005. Avoidance behavior and brain monoamines in fish. Brain Res. 1032, 104–110.

Holzer, G., Laudet, V., 2015. Thyroid hormones: a triple-edged sword for life history transitions. Curr. Biol. 25, R344–R347.

Holzer, G., Besson, M., Lambert, A., François, L., Barth, P., Gillet, B., Hughes, S., Piganeau, G., Leulier, F., Viriot, L., Lecchini, D., Laudet, V., 2017. Fish larval recruitment to reefs is a thyroid hormone-mediated metamorphosis sensitive to the pesticide chlorpyrifos. eLife 6, 1–22.

Honeycutt, J.L., Deck, C.A., Miller, S.C., Severance, M.E., Atkins, E.B., Luckenbach, J.A., Buckel, J.A., Daniels, H.V., Rice, J.A., Borski, R.J., Godwin, J., 2019. Warmer waters masculinize wild populations of a fish with temperature-dependent sex determination. Sci. Rep. 9, 6527.

Hook, S.E., 2010. Promise and progress in environmental genomics: a status report on the applications of gene expression-based microarray studies in ecologically relevant fish species. J. Fish Biol. 77, 1999–2022.

Hook, S.E., Gallagher, E.P., Batleyy, G.E., 2014. The role of biomarkers in the assessment of aquatic ecosystem health. Integr. Environ. Assess. Manag. 10, 327–341.

Houston, A.H., 1990. Blood and circulation. In: Schreck, C.B., Moyle, P.B. (Eds.), Methods for Fish Biology. American Fisheries Society, Bethesda, pp. 273–334.

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., Billen, G., 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Front. Ecol. Environ. 9, 18–26.

Hu, C.K., Southey, B.R., Romanova, E.V., Maruska, K.P., Sweedler, J.V., Fernald, R.D., 2016. Identification of prohormones and pituitary neuropeptides in the African cichlid, *Astatotilapia burtoni*. BMC Genomics 17, 660.

Hughes, T.P., Rodrigues, M.J., Belwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L., Moltschaniwskyj, N., Pratchett, M.S., Steneck, R.S., Wills, B., 2007. Phase shifts, herbivory, and the resilience of coral reefs to climate change. Curr. Biol. 17, 360–365.

Huntingford, F.A., 2004. Implications of domestication and rearing conditions for the behaviour of cultivated fishes. J. Fish Biol. 65, 122–142.

Inaba, K., Dréanno, C., Cosson, J., 2003. Control of flatfish sperm motility by CO_2 and carbonic anhydrase. Cell Motil. Cytoskeleton 55, 174–187.

Ings, J.S., George, N., Peter, M.C.S., Servos, M.R., Vijayan, M.M., 2012. Venlafaxine and atenolol disrupt epinephrine-stimulated glucose production in rainbow trout hepatocytes. Aquat. Toxicol. 106–107, 48–55.

Ivy, C.M., Robertson, C.E., Bernier, N.J., 2017. Acute embryonic anoxia exposure favours the development of a dominant and aggressive phenotype in adult zebrafish. Proc. R. Soc. B Biol. Sci. 284, 20161868.

Jacoby, D.M.P., Casselman, J.M., Crook, V., DeLucia, M.B., Ahn, H., Kaifu, K., Kurwie, T., Sasal, P., Silfvergrip, A.M.C., Smith, K.G., Uchida, K., Walker, A.M., Gollock, M.J., 2015. Synergistic patterns of threat and the challenges facing global anguillid eel conservation. Glob. Ecol. Conserv. 4, 321–333.

Janz, D.M., McMaster, M.E., Munkittrick, K.R., Van Der Kraak, G., 1997. Elevated ovarian follicular apoptosis and heat shock protein-70 expression in white sucker exposed to bleached kraft pulp mill effluent. Toxicol. Appl. Pharmacol. 147, 391–398.

Jarque, S., Piña, B., 2014. Deiodinases and thyroid metabolism disruption in teleost fish. Environ. Res. 135, 361–375.

Jeffrey, J.D., Bernier, N.J., Anderson, W.G., 2022. Endocrinology. In: Midway, S., Hasler, C., Chakrabarty, P. (Eds.), Methods in Fish Biology. American Fisheries Society, Bethesda.

Jenny, J.P., Francus, P., Normandeau, A., Lapointe, F., Perga, M.E., Ojala, A., Schimmelmann, A., Zolitschka, B., 2016. Global spread of hypoxia in freshwater ecosystems during the last three centuries is caused by rising local human pressure. Glob. Chang. Biol. 22, 1481–1489.

Jobling, S., Beresford, N., Nolan, M., Rodgers-Gray, T., Brighty, G.C., Sumpter, J.P., Tyler, C.R., 2002a. Altered sexual maturation and gamete production in wild roach (*Rutilus rutilus*) living in rivers that receive treated sewage effluents. Biol. Reprod. 66, 272–281.

Jobling, S., Coey, S., Whitmore, J.G.G., Kime, D.E.E., Van Look, K.J.W.J.W., McAllister, B.G.G., Beresford, N., Henshaw, A.C.C., Brighty, G., Tyler, C.R.R., Sumpter, J.P.P., 2002b. Wild intersex roach (*Rutilus rutilus*) have reduced fertility. Biol. Reprod. 67, 515–524.

Johnson, N.S., Siefkes, M.J., Wagner, C.M., Dawson, H., Wang, H., Steeves, T., Twohey, M., Li, W., 2013. A synthesized mating pheromone component increases adult sea lamprey (*Petromyzon marinus*) trap capture in management scenarios. Can. J. Fish. Aquat. Sci. 70, 1101–1108.

Johnson, N.S., Tix, J.A., Hlina, B.L., Wagner, C.M., Siefkes, M.J., Wang, H., Li, W., 2015. A sea lamprey (*Petromyzon marinus*) sex pheromone mixture increases trap catch relative to a single synthesized component in specific environments. J. Chem. Ecol. 41, 311–321.

Johnson, N.S., Lewandoski, S.A., Alger, B.J., O'Connor, L., Bravener, G., Hrodey, P., Huerta, B., Barber, J., Li, W., Wagner, C.M., Siefkes, M.J., 2020. Behavioral responses of sea lamprey to varying application rates of a synthesized pheromone in diverse trapping scenarios. J. Chem. Ecol. 46, 233–249.

Journey, M.L., Trudel, M., Young, G., Beckman, B.R., 2018. Evidence for depressed growth of juvenile Pacific salmon (*Oncorhynchus*) in Johnstone and Queen Charlotte Straits, British Columbia. Fish. Oceanogr. 27, 174–183.

Kaabia, Z., Laparre, J., Cesbron, N., Le Bizec, B., Dervilly-Pinel, G., 2018. Comprehensive steroid profiling by liquid chromatography coupled to high resolution mass spectrometry. J. Steroid Biochem. Mol. Biol. 183, 106–115.

Kajimura, S., Duan, C., 2007. Insulin-like growth factor-binding protein-1: an evolutionarily conserved fine tuner of insulin-like growth factor action under catabolic and stressful conditions. J. Fish Biol. 71, 309–325.

Kamei, H., 2020. Oxygen and embryonic growth: the role of insulin-like growth factor signaling. Gen. Comp. Endocrinol. 294, 113473.

Kaneko, N., Taniyama, N., Inatani, Y., Nagano, Y., Fujiwara, M., Torao, M., Miyakoshi, Y., Shimizu, M., 2015. Circulating insulin-like growth factor I in juvenile chum salmon: relationship with growth rate and changes during downstream and coastal migration in northeastern Hokkaido, Japan. Fish Physiol. Biochem. 41, 991–1003.

Kamio, M., Yambe, H., Fusetani, N., 2022. Chemical cues for intraspecific chemical communication and interspecific interactions in aquatic environments: applications for fisheries and aquaculture. Fish. Sci. 88, 203–239.

Kaneko, N., Journey, M.L., Neville, C.M., Trudel, M., Beckman, B.R., Shimizu, M., 2019a. Utilization of an endocrine growth index, insulin-like growth factor binding protein (IGFBP)-1b, for postsmolt coho salmon in the Strait of Georgia, British Columbia, Canada. Fish Physiol. Biochem. 45, 1867–1878.

Kaneko, N., Torao, M., Koshino, Y., Fujiwara, M., Miyakoshi, Y., Shimizu, M., 2019b. Evaluation of growth status using endocrine growth indices, insulin-like growth factor (IGF)-I and IGF-binding protein-1b, in out-migrating juvenile chum salmon. Gen. Comp. Endocrinol. 274, 50–59.

Karels, A., Markkula, E., Oikari, A., 2001. Reproductive, biochemical, physiological, and population responses in perch (*Perca fluviatilis* L.) and roach (*Rutilus rutilus* L.) downstream of two elemental chlorine-free pulp and paper mills. Environ. Toxicol. Chem. 20, 1517–1527.

Keller-Costa, T., Hubbard, P.C., Paetz, C., Nakamura, Y., Da Silva, J.P., Rato, A., Barata, E.N., Schneider, B., Canario, A.V.M., 2014. Identity of a tilapia pheromone released by dominant males that primes females for reproduction. Curr. Biol. 24, 2130–2135.

Kelley, K.M., Schmidt, K.E., Berg, L., Sak, K., Galima, M.M., Gillespie, C., Balogh, L., Hawayek, A., Reyes, J.A., Jamison, M., 2002. Comparative endocrinology of the insulin-like growth factor-binding protein. J. Endocrinol. 175, 3–18.

Kennedy, C.J., Smyth, K.R., 2015. Disruption of the rainbow trout reproductive endocrine axis by the polycyclic aromatic hydrocarbon benzo[a]pyrene. Gen. Comp. Endocrinol. 219, 102–111.

