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# Effects of Pollution on Fish Behavior, Personality, and Cognition

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**Abstract:** *One of the most underappreciated causes of variance in wild populations' behaviour and cognition is pollution and other environmental stressors. We review the most recent fish literature and highlight four exciting lines of inquiry into how pollution affects fish behaviour, cognition, and fitness. To begin (1), we discuss the neurotoxic consequences of contaminants on fish psyches and brains.*
*These changes in behaviour and cognition may influence the amount of pollution exposure, creating feedback loops that could magnify the negative impacts of pollution on fish fitness. Because some stressors may enhance the behavioural impacts of pollutants on fitness, we also recommend that (2) the effects of pollutants should be examined in a multistress context, i.e. in realistic environmental conditions in combination with other stressors. Thirdly (3), previous research has demonstrated that there is a strong correlation between the physiological, personality, cognitive, and fitness aspects of many disorders. The evolutionary paths of populations exposed to pollutants may be altered as a result of syndrome disruption. Thus, future research should concentrate on the intricate interrelationships between features in order to comprehend the effects of stresses on evolutionary trajectories. Fourth, (4) persistent pollution exposure might cause local adaptation or maladaptation, which can lead to wide ranges of sensitivity within the same species in the wild. The development of resistance to pollution may also constrain or be restricted by the evolution of resistance to other stresses.*

**Keywords:** Temperament, contamination, stress response, multistress, evolutionary ecotoxicology

## I. INTRODUCTION

Plastics, medicines, pesticides, and metals are just some of the organic and inorganic contaminants that come from human activities and harm both land and aquatic ecosystems (Scott and Sloman, 2004; Zala and Penn, 2004; Saaristo et al., 2018). But there are a lot of science problems that make it hard for us to know for sure how they affect wildlife. In routine ecotoxicology studies, the direct effects of pollutants on animal physiology and death have been looked at (Butcher et al., 2006; Ashauer et al., 2013), but more complex behaviour, especially in wild species and under realistic conditions with multiple stresses (Zala and Penn, 2004; Saaristo et al., 2018), has been looked at less often. Also, it's hard for us to predict the long-term effects of human activities on population persistence and evolutionary paths because we rarely look at the links between changes in behaviour, cognitive performance, and individual fitness when we study the effects of pollution.

Here, we look at the studies on fish and pollution as a whole to see how the two work together to change the way fish act. Fish have been used in a number of ways, such as as "sentinel" animals in ecotoxicology (Giulio and Hinton, 2008; Braunbeck et al., 2013) and as subjects in studies on behaviour and cognition (Brown et al., 2006). So, we put together (brief) information from the scientific literature about how chemicals change the way wild fish act (Table 1). As Table 1 shows, most of the previous studies looked at the effects of pollution alone, i.e. in a "single stressor" framework, but with pollution levels that are realistic for the environment.

Exposure to multiple natural or human-made stressors at the same time in the wild can lessen the effects of pollution, which can lead to synergistic interactions and/or bigger effects on fish health (e.g., Gandar et al., 2015, 2017a). But there aren't many real-world examples of how multistress changes the way fish act (Table 1). Pollutant effects on syndrome structure are still not clear (Killen et al., 2013; Montiglio and Royauté, 2014), even though there are often strong links between traits (Réale et al., 2007; Conrad et al., 2011; Sih, 2011; Sih and Del Giudice, 2012) (Table 1). Lastly, most earlier studies only looked at domestic species or a single wild population (Table 1), so they didn't look at how behaviour changed over time or how it changed between different populations. In the next few decades, it will be a very interesting scientific job to study the effects of contaminants on fish fitness through changes in behaviour and thought in wild populations, as well as the effects of these changes on evolution. Based on what we know and what we don't know, we come up with four possible study areas (Figure 1) to learn more about how pollution affects fish behaviour, cognition, fitness, and survival. Our first theory is that (1) pollution can have long-term effects on the health of fish by changing many parts of their behaviour, such as their ability to learn and remember. Positive feedback loops could make the bad effects of pollution on health even worse by exposing animals in the wild to more pollution because their behaviour has changed because of pollution. The second thing we'd like to suggest is that (2) since fish may now be used to being exposed to multiple stressors, pollutants should be studied along with other stresses that usually change how pollutants affect fish behaviour and fitness. And finally, (3) environmental stresses like pollution can change the connections between physiology and behaviour. This can break or strengthen syndromes, which can have big effects on how evolution works. Fourth, we look at how long-term pollution might change plastic and/or DNA structures, which could lead to local adaptation or maladaptation. Adaptive processes depend heavily on behavioural and cognitive reactions, which have been changed by evolution and can help or hurt adaptations to environmental stresses like pollution (Sih et al., 2011; Figure 1). We hope that this work will inspire future research to use integrative methods that bridge the gap between behavioural, cognitive, and evolutionary ecology to tackle these hard problems. This will help us learn more about how current and future pressures affect wild fish populations.

## II. EFFECTS OF POLLUTANTS ON FISH BEHAVIOR AND FEEDBACK LOOPS

Scott and Sloman (2004), Zala and Penn (2004), and Saaristo et al. (2018) all say that pollution is a big reason why fish act differently (Scott and Sloman, 2004; Robinson, 2009; Sloman and McNeil, 2012). Table 1 shows all the ways that inorganic and organic pollutants can change an organism's behaviour, including its movement, exploration, avoidance, sociality, aggression, sexuality, and food consumption. A few studies (Réale et al., 2007, 2010; Montiglio and Royauté, 2014) have also looked into the effects of pollution on behaviour types or personalities, that is, on fixed differences in behaviour between people. Many pollutants also hurt fish brains (see Table 1), which could hurt their ability to survive (see, for example, de Castro et al., 2009). Some of these changes are caused by changes in cholinesterase activity, neurotransmitter levels, or hormone levels (Scott and Sloman, 2004; Brodin et al., 2014; Vindas et al., 2017). Hernández-Moreno et al. (2011) found that the herbicide carbofuran changed the way the sea bass, Dicentrarchus labrax, used its nerves and how active it was. (Kohlert et al., 2012; Eisenreich and Szalda-Petree, 2015; Dzieweczynski et al., 2016) found that the antidepressant fluoxetine (Prozac) changes aggression, confidence, and learning in the Siamese fighting fish Betta splendens by interacting with the serotonin pathway. Sokolova et al. (2012) and Sokolova et al. (2013) found that detoxification and stress responses have a negative effect on energy balance. This may lead to indirect changes in behaviour (Montiglio and Royauté, 2014). For example, even at low amounts, pesticides slowed down the activity of the goldfish Carassius auratus (Gandar et al., 2015, 2017a,b). This is likely because the cost of detoxication is high and the body has better ways of protecting itself. Brodin et al. (2014) have only just started to look into the neurological and physiological causes of changes in behaviour and thought that are caused by pollution. Much more study is needed. It's interesting that the bad effects of pollution on fish health may be made worse by positive feedback loops caused by changes in behaviour caused by pollution. But there is only proof that points in a certain direction. Pollution has been shown to have a big effect on a number of important behaviours, such as moving around, being curious, and staying away from new places. Good tits Grunst et al. (2018) and Grunst et al. (2019) looked at the behaviour of Parus major in lead and cadmium polluted areas. They found that birds with higher amounts of metal in their blood were less likely to explore. (Jacquin et al., 2017) found that after being exposed to crude oil, Trinidadian guppies (Poecilia reticulata) were less likely to explore a maze. Because exploration is one of the most important ways for people to learn about their surroundings (Reader, 2015), a decrease in the desire to explore could affect how well fish can judge the quality of their environment. Contamination also often changes the way people connect with each other (e.g., Ward et al., 2008), which can make it harder to learn from other people of the same species (Laland and Williams, 1997; Brown and Laland, 2003).

Contaminants can also have a big impact on spatial thinking skills like learning and remembering. For example, Grassie et al. (2013) found that aluminium contamination made it harder for Atlantic salmon Salmo salar to learn in a maze test.

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This suggests that the metal may make it harder for the fish to process information and adapt to new situations. Organic toxins like pesticides changed the way the zebrafish Danio rerio and the rare minnow Gobiocypris rarus moved and remembered where things were (Hong and Zha, 2019). Fish are likely to be very hurt by these bad cognitive effects on their ability to learn and remember information so they can avoid being eaten, find food, and stay away from places that are dirty. So, fish that have been exposed to pollution may have trouble gathering, understanding, and remembering information about the quality of their environment and food. This may make them more likely to be exposed to pollution. Animals may also be more likely to be exposed to pollution because many pollutants affect how and where animals move. For example, pesticides and pharmaceuticals change salmonid fish's homing and downward migration behaviours (e.g., Scholz et al., 2000; Hellstrom et al., 2016; McCallum et al., 2019). If the fish can't get back to their normally clean home river, they may be exposed to more pollution.