Khansari, A.R., Balasch, J.C., Vallejos-Vidal, E., Parra, D., Reyes-López, F.E., Tort, L., 2018. Comparative immune- and stress-related transcript response induced by air exposure and *Vibrio anguillarum* bacterin in rainbow trout (*Oncorhynchus mykiss*) and gilthead seabream (*Sparus aurata*) mucosal surfaces. Front. Immunol. 9.

Kidd, K.A., Blanchfield, P.J., Mills, K.H., Palace, V.P., Evans, R.E., Lazorchak, J.M., Flick, R.W., 2007. Collapse of a fish population after exposure to a synthetic estrogen. Proc. Natl. Acad. Sci. U. S. A. 104, 8897–8901.

Kidd, C.E., Kidd, M.R., Hofmann, H.A., 2010. Measuring multiple hormones from a single water sample using enzyme immunoassays. Gen. Comp. Endocrinol. 165, 277–285.

Kidd, K.A., Paterson, M.J., Rennie, M.D., Podemski, C.L., Findlay, D.L., Blanchfield, P.J., Liber, K., 2014. Direct and indirect responses of a freshwater food web to a potent synthetic oestrogen. Philos. Trans. R. Soc. B Biol. Sci. 369, 20130578.

Kim, S.G.W., Hong, W.H., Han, S.J., Kwon, J., Ko, H., Lee, S.B., Giri, S.S., Kim, S.G.W., Kim, B.Y., Jang, G., Lee, B.C., Kim, D.W., Park, S.C., 2020. Use of synthetic salmon GnRH and domperidone (Ovaprim®) in sharks: preparation for *ex situ* conservation. Front. Mar. Sci. 7, 998.

Kim, S.S., Kan, H., Hwang, K.S., Yang, J.Y., Son, Y., Shin, D.S., Lee, B.H., Ahn, S.H., Ahn, J.H., Cho, S.H., Bae, M.A., 2021. Neurochemical effects of 4-(2chloro-4-fluorobenzyl)-3-(2-thienyl)-1,2,4-oxadiazol-5(4H)-one in the pentylenetetrazole (ptz)-induced epileptic seizure zebrafish model. Int. J. Mol. Sci. 22, 1–15.

King, H.R., Pankhurst, N.W., Watts, M., 2007. Reproductive sensitivity to elevated water temperatures in female Atlantic salmon is heightened at certain stages of vitellogenesis. J. Fish Biol. 70, 190–205.

Kohl, K.D., Yahn, J., 2016. Effects of environmental temperature on the gut microbial communities of tadpoles. Environ. Microbiol. 18, 1561–1565.

Kottmann, J.S., Jørgensen, M.G.P., Bertolini, F., Loh, A., Tomkiewicz, J., 2020. Differential impacts of carp and salmon pituitary extracts on induced oogenesis, egg quality, molecular ontogeny and embryonic developmental competence in European eel. PLoS One 15, e0235617.

Kroska, A.C., Wolf, N., Planas, J.V., Baker, M.R., Smeltz, T.S., Harris, B.P., 2021. Controlled experiments to explore the use of a multi-tissue approach to characterizing stress in wild-caught Pacific halibut (*Hippoglossus stenolepis*). Conserv. Physiol 9, coab001.

Kumar, V., Govindhaswamy, U., 2019. Non-invasive monitoring of steroid hormones in wildlife for conservation and management of endangered species-a review non-invasive reproductive steroid monitoring in Indian wild animals. Indian J. Exp. Biol. 57, 307–314.

La Merrill, M.A., Vandenberg, L.N., Smith, M.T., Goodson, W., Browne, P., Patisaul, H.B., Guyton, K.Z., Kortenkamp, A., Cogliano, V.J., Woodruff, T.J., Rieswijk, L., Sone, H., Korach, K.S., Gore, A.C., Zeise, L., Zoeller, R.T., 2020. Consensus on the key characteristics of endocrine-disrupting chemicals as a basis for hazard identification. Nat. Rev. Endocrinol. 16, 45–57.

Labadie, P., Budzinski, H., 2006a. Alteration of steroid hormone balance in juvenile turbot (*Psetta maxima*) exposed to nonylphenol, bisphenol A, tetrabromodiphenyl ether 47, diallylphthalate, oil, and oil spiked with alkylphenols. Arch. Environ. Contam. Toxicol. 50, 552–561.

Labadie, P., Budzinski, H., 2006b. Alteration of steroid hormone profile in juvenile turbot (*Psetta maxima*) as a consequence of short-term exposure to 17α-ethynylestradiol. Chemosphere 64, 1274–1286.

Laberge, F., Hara, T.J., 2001. Neurobiology of fish olfaction: a review. Brain Res. Rev. 36, 46–59.

Laberge, F., Yin-Liao, I., Bernier, N.J., 2019. Temporal profiles of cortisol accumulation and clearance support scale cortisol content as an indicator of chronic stress in fish. Conserv. Physiol. 7, coz052.

Lai, K.P., Li, J.W., Tse, A.C.K., Chan, T.F., Wu, R.S.S., 2016. Hypoxia alters steroidogenesis in female marine medaka through miRNAs regulation. Aquat. Toxicol. 172, 1–8.

Lai, K.P., Li, J.W., Wang, S.Y., Wan, M.T., Chan, T.F., Lui, W.Y., Au, D.W.T., Wu, R.S.S., Kong, R.Y.C., 2018. Transcriptomic analysis reveals transgenerational effect of hypoxia on the neural control of testicular functions. Aquat. Toxicol. 195, 41–48.

Lai, K.P., Wang, S.Y., Li, J.W., Tong, Y., Chan, T.F., Jin, N., Tse, A., Zhang, J.W., Wan, M.T., Tam, N., Au, D.W.T., Lee, B.Y., Lee, J.S., Wong, A.S.T., Kong, R.Y.C., Wu, R.S.S., 2019. Hypoxia causes transgenerational impairment of ovarian development and hatching success in fish. Environ. Sci. Technol. 53, 3917–3928.

Landry, C.A., Steele, S.L., Manning, S., Cheek, A.O., 2007. Long term hypoxia suppresses reproductive capacity in the estuarine fish, *Fundulus grandis*. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 148, 317–323.

Larsen, D.A., Beckman, B.R., Strom, C.R., Parkins, P.J., Cooper, K.A., Fast, D.E., Dickhoff, W.W., 2006. Growth modulation alters the incidence of early male maturation and physiological development of hatchery-reared spring chinook salmon: a comparison with wild fish. Trans. Am. Fish. Soc. 135, 1017–1032.

Larsson, D.G.J., Hällman, H., Förlin, L., 2000. More male fish embryos near a pulp mill. Environ. Toxicol. Chem. 19, 2911–2917.

Larsson, D.G.J., Adolfsson-Erici, M., Thomas, P., 2006. Characterization of putative ligands for a fish gonadal androgen receptor in a pulp mill effluent. Environ. Toxicol. Chem. 25, 419–427.

Lawrence, M.J., Raby, G.D., Teffer, A.K., Jeffries, K.M., Danylchuk, A.J., Eliason, E.J., Hasler, C.T., Clark, T.D., Cooke, S.J., 2020. Best practices for non-lethal blood sampling of fish via the caudal vasculature. J. Fish Biol. 97, 4–15.

Le Page, Y., Vosges, M., Servili, A., Brion, F., Kah, O., 2011. Neuroendocrine effects of endocrine disruptors in teleost fish. J. Toxicol. Environ. Health B Crit. Rev. 14, 370–386.

Lee, S., Hong, S., Liu, X., Kim, C., Jung, D., Yim, U.H., Shim, W.J., Khim, J.S., Giesy, J.P., Choi, K., 2017. Endocrine disrupting potential of PAHs and their alkylated analogues associated with oil spills. Environ Sci Process Impacts 19, 1117–1125.

Legacki, E.L., Robeck, T.R., Steinman, K.J., Conley, A.J., 2020. Comparative analysis of steroids in cyclic and pregnant killer whales, beluga whales and bottlenose dolphins by liquid chromatography tandem mass spectrometry. Gen. Comp. Endocrinol. 285, 113273.

Leong, H., Ros, A.F.H., Oliveira, R.F., 2009. Effects of putative stressors in public aquaria on locomotor activity, metabolic rate and cortisol levels in the Mozambique tilapia *Oreochromis mossambicus*. J. Fish Biol. 74, 1549–1561.

Lepage, O., Øverli, Ø., Petersson, E., Järvi, T., Winberg, S., 2000. Differential stress coping in wild and domesticated sea trout. Brain Behav. Evol. 56, 259–268.

Lerner, D.T., Björnsson, B.T., McCormick, S.D., 2007. Effects of aqueous exposure to polychlorinated biphenyls (Aroclor 1254) on physiology and behavior of smolt development of Atlantic salmon. Aquat. Toxicol. 81, 329–336.

Lerner, D.T., Sheridan, M.A., McCormick, S.D., 2012. Estrogenic compounds decrease growth hormone receptor abundance and alter osmoregulation in Atlantic salmon. Gen. Comp. Endocrinol. 179, 196–204.

Leusch, F.D.L., MacLatchy, D.L., 2003. In vivo implants of β-sitosterol cause reductions of reactive cholesterol pools in mitochondria isolated from gonads of male goldfish (*Carassius auratus*). Gen. Comp. Endocrinol. 134, 255–263.

Li, K., Scott, A.M., Riedy, J.J., Fissette, S., Middleton, Z.E., Li, W., 2017. Three novel bile alcohols of mature male sea lamprey (*Petromyzon marinus*) act as chemical cues for conspecifics. J. Chem. Ecol. 43, 543–549.

Li, K., Brant, C.O., Huertas, M., Hessler, E.J., Mezei, G., Scott, A.M., Hoye, T.R., Li, W., 2018. Fatty-acid derivative acts as a sea lamprey migratory pheromone. Proc. Natl. Acad. Sci. U. S. A. 115, 8603–8608.