**TABLE 1** | Non-extensive summary of the existing literature on the link between pollution and behavior in fish.

| Contaminant | Ecological relevance | Fish species | Behavioral traits | Multi-stress | Syndrome | Variability | Source |
|---|---|---|---|---|---|---|---|
| *Plastics* | | | | | | | |
| Microplastics | Yes | *Bathygobius krefftii* | Boldness, exploration | No | No | No | Tosetto et al. (2017) |
| Microplastics | Yes | *Acanthochromis polyacanthus* | Activity, feeding, aggression | No | No | Yes | Critchell and Hoogenboom (2018) |
| Nanoplastics | Yes | *Carassius carassius* | Activity, feeding, exploration | No | No | No | Mattsson et al. (2017) |
| *Pharmaceuticals* | | | | | | | |
| Oxazepam | Yes | *Perca fluviatilis* | Activity, boldness, sociality, feeding rate | No | Yes | No | Brodin et al. (2013) |
| Vinclozolin, flutamide (chemotherapy) | Yes | *Betta splendens* | Activity, shoaling, exploration, boldness | No | Yes | No | Dzieweczynski et al. (2018) |
| Ethinylestradiol | Yes | *Betta splendens* | Boldness, activity | No | Yes | No | Dzieweczynski et al. (2014) |
| Ethinylestradiol | Yes | *Poecilia reticulata* | Sexual behaviors | No | No | No | Bayley et al. (1999); Kristensen et al. (2005) |
| Fluoxetine | Yes | *Several species* | Antipredator behavior, boldness, aggression, associative learning | Yes | Yes | No | Eisenreich and Szalda-Petree (2015); Dzieweczynski et al. (2016); Eisenreich et al. |
| Nonylphenol (industrial surfactant) | Yes | *Fundulus diaphanus* | Shoaling, recognition | No | No | No | Ward et al. (2008) |
| Metals | | | | | | | |
| Mercury | | *Danio rerio* | Activity, escape | Yes | No | No | Weber (2006) |
| Methylmercury MeHg | | *Danio rerio* | Anxiety, locomotion | No | No | No | Maximino et al. (2011) |
| MeHg | Yes | *Fundulus heteroclitus* | Activity, feeding | No | No | Yes | Zhou and Weis (1998); Weis et al. (1999, 2001) |
| Metal mixture | Yes | *Pimephales promelas* | Swimming performance | No | No | No | Kolok et al. (1998) |
| MeHg | Yes | *Fundulus heteroclitus* | Sociality | No | No | Yes | Ososkov and Weis (1996) |
| MeHg | No | *Danio rerio* | Spatial learning | No | No | No | Smith et al. (2010) |
| Several metals (Cu, Zn,…) | No | *Several species* | Avoidance, activity | No | No | No | Atchison et al. (1987) |
| Ag | Yes | *Danio rerio* | Avoidance, swimming, spatial learning | No | No | No | Powers et al. (2011) |
| Cd | Yes | *Oncorhynchus mykiss* | Sociality | No | No | No | Sloman et al. (2003) |
| PCBs and PAHs | Yes | *Ameiurus nebulosus* | Aggression, activity, escape response | No | No | Yes | Breckels and Neff (2010) |
| Trenbolone (agricultural pollution) | Yes | *Poecilia reticulata* | Reproductive behaviors | No | No | No | Bertram et al. (2015); Tomkins et al. (2018) |
| PAHs Polycyclic aromatic hydrocarbons | NA | *Poecilia reticulata* | Exploration, activity, sociality | No | No | Yes | Jacquin et al. (2017) |
| Benzo[a]pyrene | NA | *Oncorhynchus kisutch* | Territoriality | No | No | No | Ostrander et al. (1988) |
| PAHs | Yes | *Neogobius* | Competition | No | No | Yes | Sopinka et al. (2010) |

But further research is required to confirm these possibilities. Fish may be more likely to ingest contaminated food due to pollution's effects on their confidence, appetite, and foraging habits (Montiglio and Royauté, 2014). For instance, in comparison to control fish, perch (Perca fluviatilis) that were given psychiatric medicines were more outgoing and active, and they started feeding sooner (Brodin et al., 2013). This could make them more vulnerable to contamination in the wild, but testing this hypothesis will require empirical methods.