Lim, H., Sorensen, P.W., 2011. Polar metabolites synergize the activity of prostaglandin F2α in a species-specific hormonal sex pheromone released by ovulated common carp. J. Chem. Ecol. 37, 695–704.

Lim, H., Sorensen, P.W., 2012. Common carp implanted with prostaglandin F2α release a sex pheromone complex that attracts conspecific males in both the laboratory and field. J. Chem. Ecol. 38, 127–134.

Lindholm-Lehto, P.C., Knuutinen, J.S., Ahkola, H.S.J., Herve, S.H., 2015. Refractory organic pollutants and toxicity in pulp and paper mill wastewaters. Environ. Sci. Pollut. Res. 22, 6473–6499.

Little, A.G., Seebacher, F., 2014. The evolution of endothermy is explained by thyroid hormone-mediated responses to cold in early vertebrates. J. Exp. Biol. 217, 1642–1648.

Liu, X., Jung, D., Zhou, K., Lee, S., Noh, K., Khim, J.S., Giesy, J.P., Yim, U.H., Shim, W.J., Choi, K., 2018. Characterization of endocrine disruption potentials of coastal sediments of Taean, Korea employing H295R and MVLN assays–Reconnaissance at 5 years after Hebei Spirit oil spill. Mar. Pollut. Bull. 127, 264–272.

Lokman, P.M., Vermeulen, G.J., Lambert, J.G.D., Young, G., 1998. Gonad histology and plasma steroid profiles in wild New Zealand freshwater eels (*Anguilla dieffenbachii* and *A. australis*) before and at the onset of the natural spawning migration. I. Females. Fish Physiol. Biochem. 19, 325–338.

Lokman, P.M., Damsteegt, E.L., Wallace, J., Downes, M., Goodwin, S.L., Facoory, L.J., Wylie, M.J., 2016. Dose-responses of male silver eels, *Anguilla australis*, to human chorionic gonadotropin and 11-ketotestosterone *in vivo*. Aquaculture 463, 97–105.

Lower, N., Moore, A., 2007. The impact of a brominated flame retardant on smoltification and olfactory function in Atlantic salmon (*Salmo salar* L.) smolts. Mar. Freshw. Behav. Physiol. 40, 267–284.

Lu, X., Yu, R.M.K., Murphy, M.B., Lau, K., Wu, R.S.S., 2014. Hypoxia disrupts gene modulation along the brain-pituitary-gonad (BPG)-liver axis. Ecotoxicol. Environ. Saf. 102, 70–78.

Lupica, S.J., Turner, J.W., 2009. Validation of enzyme-linked immunosorbent assay for measurement of faecal cortisol in fish. Aquacult. Res. 40, 437–441.

MacDougall-Shackleton, S.A., Bonier, F., Romero, L.M., Moore, I.T., 2019. Glucocorticoids and "stress" are not synonymous. Integr. Org. Biol. 1, 1–8.

Madison, B.N., Heath, J.W., Heath, D.D., Bernier, N.J., 2015a. Effects of early rearing environment and breeding strategy on social interactions and the hormonal response to stressors in juvenile Chinook salmon. Can. J. Fish. Aquat. Sci. 72, 673–683.

Madison, B.N., Tavakoli, S., Kramer, S., Bernier, N.J., 2015b. Chronic cortisol and the regulation of food intake and the endocrine growth axis in rainbow trout. J. Endocrinol. 226, 103–119.

Madliger, C.L., Love, O.P., 2014. The need for a predictive, context-dependent approach to the application of stress hormones in conservation. Conserv. Biol. 28, 283–287.

Mahanty, A., Purohit, G.K., Mohanty, S., Mohanty, B.P., 2019. Heat stress–induced alterations in the expression of genes associated with gonadal integrity of the teleost *Puntius sophore*. Fish Physiol. Biochem. 45, 1409–1417.

Marcon, M., Mocelin, R., Benvenutti, R., Costa, T., Herrmann, A.P., De Oliveira, D.L., Koakoski, G., Barcellos, L.J.G., Piato, A., 2018. Environmental enrichment modulates the response to chronic stress in zebrafish. J. Exp. Biol. 221, jeb176735.

Martel, P.H., O'Connor, B.I., Kovacs, T.G., Van Den Heuvel, M.R., Parrott, J.L., McMaster, M.E., MacLatchy, D.L., Van Der Kraak, G.J., Hewitt, L.M., 2017. The relationship between organic loading and effects on fish reproduction for pulp mill effluents across Canada. Environ. Sci. Technol. 51, 3499–3507.

Martinović-Weigelt, D., Mehinto, A.C., Ankley, G.T., Denslow, N.D., Barber, L.B., Lee, K.E., King, R.J., Schoenfuss, H.L., Schroeder, A.L., Villeneuve, D.L., 2014. Transcriptomic effects-based monitoring for endocrine active chemicals: assessing relative contribution of treated wastewater to downstream pollution. Environ. Sci. Technol. 48, 2385–2394.

Martyniuk, C.J., Feswick, A., Munkittrick, K.R., Dreier, D.A., Denslow, N.D., 2020. Twenty years of transcriptomics, 17alpha-ethinylestradiol, and fish. Gen. Comp. Endocrinol. 286, 113325.

Matthews, J., Gustafsson, J.-Å., 2006. Estrogen receptor and aryl hydrocarbon receptor signaling pathways. Nucl. Recept. Signal. 4, nrs.04016.

Matthiessen, P., Wheeler, J.R., Weltje, L., 2018. A review of the evidence for endocrine disrupting effects of current-use chemicals on wildlife populations. Crit. Rev. Toxicol. 48, 195–216.

Maule, A.G., Schreck, C.B., Kaattari, S.L., 1987. Changes in the immune system of coho salmon (*Oncorhynchus kisutch*) during the parr-to-smolt transformation and after implantation of cortisol. Can. J. Fish. Aquat. Sci. 44, 161–166.

Mazur, C.F., Iwama, G.K., 1993. Effect of handling and stocking density on hematocrit, plasma cortisol, and survival in wild and hatchery-reared chinook salmon (*Oncorhynchus tshawytscha*). Aquaculture 112, 291–299.

Mazzeo, I., Peñaranda, D.S., Gallego, V., Baloche, S., Nourizadeh-Lillabadi, R., Tveiten, H., Dufour, S., Asturiano, J.F., Weltzien, F.A., Pérez, L., 2014. Temperature modulates the progression of vitellogenesis in the European eel. Aquaculture 434, 38–47.

McConnachie, S.H., Cook, K.V., Patterson, D.A., Gilmour, K.M., Hinch, S.G., Farrell, A.P., Cooke, S.J., 2012. Consequences of acute stress and cortisol manipulation on the physiology, behavior, and reproductive outcome of female Pacific salmon on spawning grounds. Horm. Behav. 62, 67–76.

McCormick, S.D., 2013. Smolt physiology and endocrinology. In: McCormick, S.D., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology: Euryhaline Fishes, vol. 32. Academic Press, London, pp. 199–251.

McCormick, M.I., Makey, L., Dufour, V., 2002. Comparative study of metamorphosis in tropical reef fishes. Mar. Biol. 141, 841–853.

McCormick, S.D., Regish, A., O'Dea, M.F., Shrimpton, J.M., 2008. Are we missing a mineralocorticoid in teleost fish? Effects of cortisol, deoxycorticosterone and aldosterone on osmoregulation, gill Na^+,K^+-ATPase activity and isoform mRNA levels in Atlantic salmon. Gen. Comp. Endocrinol. 157, 35–40.

McCormick, S.D., Lerner, D.T., Monette, M.Y., Nieves-Puigdoller, K., Kelly, J.T., Björnsson, B.T., 2009. Taking it with you when you go: how perturbations to the freshwater environment, including temperature, dams, and contaminants, affect marine survival of salmon. Am. Fish. Soc. Symp. 69, 195–214.

McCormick, S.D., Farrell, A.P., Brauner, C.J., 2012. Fish Physiology: Euryhaline Fishes, vol. 32. Academic Press, London.

McCormick, S.D., Romero, M., 2017. Conservation endocrinology. BioScience 67, 429–442.

McMaster, M.E., Van Der Kraak, G.J., Portt, C.B., Munkittrick, K.R., Sibley, P.K., Smith, I.R., Dixon, D.G., 1991. Changes in hepatic mixed-function oxygenase (MFO) activity, plasma steroid levels and age at maturity of a white sucker (*Catostomus commersoni*) population exposed to bleached kraft pulp mill effluent. Aquat. Toxicol. 21, 199–217.

McMaster, M.E., Hewitt, L.M., Parrott, J.L., 2006. A decade of research on the environmental impacts of pulp and paper mill effluents in Canada: field studies and mechanistic research. J. Toxicol. Environ. Health B Crit. Rev. 9, 319–339.

McMaster, M.E., Van Der Kraak, G.J., Munkittrick, K.R., 1995. Exposure to bleached kraft pulp mill effluent reduces the steroid biosynthetic capacity of white sucker ovarian follicles. Comp. Biochem. Physiol. 112, 169–178.

McMenamin, S.K., Parichy, D.M., 2013. Metamorphosis in teleosts. Curr. Top. Dev. Biol. 103, 127–165.

McPhie, R.P., Campana, S.E., 2009. Reproductive characteristics and population decline of four species of skate (*Rajidae*) off the eastern coast of Canada. J. Fish Biol. 75, 223–246.

Meckley, T.D., Wagner, C.M., Gurarie, E., 2014. Coastal movements of migrating sea lamprey (*Petromyzon marinus*) in response to a partial pheromone added to river water: implications for management of invasive populations. Can. J. Fish. Aquat. Sci. 71, 533–544.

Medeiros, L.R., Galbreath, P.F., Knudsen, C.M., Stockton, C.A., Koch, I.J., Bosch, W.J., Narum, S.R., Nagler, J.J., Pierce, A.L., 2018. Plasma 11-ketotestosterone in individual age-1 spring chinook salmon males accurately predicts age-2 maturation status. Trans. Am. Fish. Soc. 147, 1042–1051.