In conclusion, pollution causes changes in curiosity, sociability, memory, learning, appetite, bravery, and Foraging may have significant effects on fish fitness by increasing their exposure to environmental or nutritional contamination through positive feedback loops (Montiglio and Royauté, 2014). However, at this time, only circumstantial evidence exists; hence, additional experimental research are required to test this concept.To wit: (Brodin et al., 2013; 2014). Because detoxifying and repairing processes are energy-intensive, organisms that are exposed to pollution may be more active and forage more frequently, increasing their exposure to dietarytransmitted pollutants (Montiglio and Royauté, 2014). Take the crucian carp as an example. Fish of the genus Carassius, when fed polystyrene nanoparticles up the food chain, show changes in behaviour and feeding behaviour consistent with increased energy requirements and/or changes in brain structure (Mattsson et al., 2015, 2017).

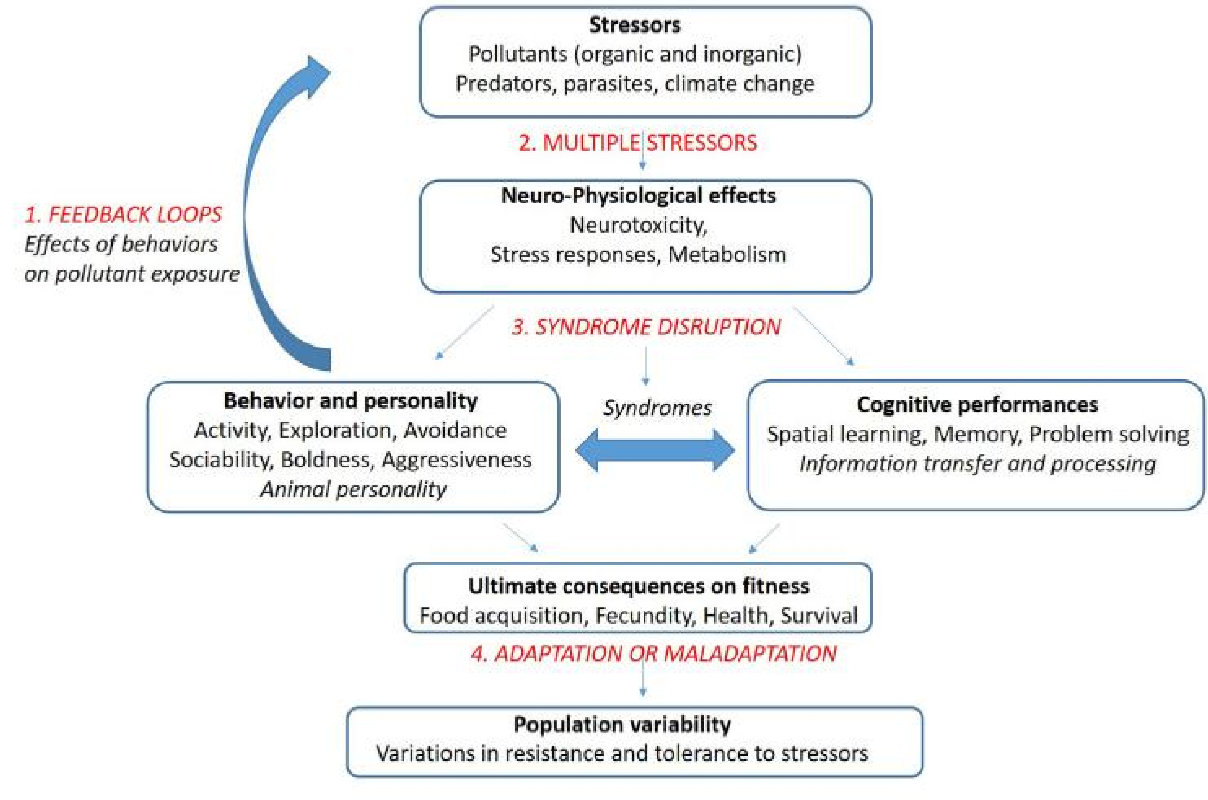


**FIGURE 1** | Potential links between pollution, behavior and cognition, and proposed research perspectives (in red).

## III. MULTIPLE STRESSOR EFFECTS ON BEHAVIOR AND FITNESS

Many of the strange behaviours that pollution causes could be made worse by other stresses, such as predators, diseases, or climate change. For example, Weis et al. (1999, 2001) and Lürling and Scheffer (2007) say that pollution may make it harder for people to escape from predators because they change how active, aggressive, and smart they are. So, copper hurts the nerve cells in fathead minnows that sense smell. Dew et al. (2014) found that Pimephales promelas makes them less resistant to predators by making them less sensitive to danger signals. Another study (Sandoval-Herrera et al., 2019) found that the banded tetra Astyanax aeneus couldn't avoid predators as well as it did before it was exposed to an organophosphate pesticide.

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Parasites are just one example of a biological stressor that can change how toxins affect the body and how people act. There is evidence that resistance to environmental and parasitic stresses is based on the same neurological and physiological processes (Thilakaratne et al., 2007; Blanar et al., 2009; Marcogliese and Pietrock, 2011). This could lead to important interactions between these stressors.

Climate change and water warming are two examples of environmental stressors that may lessen the effects of pollutants in one of two ways: by changing the chemical properties of the pollutants themselves, or by having complicated, interacting effects on neurophysiological pathways (Schiedek et al., 2007; Noyes et al., 2009).

## IV. POLLUTION AS A REVEALING OR MASKING FACTOR OF BEHAVIORAL SYNDROMES

(Sih et al., 2004; Réale et al., 2007; Conrad et al., 2011; Sih 2011; Sih and Del Giudice, 2012). Personalities in animals are usually made up of groups of actions that happen together. Syndromes (Conrad et al., 2011; Dochtermann and Dingemanse, 2013) are groups of consistent fish behaviours, like bravado, activity discovery, and friendliness, that are linked together. These syndromes have big effects on fitness and evolutionary paths. Gasterosteus aculeatus that are more aggressive and