Mendoza Alfaro, R., González, C.A., Ferrara, A.M., 2008. Gar biology and culture: status and prospects. Aquacult. Res. 39, 748–763.

Mennigen, J.A., Stroud, P., Zamora, J.M., Moon, T.W., Trudeau, V.L., 2011. Pharmaceuticals as neuroendocrine disruptors: lessons learned from fish on prozac. J. Toxicol. Environ. Health B Crit. Rev. 14, 387–412.

Mes, D., von Krogh, K., Gorissen, M., Mayer, I., Vindas, M.A., 2018. Neurobiology of wild and hatchery-reared Atlantic salmon: how nurture drives neuroplasticity. Front. Behav. Neurosci. 12, 210.

Mes, D., Van Os, R., Gorissen, M., Ebbesson, L.O.E., Finstad, B., Mayer, I., Vindas, M.A., 2019. Effects of environmental enrichment on forebrain neural plasticity and survival success of stocked Atlantic salmon. J. Exp. Biol. 22, jeb212258.

Meyer, J.S., Novak, M.A., 2012. Minireview: hair cortisol: a novel biomarker of hypothalamic-pituitary- adrenocortical activity. Endocrinology 153, 4120–4127.

Middleton, M.A., Larsen, D.A., Dickey, J.T., Swanson, P., 2019. Evaluation of endocrine and transcriptomic markers of male maturation in winter-run Steelhead Trout (*Oncorhynchus mykiss*). Gen. Comp. Endocrinol. 281, 30–40.

Milazzo, M., Cattano, C., Alonzo, S.H., Foggo, A., Gristina, M., Rodolfo-Metalpa, R., Sinopoli, M., Spatafora, D., Stiver, K.A., Hall-Spencer, J.M., 2016. Ocean acidification affects fish spawning but not paternity at CO_2 seeps. Proc. R. Soc. B Biol. Sci. 283, 20161021.

Milla, S., Pasquet, A., El Mohajer, L., Fontaine, P., 2021. How domestication alters fish phenotypes. Rev. Aquac. 13, 388–405.

Miller, G.M., Watson, S.A., Mccormick, M.I., Munday, P.L., 2013. Increased CO_2 stimulates reproduction in a coral reef fish. Glob. Chang. Biol. 19, 3037–3045.

Miller, G.M., Kroon, F.J., Metcalfe, S., Munday, P.L., 2015. Temperature is the evil twin: effects of increased temperature and ocean acidification on reproduction in a reef fish. Ecol. Appl. 25, 603–620.

Mills, L.J., Chichester, C., 2005. Review of evidence: are endocrine-disrupting chemicals in the aquatic environment impacting fish populations? Sci. Total Environ. 343, 1–34.

Mohammadzadeh, S., Yeganeh, S., Moradian, F., Milla, S., Falahatkar, B., 2021. Spawning induction in Sterlet sturgeon (*Acipenser ruthenus*) with recombinant GnRH: analysis of hormone profiles and spawning indices. Aquaculture 533, 736108.

Molés, G., Hausken, K., Carrillo, M., Zanuy, S., Levavi-Sivan, B., Gómez, A., 2020. Generation and use of recombinant gonadotropins in fish. Gen. Comp. Endocrinol. 299, 113555.

Mommsen, T.P., Vijayan, M.M., Moon, T.W., 1999. Cortisol in teleosts: dynamics, mechanisms of action, and metabolic regulation. Rev. Fish Biol. Fish. 9, 211–268.

Monette, M.Y., Björnsson, B.T., McCormick, S.D., 2008. Effects of short-term acid and aluminum exposure on the parr-smolt transformation in Atlantic salmon (*Salmo salar*): disruption of seawater tolerance and endocrine status. Gen. Comp. Endocrinol. 158, 122–130.

Monfort, S.L., 2002. Non-invasive endocrine measures of reproduction and stress in wild populations. In: Holt, W.V., Pickard, A.R., Rodger, J.C., Wildt, D.E. (Eds.), Reproductive Science and Integrated Conservation. Cambridge University Press, Cambridge, pp. 147–165.

Monteiro, P.R.R., Reis-Henriques, M.A., Coimbra, J., 2000. Plasma steroid levels in female flounder (*Platichthys flesus*) after chronic dietary exposure to single polycyclic aromatic hydrocarbons. Mar. Environ. Res. 49, 453–467.

Morita, K., Saito, T., Miyakoshi, Y., Fukuwaka, M.-A., Nagasawa, T., Kaeriyama, M., 2006. A review of Pacific salmon hatchery programmes on Hokkaido Island, Japan. ICES J. Mar. Sci. 63, 1353–1363.

Mortensen, A.S., Arukwe, A., 2007. Interactions between estrogen- and ah-receptor signalling pathways in primary culture of salmon hepatocytes exposed to nonylphenol and 3,3′,4,4′-tetrachlorobiphenyl (Congener 77). Comp. Hepatol. 6, 1–14.

Mortensen, A.S., Arukwe, A., 2008. Estrogenic effect of dioxin-like aryl hydrocarbon receptor (AhR) agonist (PCB congener 126) in salmon hepatocytes. Mar. Environ. Res. 66, 119–120.

Munday, P.L., Donelson, J.M., Dixson, D.L., Endo, G.G.K., 2009. Effects of ocean acidification on the early life history of a tropical marine fish. Proc. R. Soc. B Biol. Sci. 276, 3275–3283.

Munday, P.L., Gagliano, M., Donelson, J.M., Dixson, D.L., Thorrold, S.R., 2011. Ocean acidification does not affect the early life history development of a tropical marine fish. Mar. Ecol. Prog. Ser. 423, 211–221.

Munkittrick, K.R., Portt, C.B., Van Der Kraak, G.J., Smith, I.R., Rokosh, D.A., 1991. Impact of bleached kraft mill effluent on population characteristics, liver MFO activity, and serum steroid levels of a Lake Superior white sucker (*Catostomus commersoni*) population. Can. J. Fish. Aquat. Sci. 48, 1371–1380.

Murphy, C.A., Stacey, N.E., Corkum, L.D., 2001. Putative steroidal pheromones in the round goby, *Neogobius melanostomus*: olfactory and behavioral responses. J. Chem. Ecol. 27, 443–470.

Myers, R.A., Rosenberg, A.A., Mace, P.M., Barrowman, N., Restrepo, V.R., 1994. In search of thresholds for recruitment overfishing. ICES J. Mar. Sci. 51, 191–205.

Mylonas, C.C., Fostier, A., Zanuy, S., 2010. Broodstock management and hormonal manipulations of fish reproduction. Gen. Comp. Endocrinol. 165, 516–534.

Mylonas, C.C., Duncan, N.J., Asturiano, J.F., 2017. Hormonal manipulations for the enhancement of sperm production in cultured fish and evaluation of sperm quality. Aquaculture 472, 21–44.

Näslund, J., Johnsson, J.I., 2016. Environmental enrichment for fish in captive environments: effects of physical structures and substrates. Fish Fish. 17, 1–30.

Näslund, J., Rosengren, M., Del Villar, D., Gansel, L., Norrgård, J.R., Persson, L., Winkowski, J.J., Kvingedal, E., 2013. Hatchery tank enrichment affects cortisol levels and shelter-seeking in Atlantic salmon (*Salmo salar*). Can. J. Fish. Aquat. Sci. 70, 585–590.

Navarrete, P., Mardones, P., Opazo, R., Espejo, R., Romero, J., 2008. Oxytetracycline treatment reduces bacterial diversity of intestinal microbiota of Atlantic salmon. J. Aquat. Anim. Health 20, 177–183.

Navarro-Martín, L., Viñas, J., Ribas, L., Díaz, N., Gutiérrez, A., Di Croce, L., Piferrer, F., 2011. DNA methylation of the gonadal aromatase (cyp19a) promoter is involved in temperature-dependent sex ratio shifts in the European sea bass. PLoS Genet. 7, e1002447.

Nelson, E.R., Habibi, H.R., 2009. Thyroid receptor subtypes: structure and function in fish. Gen. Comp. Endocrinol. 161, 90–96.

Nesan, D., Vijayan, M.M., 2013. Role of glucocorticoid in developmental programming: evidence from zebrafish. Gen. Comp. Endocrinol. 181, 35–44.

Nesan, D., Kamkar, M., Burrows, J., Scott, I.C., Marsden, M., Vijayan, M.M., 2012. Glucocorticoid receptor signaling is essential for mesoderm formation and muscle development in zebrafish. Endocrinology 153, 1288–1300.

Neuman, H., Debelius, J.W., Knight, R., Koren, O., 2015. Microbial endocrinology: the interplay between the microbiota and the endocrine system. FEMS Microbiol. Rev. 39, 509–521.

Nilsson, S., 1983. Chromaffin tissue. In: Nilsson, S. (Ed.), Autonomic Nerve Function in the Vertebrates. Zoophysiology. vol. 13. Springer, Berlin, pp. 100–111.

Noguera, J.C., Aira, M., Pérez-Losada, M., Domínguez, J., Velando, A., 2018. Glucocorticoids modulate gastrointestinal microbiome in a wild bird. R. Soc. Open Sci. 5, 171743.

Nordgarden, U., Fjelldal, P.G., Hansen, T., Björnsson, B.T., Wargelius, A., 2006. Growth hormone and insulin-like growth factor-I act together and independently when regulating growth in vertebral and muscle tissue of atlantic salmon postsmolts. Gen. Comp. Endocrinol. 149, 253–260.

Nugegoda, D., Kibria, G., 2017. Effects of environmental chemicals on fish thyroid function: implications for fisheries and aquaculture in Australia. Gen. Comp. Endocrinol. 244, 40–53.

O'Connor, C.M., Gilmour, K.M., Arlinghaus, R., Matsumura, S., Suski, C.D., Philipp, D.P., Cooke, S.J., 2011. The consequences of short-term cortisol elevation on individual physiology and growth rate in wild largemouth bass (*Micropterus salmoides*). Can. J. Fish. Aquat. Sci. 68, 693–705.

Ochs, C.L., Laframboise, A.J., Green, W.W., Basilious, A., Johnson, T.B., Zielinski, B.S., 2013. Response to putative round goby (*Neogobius melanostomus*) pheromones by centrarchid and percid fish species in the Laurentian Great Lakes. J. Great Lakes Res. 39, 186–189.

O'Connor, C.M., Gilmour, K.M., Arlinghaus, R., Van Der Kraak, G., Cooke, S.J., 2009. Stress and parental care in a wild teleost fish: insights from exogenous supraphysiological cortisol implants. Physiol. Biochem. Zool. 82, 709–719.

Okuzawa, K., Gen, K., 2013. High water temperature impairs ovarian activity and gene expression in the brain-pituitary-gonadal axis in female red seabream during the spawning season. Gen. Comp. Endocrinol. 194, 24–30.

Olesti, E., Boccard, J., Visconti, G., González-Ruiz, V., Rudaz, S., 2021. From a single steroid to the steroidome: trends and analytical challenges. J. Steroid Biochem. Mol. Biol. 206, 105797.

Oliveira, R.F., Almada, V.C., Canario, A.V.M., 1996. Social modulation of sex steroid concentrations in the urine of male cichlid fish *Oreochromis mossambicus*. Horm. Behav. 30, 2–12.

Oliveira, R.F., Lopes, M., Carneiro, L.A., Canário, A.V.M., 2001. Watching fights raises fish hormone levels. Nature 409, 475.

Olla, B.L., Davis, M.W., Ryer, C.H., 1998. Understanding how the hatchery environment represses or promotes the development of behavioral survival skills. Bull. Mar. Sci. 62, 531–550.

Ondricek, K., Thomas, P., 2018. Effects of hypoxia exposure on apoptosis and expression of membrane steroid receptors, ZIP9, mPRα and GPER in Atlantic croaker ovaries. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 224, 84–92.

Orias, F., Bony, S., Devaux, A., Durrieu, C., Aubrat, M., Hombert, T., Wigh, A., Perrodin, Y., 2015. Tamoxifen ecotoxicity and resulting risks for aquatic ecosystems. Chemosphere 128, 79–84.

Orrego, R., Milestone, C.B., Hewitt, L.M., Guchardi, J., Heid-Furley, T., Slade, A., MacLatchy, D.L., Holdway, D., 2017. Evaluating the potential of effluent extracts from pulp and paper mills in Canada, Brazil, and New Zealand to affect fish reproduction: estrogenic effects in fish. Environ. Toxicol. Chem. 36, 1547–1555.

Ortega-Recalde, O., Goikoetxea, A., Hore, T.A., Todd, E.V., Gemmell, N.J., 2020. The genetics and epigenetics of sex change in fish. Annu. Rev. Anim. Biosci. 8, 47–69.

Ospina-Álvarez, N., Piferrer, F., 2008. Temperature-dependent sex determination in fish revisited: prevalence, a single sex ratio response pattern, and possible effects of climate change. PLoS One 3, e2837.

Øverli, Ø., Winberg, S., Pottinger, T.G., 2005. Behavioral and neuroendocrine correlates of selection for stress responsiveness in rainbow trout—a review. Integr. Comp. Biol. 45, 463–474.

Overturf, M.D., Anderson, J.C., Pandelides, Z., Beyger, L., Holdway, D.A., 2015. Pharmaceuticals and personal care products: a critical review of the impacts on fish reproduction. Crit. Rev. Toxicol. 45, 469–491.

Pait, A.S., Nelson, J.O., 2009. A survey of indicators for reproductive endocrine disruption in *Fundulus heteroclitus* (killifish) at selected sites in the Chesapeake Bay. Mar. Environ. Res. 68, 170–177.

Palace, V.P., Evans, R.E., Wautier, K.G., Mills, K.H., Blanchfield, P.J., Park, B.J., Baron, C.L., Kidd, K.A., 2009. Interspecies differences in biochemical, histopathological, and population responses in four wild fish species exposed to ethynylestradiol added to a whole lake. Can. J. Fish. Aquat. Sci. 66, 1920–1935.

Palme, R., 2019. Non-invasive measurement of glucocorticoids: advances and problems. Physiol. Behav. 199, 229–243.

Pankhurst, N.W., 2011. The endocrinology of stress in fish: an environmental perspective. Gen. Comp. Endocrinol. 170, 265–275.

Pankhurst, N.W., 2016. Reproduction and development. In: Schreck, C.B., Tort, L., Farrell P., A, Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 295–331.

Pankhurst, N.W., Munday, P.L., 2011. Effects of climate change on fish reproduction and early life history stages. Mar. Freshw. Res. 62, 1015–1026.

Pankhurst, N.W., King, H.R., Anderson, K., Elizur, A., Pankhurst, P.M., Ruff, N., 2011. Thermal impairment of reproduction is differentially expressed in maiden and repeat spawning Atlantic salmon. Aquaculture 316, 77–87.

Pankhurst, N.W., Van Der Kraak, G., 1997. Effects of stress on growth and reproduction. In: Iwama, G.K., Pickering, A.D., Sumpter, J.P., Schreck, C.B. (Eds.), Fish Stress and Health in Aquaculture. Cambridge University Press, Cambridge, pp. 73–93.

Parrott, J.L., McMaster, M.E., Hewitt, L.M., 2006. A decade of research on the environmental impacts of pulp and paper mill effluents in Canada: development and application of fish bioassays. J. Toxicol. Environ. Health B Crit. Rev. 9, 297–317.

Peñaranda, D.S., Gallego, V., Rozenfeld, C., Herranz-Jusdado, J.G., Pérez, L., Gómez, A., Giménez, I., Asturiano, J.F., 2018. Using specific recombinant gonadotropins to induce spermatogenesis and spermiation in the European eel (*Anguilla anguilla*). Theriogenology 107, 6–20.

Pepin, P., 2016. Reconsidering the impossible—linking environmental drivers to growth, mortality, and recruitment of fish. Can. J. Fish. Aquat. Sci. 73, 205–215.

Pérez, L., Peñaranda, D.S., Dufour, S., Baloche, S., Palstra, A.P., Van Den Thillart, G.E.E.J.M., Asturiano, J.F., 2011. Influence of temperature regime on endocrine parameters and vitellogenesis during experimental maturation of European eel (*Anguilla anguilla*) females. Gen. Comp. Endocrinol. 174, 51–59.

Pérez-Sánchez, J., Terova, G., Simó-Mirabet, P., Rimoldi, S., Folkedal, O., Calduch-Giner, J.A., Olsen, R.E., Sitjà-Bobadilla, A., 2017. Skin mucus of gilthead sea bream (*Sparus aurata* L.). protein mapping and regulation in chronically stressed fish. Front. Physiol. 8, 34.

Perry, S.F., Bernier, N.J., 1999. The acute humoral adrenergic stress response in fish: facts and fiction. Aquaculture 177, 285–295.

Peter, R.E., Lin, H.R., Van Der Kraak, G., 1988. Induced ovulation and spawning of cultured freshwater fish in China: advances in application of GnRH analogues and dopamine antagonists. Aquaculture 74, 1–10.

Peterson, B.C., Waldbieser, G.C., 2009. Effects of fasting on IGF-I, IGF-II, and IGF-binding protein mRNA concentrations in channel catfish (*Ictalurus punctatus*). Domest. Anim. Endocrinol. 37, 74–83.

Petochi, T., Di Marco, P., Priori, A., Finoia, M.G., Mercatali, I., Marino, G., 2011. Coping strategy and stress response of European sea bass *Dicentrarchus labrax* to acute and chronic environmental hypercapnia under hyperoxic conditions. Aquaculture 315, 312–320.

Pfalzgraff, T., Lund, I., Skov, P.V., 2021. Cortisol affects feed utilization, digestion and performance in juvenile rainbow trout (*Oncorhynchus mykiss*). Aquaculture 536, 736472.

Philip, A.M., Vijayan, M.M., 2015. Stress-immune-growth interactions: cortisol modulates suppressors of cytokine signaling and JAK/STAT pathway in rainbow trout liver. PLoS One 10, e0129299.

Picha, M.E., Turano, M.J., Beckman, B.R., Borski, R.J., 2008. Endocrine biomarkers of growth and applications to aquaculture: a minireview of growth hormone, insulin-like growth factor (IGF)-I, and IGF-binding proteins as potential growth indicators in fish. N. Am. J. Aquac. 70, 196–211.

Pickering, A.D., Pottinger, T.G., 1989. Stress responses and disease resistance in salmonid fish: effects of chronic elevation of plasma cortisol. Fish Physiol. Biochem. 7, 253–258.

Pikulkaew, S., Benato, F., Celeghin, A., Zucal, C., Skobo, T., Colombo, L., Dalla Valle, L., 2011. The knockdown of maternal glucocorticoid receptor mRNA alters embryo development in zebrafish. Dev. Dyn. 240, 874–889.

Pottinger, T.G., Carrick, T.R., 1999. Modification of the plasma cortisol response to stress in rainbow trout by selective breeding. Gen. Comp. Endocrinol. 116, 122–132.

Pounder, K.C., Mitchell, J.L., Thomson, J.S., Pottinger, T.G., Buckley, J., Sneddon, L.U., 2016. Does environmental enrichment promote recovery from stress in rainbow trout? Appl. Anim. Behav. Sci. 176, 136–142.

Power, D.M., Llewellyn, L., Faustino, M., Nowell, M.A., Björnsson, B.T., Einarsdottir, I.E., Canario, A.V.M., Sweeney, G.E., 2001. Thyroid hormones in growth and development of fish. Comp. Biochem. Physiol., Part C: Toxicol. Pharmacol. 130, 447–459.