confident have a higher fitness (Bell and Sih, 2007; Dingemanse et al., 2007) because they are less likely to be eaten by predators. People often forget that behavioural problems can help people learn and think better. (Nomakuchi et al., 2009) found that sticklebacks that like to explore labyrinths are also more likely to follow other sticklebacks that know what to do. This may make social learning easier. These illnesses should be taken into account because they can be used to predict how external stresses will affect the health and brain function of fish.

Pollutants can change the structure of behavioural syndromes, which can affect a person's ability to think clearly and respond properly to the world around them (Killen et al., 2013). Pollution, in particular, can cause a stress reaction (the production of cortisol), which has big effects on energy balance, food intake, and metabolism (Schreck et al., 2016). Killen et al. (2013) say that pollution may change the relationship between physiology and behaviour by making people feel stressed and making them need more energy.

Killen et al. (2013) say that stress may shed light on syndromes by making links between traits stronger. Oxazepam, an anti-anxiety drug, made a link between being brave and being active in the perch Perca fluviatilis that didn't exist before (Brodin et al., 2013). But fish may not be able to show all of their behaviours due to the negative neurophysiological effects of stressors. This may also reduce the phenotypic differences that can be seen and hide any relationship between traits that could be seen when fish were exposed to a mild or single stressor (Killen et al., 2013). Stressors may be able to hide the effects of conditions by making the link between symptoms weaker. Dzieweczynski et al. (2016) looked at the Siamese fighting fish Betta splendens and found that fluoxetine made the fish's behaviour less similar from one situation to the next. Damselflies of the species Ischnura that were given zinc did not change in how they reacted to stress or how their bodies worked (Debecker and Stoks, 2019). Pollution may also work as a form of natural selection, favouring certain combinations of traits (see Table 1), but this theory has only been tested in a few experiments. Also, the underlying processes, such as genetic correlations or physiological trade-offs (Bell and Aubin-Horth, 2010; Conrad et al., 2011; Dochtermann and Dingemanse, 2013), may cause behavioural disorders to have different evolutionary meanings. Genes that have pleiotropy, for example, may make it harder for organisms to develop defences against threats in their surroundings. It will be hard for natural selection to break these links between behaviours, so they will be stable in most situations (Dochtermann and Dingemanse, 2013). But natural populations may show different combinations of traits in reaction to pollution, lack of resources, and other stressors (Bell and Aubin-Horth, 2010; Killen et al., 2013). This is because of syndromes caused by physiological trade-offs that result from how resources are used. But right now (Conrad et al., 2011) (Table 1), we don't know much about the processes behind the correlations and symptoms of behaviour in polluted wild fish and what that means for their evolutionary paths.