Preus-Olsen, G., Olufsen, M.O., Pedersen, S.A., Letcher, R.J., Arukwe, A., 2014. Effects of elevated dissolved carbon dioxide and perfluorooctane sulfonic acid, given singly and in combination, on steroidogenic and biotransformation pathways of Atlantic cod. Aquat. Toxicol. 155, 222–235.

Rand, P.S., Berejikian, B.A., Bidlack, A., Bottom, D., Gardner, J., Kaeriyama, M., Lincoln, R., Nagata, M., Pearsons, T.N., Schmidt, M., Smoker, W.W., Weitkamp, L.A., Zhivotovsky, L.A., 2012. Ecological interactions between wild and hatchery salmonids and key recommendations for research and management actions in selected regions of the North Pacific. Environ. Biol. Fishes 94, 343–358.

Reid, S.G., Bernier, N.J., Perry, S.F., 1998. The adrenergic stress response in fish: control of catecholamine storage and release. Comp. Biochem. Physiol. C Pharmacol. Toxicol. Endocrinol. 120, 1–27.

Reid, G.M., Hall, H., 2003. Reproduction in fishes in relation to conservation. In: Holt, W.V., Pickard, A.R., Rodger, J.C., Wildt, D.E. (Eds.), Reproductive Science and Integrated Conservation. Cambridge University Press, Cambridge, p. 375. 39.

Reid, N.M., Whitehead, A., 2016. Functional genomics to assess biological responses to marine pollution at physiological and evolutionary timescales: toward a vision of predictive ecotoxicology. Brief. Funct. Genomics 15, 358–364.

Reindl, K.M., Sheridan, M.A., 2012. Peripheral regulation of the growth hormone-insulin-like growth factor system in fish and other vertebrates. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 163, 231–245.

Reinecke, M., Björnsson, B.T., Dickhoff, W.W., McCormick, S.D., Navarro, I., Power, D.M., Gutiérrez, J., 2005. Growth hormone and insulin-like growth factors in fish: where we are and where to go. Gen. Comp. Endocrinol. 142, 20–24.

Rhodes, J.S., Quinn, T.P., 1998. Factors affecting the outcome of territorial contests between hatchery and naturally reared coho salmon parr in the laboratory. J. Fish Biol. 53, 1220–1230.

Riley, S.C., Tatara, C.P., Scheurer, J.A., 2005. Aggression and feeding of hatchery-reared and naturally reared steelhead (*Oncorhynchus mykiss*) fry in a laboratory flume and a comparison with observations in natural streams. Can. J. Fish. Aquat. Sci. 62, 1400–1409.

Robertson, C.E., Wright, P.A., Köblitz, L., Bernier, N.J., 2014. Hypoxia-inducible factor-1 mediates adaptive developmental plasticity of hypoxia tolerance in zebrafish, *Danio rerio*. Proc. R. Soc. B Biol. Sci. 281, 20140637.

Rogers, N.J., Urbina, M.A., Reardon, E.E., McKenzie, D.J., Wilson, R.W., 2016. A new analysis of hypoxia tolerance in fishes using a database of critical oxygen level (Pcrit). Conserv. Physiol. 4, cow012.

Romanova, E.V., Sweedler, J.V., 2015. Peptidomics for the discovery and characterization of neuropeptides and hormones. Trends Pharmacol. Sci. 36, 579–586.

Romero, L.M., Beattie, U.K., 2022. Common myths of glucocorticoid function in ecology and conservation. J. Exp. Zool. A Ecol. Integr. Physiol. 337, 7–14.

Romero, L.M., Fairhurst, G.D., 2016. Measuring corticosterone in feathers: strengths, limitations, and suggestions for the future. Comp. Biochem. Physiol. A Mol. Integr. Physiol. 202, 112–122.

Rosengren, M., Kvingedal, E., Näslund, J., Johnsson, J.I., Sundell, K., 2017. Born to be wild: effects of rearing density and environmental enrichment on stress, welfare, and smolt migration in hatchery-reared Atlantic salmon. Can. J. Fish. Aquat. Sci. 74, 396–405.

Russell, E., Koren, G., Rieder, M., Van Uum, S., 2012. Hair cortisol as a biological marker of chronic stress: current status, future directions and unanswered questions. Psychoneuroendocrinology 37, 589–601.

Sadoul, B., Vijayan, M.M., 2016. Stress and growth. In: Schreck, C.B., Tort, L., Farrell P., A, Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 167–205.

Salonius, K., Iwama, G.K., 1993. Effects of early rearing environment on stress response, immune function, and disease resistance in juvenile coho (*Oncorhynchus kisutch*) and chinook salmon (*O. tshawytscha*). Can. J. Fish. Aquat. Sci. 50, 759–766.

Salvanes, A.G.V., Moberg, O., Ebbesson, L.O.E., Nilsen, T.O., Jensen, K.H., Braithwaite, V.A., 2013. Environmental enrichment promotes neural plasticity and cognitive ability in fish. Proc. R. Soc. B Biol. Sci. 280, 20131331.

San Juan, P.A., Hendershot, J.N., Daily, G.C., Fukami, T., 2020. Land-use change has host-specific influences on avian gut microbiomes. ISME J. 14, 318–321.

Sandstrom, O., 1994. Incomplete recovery in a coastal fish community exposed to effluent from a modernized Swedish bleached kraft mill. Can. J. Fish. Aquat. Sci. 51, 2195–2202.

Schade, F.M., Clemmesen, C., Mathias Wegner, K., 2014. Within- and transgenerational effects of ocean acidification on life history of marine three-spined stickleback (*Gasterosteus aculeatus*). Mar. Biol. 161, 1667–1676.

Schiffer, L., Barnard, L., Baranowski, E.S., Gilligan, L.C., Taylor, A.E., Arlt, W., Shackleton, C.H.L., Storbeck, K.H., 2019. Human steroid biosynthesis, metabolism and excretion are differentially reflected by serum and urine steroid metabolomes: a comprehensive review. J. Steroid Biochem. Mol. Biol. 194, 105439.

Schreck, C.B., Scanlon, P.F., 1977. Endocrinology in fisheries and wildlife: biology and management. Fisheries 2, 20–30.

Schultz, D.R., Perez, N., Tan, C.K., Mendez, A.J., Capo, T.R., Snodgrass, D., Prince, E.D., Serafy, J.E., 2005. Concurrent levels of 11-ketotestosterone in fish surface mucus, muscle tissue and blood. J. Appl. Ichthyol. 21, 394–398.

Schultz, D.R., Perez, N., Mendez, A.J., Snodgrass, D., Serafy, J.E., Prince, E.D., Crow, W.A., Capo, T.R., 2007. Tracking gender factors in fish surface mucus: temporal patterns in individual Koi (*Cyprinus carpio*). J. Appl. Ichthyol. 23, 184–188.

Scott, A.P., Ellis, T., 2007. Measurement of fish steroids in water-a review. Gen. Comp. Endocrinol. 153, 392–400.

Scott, A.P., Sorensen, P.W., 1994. Time course of release of pheromonally active gonadal steroids and their conjugates by ovulatory goldfish. Gen. Comp. Endocrinol. 96, 309–323.

Scott, A.P., Hirschenhauser, K., Bender, N., Oliveira, R., Earley, R.L., Sebire, M., Ellis, T., Pavlidis, M., Hubbard, P.C., Huertas, M., Canario, A., 2008. Non-invasive measurement of steroids in fish-holding water: important considerations when applying the procedure to behaviour studies. Behaviour 145, 1307–1328.

Scott, A.P., Sumpter, J.P., Stacey, N., 2010. The role of the maturation-inducing steroid, 17,20β-dihydroxypregn-4-en-3-one, in male fishes: a review. J. Fish Biol. 76, 183–224.

Scott, A.P., Ellis, T., Tveiten, H., 2014. Identification of cortisol metabolites in the bile of Atlantic cod *Gadus morhua* L. Steroids 88, 26–35.

Sebire, M., Katsiadaki, I., Scott, A.P., 2007. Non-invasive measurement of 11-ketotestosterone, cortisol and androstenedione in male three-spined stickleback (*Gasterosteus aculeatus*). Gen. Comp. Endocrinol. 152, 30–38.

Segner, H., 2011. Reproductive and developmental toxicity in fishes. In: Gupta, R.C. (Ed.), Reproductive and Developmental Toxicology. Academic Press, London, pp. 1145–1166.

Servili, A., Canario, A.V.M., Mouchel, O., Muñoz-Cueto, J.A., 2020. Climate change impacts on fish reproduction are mediated at multiple levels of the brain-pituitary-gonad axis. Gen. Comp. Endocrinol. 291, 113439.

Shahjahan, M., Kitahashi, T., Ogawa, S., Parhar, I.S., 2013. Temperature differentially regulates the two kisspeptin systems in the brain of zebrafish. Gen. Comp. Endocrinol. 193, 79–85.

Servos, M.R., Bennie, D.T., Burnison, B.K., Jurkovic, A., McInnis, R., Neheli, T., Schnell, A., Seto, P., Smyth, S.A., Ternes, T.A., 2005. Distribution of estrogens, 17beta-estradiol and estrone, in Canadian municipal wastewater treatment plants. Sci. Total Environ. 336, 155–170.

Shahjahan, M., Kitahashi, T., Ando, H., 2017. Temperature affects sexual maturation through the control of kisspeptin, kisspeptin receptor, GnRH and GTH subunit gene expression in the grass puffer during the spawning season. Gen. Comp. Endocrinol. 243, 138–145.

Shang, E.H.H., Yu, R.M.K., Wu, R.S.S., 2006. Hypoxia affects sex differentiation and development leading to a male-dominated population in zebrafish (*Danio rerio*). Environ. Sci. Technol. 40, 3118–3122.