## V. EVOLUTIONARY DIVERGENCE IN BEHAVIOR UNDER POLLUTION

(Bélanger-Deschênes et al., 2013; Oziolor et al., 2016; Brady et al., 2017) Some fish populations that have grown up in a polluted environment for a long time react differently to an experimental pollutant than other populations that haven't grown up in a polluted environment. This suggests that local populations have adapted to polluters. Killifish Fundulus heteroclitus in very polluted environments have changed their genes to deal with organic pollution (Reid et al., 2016; Whitehead et al., 2017). Some study has been done on how different behaviours are caused by pollution, but there isn't much proof yet that populations have adapted to pollution in their local environments, either through genetic evolution or by being able to change. In a study of brown bullhead fish (Ameiurus nebulosus) from dirty rivers vs. rivers that weren't polluted (Breckels and Neff, 2010), only F0 fish that were caught in the wild were tested for aggression. We can't tell how much genetic and plastic factors contributed to the different behaviours seen in the F0 generation, which makes it hard to predict the long-term effects of pollution. A study of guppies (Poecilia reticulata) that evolved in polycyclic aromatic hydrocarbon (PAH)-polluted rivers in Trinidad and Tobago compared to fish from unpolluted rivers after several generations raised in common garden conditions (F1 to F3 generations) (Jacquin et al., 2017) also showed that the behaviour of different populations may be different because of their genes. Rolshausen et al. (2015) and Hamilton et al. (2017) looked at the same model species and found little evidence of adaptive plasticity that would limit the bad effects of pollutants on fitness, especially in unpolluted areas. More study is needed to figure out how much plasticity and genetic-based evolution are to blame for this possible maladaptation (Rolshausen et al., 2015; Hamilton et al., 2017; Brady et al., 2019), but these results suggest that adapting to pollution may be bad in environments that aren't polluted.

Because different stressors can have different effects on evolution, it is still hard to tell the difference between the effects of pollution and other natural stressors on evolution in the wild (Jansen et al., 2011; Saaristo et al., 2018).

For example, being able to deal with one stressor (like pollution) may make it harder to deal with another (like a disease). Because of this, adapting to pollution could be expensive, based on other stressors (e.g., Dutilleul et al., 2017).

Pollution can cause changes in behaviour and thought, which may improve fitness in polluted areas but hurt fitness in other places. For example, we might think that less exploration due to pollution (e.g., Jacquin et al., 2017; Grunst et al., 2018) might limit toxicant uptake in polluted areas but cause problems when food is short (Reader, 2015). So, it's possible that pollution will change how animals weigh the costs and benefits of processing information. However, the predicted result for fish fitness and evolutionary paths may depend on a number of environmental and social factors that haven't been studied yet.

Because of this, Sih et al. (2011) say that adaptive responses to pollution are unlikely to have developed in the past, although this may depend a lot on the species and the type and amount of stressor. Pollution-caused changes in behaviour (Sih et al., 2011; Brady et al., 2019) could lead to bad outcomes and evolutionary traps, but this idea hasn't been proven yet.

## VI. CONCLUSION

As the existing literature shows, it is important to think about pollution and its effects on behaviour, cognition, and fitness in a multistress environment in order to understand how wild fish respond to pollution and how it might cause feedback loops. Pollutants and other stressors can also mess up the structure of a syndrome, which can lead to differences in behaviour and personality between groups. Future study needs to figure out what this means for the evolutionary paths of wild populations and the evolutionary mechanisms that are causing such a wide range of behaviours in the face of rising pollution. We hope that this work will encourage more research to bridge the gap between ecotoxicology, behavioural ecology, and evolutionary ecology. This will help us predict the effects of pollutants on evolutionary processes and population resilience in ecosystems that have been changed by humans.

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