Shearer, K., Parkins, P., Gadberry, B., Beckman, B., Swanson, P., 2006. Effects of growth rate/body size and a low lipid diet on the incidence of early sexual maturation in juvenile male spring chinook salmon (*Oncorhynchus tshawytscha*). Aquaculture 252, 545–556.

Shephard, K.L., 1994. Functions for fish mucus. Rev. Fish Biol. Fish. 4, 401–429.

Shimizu, M., Dickhoff, W.W., 2017. Circulating insulin-like growth factor binding proteins in fish: their identities and physiological regulation. Gen. Comp. Endocrinol. 252, 150–161.

Shimizu, M., Cooper, K.A., Dickhoff, W.W., Beckman, B.R., 2009. Postprandial changes in plasma growth hormone, insulin, insulin-like growth factor (IGF)-I, and IGF-binding proteins in coho salmon fasted for varying periods. Am. J. Physiol. Regul. Integr. Comp. Physiol. 297, 352–361.

Shrimpton, J.M., Bernier, N.J., Iwama, G.K., Randall, D.J., 1994a. Differences in measurements of smolt development between wild and hatchery-reared juvenile coho salmon (*Oncorhynchus kisutch*) before and after saltwater exposure. Can. J. Fish. Aquat. Sci. 51, 2170–2178.

Shrimpton, J.M., Bernier, N.J., Randall, D.J., 1994b. Changes in cortisol dynamics in wild and hatchery-reared juvenile coho salmon (*Oncorhynchus kisutch*) during smoltification. Can. J. Fish. Aquat. Sci. 51, 2179–2187.

Shuter, B.J., Post, J.R., 1990. Climate, population viability, and the zoogeography of temperate fishes. Trans. Am. Fish. Soc. 119, 314–336.

Siefkes, M.J., 2017. Use of physiological knowledge to control the invasive sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes. Conserv. Physiol. 5, 1–18.

Simontacchi, C., Poltronieri, C., Carraro, C., Bertotto, D., Xiccato, G., Trocino, A., Radaelli, G., 2008. Alternative stress indicators in sea bass *Dicentrarchus labrax*, L. J. Fish Biol. 72, 747–752.

Singh, A.K., Chandra, R., 2019. Pollutants released from the pulp paper industry: aquatic toxicity and their health hazards. Aquat. Toxicol. 211, 202–216.

Söffker, M., Tyler, C.R., 2012. Endocrine disrupting chemicals and sexual behaviors in fish a critical review on effects and possible consequences. Crit. Rev. Toxicol. 42, 653–668.

Sogard, S.M., 1997. Size-selective mortality in the juvenile stage of teleost fishes: a review. Bull. Mar. Sci. 60, 1129–1157.

Son, H.H., Yun, W.S., Cho, S.H., 2020. Development and validation of an LC-MS/MS method for profiling 39 urinary steroids (estrogens, androgens, corticoids, and progestins). Biomed. Chromatogr. 34, e4723.

Sopinka, N.M., Donaldson, M.R., O'Connor, C.M., Suski, C.D., Cooke, S.J., 2016. Stress indicators in fish. In: Schreck, C.B., Tort, L., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 405–462.

Sorensen, P.W., Johnson, N.S., 2016. Theory and application of semiochemicals in nuisance fish control. J. Chem. Ecol. 42, 698–715.

Sorensen, P.W., Stacey, N.E., 2004. Brief review of fish pheromones and discussion of their possible uses in the control of non-indigenous teleost fishes. New Zeal. J. Mar. Freshw. Res. 38, 399–417.

Sorensen, P.W., Pinillos, M., Scott, A.P., 2005. Sexually mature male goldfish release large quantities of androstenedione into the water where it functions as a pheromone. Gen. Comp. Endocrinol. 140, 164–175.

Sorensen, P.W., Rue, M.C.P., Leese, J.M., Ghosal, R., Lim, H., 2019. A blend of F prostaglandins functions as an attractive sex pheromone in silver carp. Fishes 4, 27.

Soria, F.N., Strüssmann, C.A., Miranda, L.A., 2008. High water temperatures impair the reproductive ability of the pejerrey fish *Odontesthes bonariensis*: effects on the hypophyseal-gonadal axis. Physiol. Biochem. Zool. 81, 898–905.

Stacey, N.E., Sorensen, P.W., 2002. Hormonal pheromones in fish. In: Pfaff, D.W., Arnold, A.P., Etgen, A.M., Fharbach, A.M., Rubin, R.T. (Eds.), Hormones, Brain and Behavior. Academic Press, London, pp. 375–434.

Stacey, N., Sorensen, P.W., 2011. Hormonal pheromones. In: Farrell, A.P. (Ed.), Encyclopedia of Fish Physiology: From Genome to Environment. Elsevier Science & Technology, San Diego, pp. 1553–1562.

Stacey, N.E., Sorensen, P.W., Van Der Kraak, G.J., Dulka, J.G., 1989. Direct evidence that 17α,20β-dihydroxy-4-pregnen-3-one functions as a goldfish primer pheromone: preovulatory release is closely associated with male endocrine responses. Gen. Comp. Endocrinol. 75, 62–70.

Stothart, M.R., Bobbie, C.B., Schulte-Hostedde, A.I., Boonstra, R., Palme, R., Mykytczuk, N.C.S., Newman, A.E.M., 2016. Stress and the microbiome: linking glucocorticoids to bacterial community dynamics in wild red squirrels. Biol. Lett. 12, 20150875.

Sullam, K.E., Essinger, S.D., Lozupone, C.A., O'Connor, M.P., Rosen, G.L., Knight, R., Kilham, S.S., Russell, J.A., 2012. Environmental and ecological factors that shape the gut bacterial communities of fish: a meta-analysis. Mol. Ecol. 21, 3363–3378.

Sundström, L.F., Lõhmus, M., Johnsson, J.I., 2003. Investment in territorial defence depends on rearing environment in brown trout (*Salmo trutta*). Behav. Ecol. Sociobiol. 54, 249–255.

Swanson, P., Campbell, B., Shearer, K., Dickey, J., Beckman, B., Larsen, D., Park, L., Berejikian, B., 2008. Application of reproductive technologies to captive breeding programs for conservation of imperiled stocks of Pacific salmon. Cybium 32, 279–282.

Taranger, G.L., Muncaster, S., Norberg, B., Thorsen, A., Andersson, E., 2015. Environmental impacts on the gonadotropic system in female Atlantic salmon (*Salmo salar*) during vitellogenesis: photothermal effects on pituitary gonadotropins, ovarian gonadotropin receptor expression, plasma sex steroids and oocyte growth. Gen. Comp. Endocrinol. 221, 86–93.

Taylor, M.D., Chick, R.C., Lorenzen, K., Agnalt, A.L., Leber, K.M., Blankenship, H.L., Haegen, G.V., Loneragan, N.R., 2017. Fisheries enhancement and restoration in a changing world. Fish. Res. 186, 407–412.

Tellier, J.M., Kalejs, N.I., Leonhardt, B.S., Cannon, D., Höök, T.O., Collingsworth, P.D., 2022. Widespread prevalence of hypoxia and the classification of hypoxic conditions in the Laurentian Great Lakes. J. Great Lakes Res. 48, 13–23.

Thomas, P., Rahman, M.S., 2009. Chronic hypoxia impairs gamete maturation in atlantic croaker induced by progestins through nongenomic mechanisms resulting in reduced reproductive success. Environ. Sci. Technol. 43, 4175–4180.

Thomas, P., Rahman, M.S., 2012. Extensive reproductive disruption, ovarian masculinization and aromatase suppression in Atlantic croaker in the northern Gulf of Mexico hypoxic zone. Proc. R. Soc. B Biol. Sci. 279, 28–38.

Thomas, P., Rahman, M.S., Khan, I.A., Kummer, J.A., 2007. Widespread endocrine disruption and reproductive impairment in an estuarine fish population exposed to seasonal hypoxia. Proc. R. Soc. B Biol. Sci. 274, 2693–2701.

Thomas, P., Rahman, M.S., Picha, M.E., Tan, W., 2015. Impaired gamete production and viability in Atlantic croaker collected throughout the 20,000 km2 hypoxic region in the northern Gulf of Mexico. Mar. Pollut. Bull. 101, 182–192.

Tintos, A., Gesto, M., Míguez, J.M., Soengas, J.L., 2007. Naphthalene treatment alters liver intermediary metabolism and levels of steroid hormones in plasma of rainbow trout (*Oncorhynchus mykiss*). Ecotoxicol. Environ. Saf. 66, 139–147.

Tipping, J.M., 1997. Effect of smolt length at release on adult returns of hatchery-reared winter steelhead. Prog. Fish. Cult. 59, 310–311.

Tokarz, J., Möller, G., Hrabě De Angelis, M., Adamski, J., 2015. Steroids in teleost fishes: a functional point of view. Steroids 103, 123–144.

Turner, J.W., Nemeth, R., Rogers, C., 2003. Measurement of fecal glucocorticoids in parrotfishes to assess stress. Gen. Comp. Endocrinol. 133, 341–352.

Tyler, C.R., Filby, A.L., van Aerle, R., Lange, A., Ball, J., Santos, E.M., 2008. Fish toxicogenomics. Adv. Exp. Biol. 2, 75–325.

Ullah, I., Zuberi, A., Rehman, H., Ali, Z., Thörnqvist, P.O., Winberg, S., 2020. Effects of early rearing enrichments on modulation of brain monoamines and hypothalamic–pituitary–interrenal axis (HPI axis) of fish mahseer (*Tor putitora*). Fish Physiol. Biochem. 46, 75–88.

Uren Webster, T.M., Rodriguez-Barreto, D., Consuegra, S., Garcia de Leaniz, C., 2020. Cortisol-related signatures of stress in the fish microbiome. Front. Microbiol. 11, 1621.

Ussery, E.J., McMaster, M.E., Servos, M.R., Miller, D.H., Munkittrick, K.R., 2021. A 30-year study of impacts, recovery, and development of critical effect sizes for endocrine disruption in white sucker (*Catostomus commersonii*) exposed to bleached-kraft pulp mill effluent at Jackfish Bay, Ontario, Canada. Front. Endocrinol. (Lausanne) 12, 369.

Vainikka, A., Huusko, R., Hyvärinen, P., Korhonen, P.K., Laaksonen, T., Koskela, J., Vielma, J., Hirvonen, H., Salminen, M., 2012. Food restriction prior to release reduces precocious maturity and improves migration tendency of Atlantic salmon (*Salmo salar*) smolts. Can. J. Fish. Aquat. Sci. 69, 1981–1993.

Van Camp, K.A., Baggerman, G., Blust, R., Husson, S.J., 2017. Peptidomics of the zebrafish *Danio rerio*: in search for neuropeptides. J. Proteomics 150, 290–296.

Van Der Kraak, G.J., Munkittrick, K.R., McMaster, M.E., Portt, C.B., Chang, J.P., 1992. Exposure to bleached kraft pulp mill effluent disrupts the pituitary-gonadal axis of white sucker at multiple sites. Toxicol. Appl. Pharmacol. 115, 224–233.

Vargas-Chacoff, L., Regish, A.M., Weinstock, A., McCormick, S.D., 2018. Effects of elevated temperature on osmoregulation and stress responses in Atlantic salmon *Salmo salar* smolts in fresh water and seawater. J. Fish Biol. 93, 550–559.

Vargas-Chacoff, L., Regish, A.M., Weinstock, A., Björnsson, B.T., McCormick, S.D., 2021. Effects of long-term cortisol treatment on growth and osmoregulation of Atlantic salmon and brook trout. Gen. Comp. Endocrinol. 308, 113769.

Verbeek, P., Iwamoto, T., Murakami, N., 2008. Variable stress-responsiveness in wild type and domesticated fighting fish. Physiol. Behav. 93, 83–88.

Vermeirssen, E.L.M., Scott, A.P., 1996. Excretion of free and conjugated steroids in rainbow trout (*Oncorhynchus mykiss*): evidence for branchial excretion of the maturation-inducing steroid, 17,20β-dihydroxy-4-pregnen-3-one. Gen. Comp. Endocrinol. 101, 180–194.

Vikingstad, E., Andersson, E., Hansen, T.J., Norberg, B., Mayer, I., Stefansson, S.O., Fjelldal, P.G., Taranger, G.L., 2016. Effects of temperature on the final stages of sexual maturation in Atlantic salmon (*Salmo salar* L.). Fish Physiol. Biochem. 42, 895–907.

Vindas, M.A., Madaro, A., Fraser, T.W.K., Höglund, E., Olsen, R.E., Øverli, Ø., Kristiansen, T.S., 2016. Coping with a changing environment: the effects of early life stress. R. Soc. Open Sci. 3, 160382.

Wagner, C.M., Jones, M.L., Twohey, M.B., Sorensen, P.W., 2006. A field test verifies that pheromones can be useful for sea lamprey (*Petromyzon marinus*) control in the Great Lakes. Can. J. Fish. Aquat. Sci. 63, 475–479.

Wang, S., Yuen, S.S., Randall, D.J., Hung, C.Y., Tsui, T.K., Poon, W.L., Lai, J.C., Zhang, Y., Lin, H., 2008. Hypoxia inhibits fish spawning via LH-dependent final oocyte maturation. Comp. Biochem. Physiol. C Toxicol. Pharmacol. 148, 363–369.

Watson, S.E., Hauffe, H.C., Bull, M.J., Atwood, T.C., McKinney, M.A., Pindo, M., Perkins, S.E., 2019. Global change-driven use of onshore habitat impacts polar bear faecal microbiota. ISME J. 13, 2916–2926.

Watts, M., Pankhurst, N.W., King, H.R., 2004. Maintenance of Atlantic salmon (*Salmo salar*) at elevated temperature inhibits cytochrome P450 aromatase activity in isolated ovarian follicles. Gen. Comp. Endocrinol. 135, 381–390.

Waye, A., Trudeau, V.L., 2011. Neuroendocrine disruption: more than hormones are upset. J. Toxicol. Environ. Health B Crit. Rev. 14, 270–291.

Weber, R., Gaus, C., Tysklind, M., Johnston, P., Forter, M., Hollert, H., Heinisch, E., Holoubek, I., Lloyd-Smith, M., Masunaga, S., Moccarelli, P., Santillo, D., Seike, N., Symons, R., Torres, J.P.M., Verta, M., Varbelow, G., Vijgen, J., Watson, A., Costner, P., Woelz, J., Wycisk, P., Zennegg, M., 2008. Dioxin- and POP-contaminated sites—contemporary and future relevance and challenges: overview on background, aims and scope of the series. Environ. Sci. Pollut. Res. 15, 363–393.

Weirup, L., Schulz, C., Seibel, H., Aerts, J., 2021. Scale cortisol is positively correlated to fin injuries in rainbow trout (*Oncorhynchus mykiss*) reared in commercial flow through systems. Aquaculture 543, 736924.

Welch, M.J., Munday, P.L., 2016. Contrasting effects of ocean acidification on reproduction in reef fishes. Coral Reefs 35, 485–493.

Wendelaar Bonga, S.E., 1997. The stress response in fish. Physiol. Rev. 77, 591–625.

White, L.J., Thomson, J.S., Pounder, K.C., Coleman, R.C., Sneddon, L.U., 2017. The impact of social context on behaviour and the recovery from welfare challenges in zebrafish, *Danio rerio*. Anim. Behav. 132, 189–199.

Whitehead, A., Pilcher, W., Champlin, D., Nacci, D., 2012. Common mechanism underlies repeated evolution of extreme pollution tolerance. Proc. R. Soc. B Biol. Sci. 279, 427–433.

Whitehead, A., Clark, B.W., Reid, N.M., Hahn, M.E., Nacci, D., 2017. When evolution is the solution to pollution: key principles, and lessons from rapid repeated adaptation of killifish (*Fundulus heteroclitus*) populations. Evol. Appl. 10, 762–783.

Wilkes, L., Owen, S.F., Readman, G.D., Sloman, K.A., Wilson, R.W., 2012. Does structural enrichment for toxicology studies improve zebrafish welfare? Appl. Anim. Behav. Sci. 139, 143–150.

Winberg, S., Höglund, E., Øverli, Ø., 2016. Variation in the neuroendocrine stress response. In: Schreck, C.B., Tort, L., Farrell, A.P., Brauner, C.J. (Eds.), Fish Physiology: Biology of Stress in Fish, vol. 35. Academic Press, London, pp. 35–74.

Woodward, C.C., Strange, R.J., 1987. Physiological stress responses in wild and hatchery-reared rainbow trout. Trans. Am. Fish. Soc. 116, 574–579.

Wu, R.S.S., Zhou, B.S., Randall, D.J., Woo, N.Y.S., Lam, P.K.S., 2003. Aquatic hypoxia is an endocrine disruptor and impairs fish reproduction. Environ. Sci. Technol. 37, 1137–1141.

Yamaguchi, T., Yoshinaga, N., Yazawa, T., Gen, K., Kitano, T., 2010. Cortisol is involved in temperature-dependent sex determination in the Japanese flounder. Endocrinology 151, 3900–3908.

Yan, Z., Lu, G., He, J., 2012. Reciprocal inhibiting interactive mechanism between the estrogen receptor and aryl hydrocarbon receptor signaling pathways in goldfish (*Carassius auratus*) exposed to 17β-estradiol and benzo[a]pyrene. Comp. Biochem. Physiol., Part C: Toxicol. Pharmacol. 156, 17–23.

Yanong, R.P.E.E., Martinez, C., Watson, A., 2009. Use of Ovaprim in Ornamental Fish Aquaculture. IFAS Extension University of Florida, Gainesville, FL.

Young, G., Björnsson, B.T., Prunet, P., Lin, R.J., Bern, H.A., 1989. Smoltification and seawater adaptation in coho salmon (*Oncorhynchus kisutch*): plasma prolactin, growth hormone, thyroid hormones, and cortisol. Gen. Comp. Endocrinol. 74, 335–345.

Zadmajid, V., Bashiri, S., Sharafi, N., Butts, I.A.E., 2018. Effect of hCG and Ovaprim™ on reproductive characteristics of male Levantine scraper, *Capoeta damascina* (Valenciennes, 1842). Theriogenology 115, 45–56.

Zhou, L.F., Zhao, B.W., Guan, N.N., Wang, W.M., Gao, Z.X., 2017. Plasma metabolomics profiling for fish maturation in blunt snout bream. Metabolomics 13, 40.

Zohar, Y., 2021. Fish reproductive biology—reflecting on five decades of fundamental and translational research. Gen. Comp. Endocrinol. 300, 113544.

Zohar, Y., Mylonas, C.C., 2001. Endocrine manipulations of spawning in cultured fish: from hormones to genes. Aquaculture 197, 99–136.

Zohar, Y., Muñoz-Cueto, J.A., Elizur, A., Kah, O., 2010. Neuroendocrinology of reproduction in teleost fish. Gen. Comp. Endocrinol. 165, 438–455.

Zubair, S.N., Peake, S.J., Hare, J.F., Anderson, W.G., 2012. The effect of temperature and substrate on the development of the cortisol stress response in the lake sturgeon, *Acipenser fulvescens*, Rafinesque (1817). Environ. Biol. Fishes 93, 577–587.

Zuberi, A., Ali, S., Brown, C., 2011. A non-invasive assay for monitoring stress responses: a comparison between wild and captive-reared rainbowfish (*Melanoteania duboulayi*). Aquaculture 321, 267–272.