Individual-based Ecology

Individual-based Ecology 1: e137398 (2025)
DOI: 10.3897/ibe.1.137398

Research Article

Influence of personality traits on the response of a modelled population of stream-dwelling rainbow trout (*Oncorhynchus mykiss*) to microplastics consumption

Kathleen D. W. Church[1], Steven F. Railsback[2], Christina A. D. Semeniuk[1]

1 *Great Lakes Institute for Environmental Research (GLIER), University of Windsor, Windsor, ON, Canada*
2 *Lang Railsback & Associates; Department of Mathematics, Humboldt State University, Arcata, CA, USA*
Corresponding author: Kathleen D. W. Church (kathleen.church@mail.mcgill.ca)

Academic editor: Cara Gallagher
Received: 18 September 2024
Accepted: 4 February 2025
Published: 27 March 2025

Citation: Church KDW, Railsback SF, Semeniuk CAD (2025) Influence of personality traits on the response of a modelled population of stream-dwelling rainbow trout (*Oncorhynchus mykiss*) to microplastics consumption. Individual-based Ecology 1: e137398. https://doi.org/10.3897/ibe.1.137398

Abstract

Microplastics in freshwater habitats are consumed by fish, including stream-dwelling salmonids, which can alter food consumption or negatively affect swimming and foraging behaviour. As population-level effects are largely unknown, a population of stream-dwelling rainbow trout (*Oncorhynchus mykiss*) was simulated using the agent-based model 'inSTREAM 7' to model population-level effects (biomass) of behavioural changes caused by microplastics consumption. Individual fish were assigned all possible combinations of two personality traits (dominance, boldness/shyness) and consumed microplastics while foraging; and their microplastics consumption, body length and abundance were tracked for three different life stages (fry, juvenile, adult) for a period of 10 years. Three scenarios were explored: a low-impact scenario with microplastics causing decreased food consumption, a medium-impact scenario which added lower swimming speed and a high-impact scenario with additional reductions of foraging efficiency. Each scenario was tested for microplastics concentrations of 0%, 1% (i.e. current levels) and 3% (i.e. future levels) of drift food. Overall, microplastics consumption did not strongly affect trout abundance. Dominant adult trout consumed disproportionally more microplastics than all other fish, especially at higher microplastic concentrations. Personality traits influenced the response of the trout to microplastics ingestion: dominant and bold adults were smaller when food consumption was reduced; shy and subordinate adults were smaller when swimming speed was lowered; and all dominant adults, regardless of boldness, were smaller when foraging efficiency was impeded, with dominant and bold fry also less abundant in this scenario. However, effects on fish body length were only found at microplastic concentrations of 3%, indicating these outcomes can be prevented, as current levels of microplastics pollution are below this concentration. Nevertheless, microplastics ingestion may become an additional stressor that interacts with the myriad of mostly anthropogenic stressors that already affect wild salmonid populations.

Key words: Agent-based models (ABMs), behaviour, microplastics, population abundance, salmonids

Introduction

Microplastics, defined as plastic particles < 5 mm (i.e. Thompson et al. (2009)), are ubiquitous in virtually all marine, freshwater and terrestrial ecosystems (Rochman 2018). Historically, the impacts of microplastics pollution have been studied mostly in marine systems, while research on freshwater and terrestrial systems is more recent (Li et al. 2018). Freshwater ecosystems are highly susceptible to microplastics pollution (Thompson et al. 2009), with urban freshwater habitats being especially vulnerable, due to their proximity to pollutant sources (i.e. Silva-Cavalcanti et al. (2017)). A wide range of microplastic concentrations are commonly found across freshwater habitats (i.e. 0.08–7.4 items per litre; Luo et al. (2019)), with microplastics-free ecosystems becoming exceedingly rare (Rochman 2018).

Microplastics have been found in the gut of numerous freshwater animals (Hurley et al. 2017; Collard et al. 2019; O’Connor et al. 2022), including salmonids (O’Connor et al. 2020). Indeed, the quantification of microplastics in the gut of freshwater fish is considered a proxy of microplastic pollution within a given environment (Silva-Cavalcanti et al. 2017; Steer et al. 2017; Parker et al. 2021; but see O’Connor et al. (2020)). Nevertheless, the impacts of microplastics pollution on the growth, reproduction and survival of freshwater and marine taxa are highly variable, but this lack of consistent, strong effects on fish performance or fitness suggests that the effects of microplastics ingestion may be more subtle than anticipated, with more elusive behavioural effects occurring, rather than drastic physiological changes (i.e. Foley et al. (2018)). Changes in behaviour are typically the first line of defence against human-induced rapid environmental changes (Wong and Candolin 2015). Behavioural screenings serve as fast, sensitive toxicological tests, as changes in behaviour occur at concentrations well below those used in traditional toxicological assays (Melvin and Wilson 2013). Fish are an excellent model organism for evaluating the effects of microplastic pollution, as they are commonly used in toxicology assays (Scott and Sloman 2004).

Previous research on the behavioural responses of individuals to microplastics has shown that fish that ingest microplastics often exhibit changes in their swimming behaviour. For example, zebrafish (*Danio rerio*) engaged in hyperactive swimming behaviour following microplastics ingestion (exposure concentration: 1 mg/l; Chen et al. (2020)), while the common goby (*Pomatoschistus microps*) was less able to forage effectively on live prey (exposure concentration: 0.184 mg/l; Ferreira et al. (2016)). The European sea bass (*Dicentrarchus labrax*) also showed behavioural changes after exposure to both low (exposure concentration: 0.26 mg/l) and high (exposure concentration: 0.69 mg/l) levels of microplastics, including erratic and lethargic swimming behaviour and decreased resistance time (i.e. ability to maintain swimming ability while subjected to increasing water velocity), although reduced swimming velocity only occurred following exposure to the highest concentration (Barboza et al. 2018). Resistance is especially relevant for stream dwelling salmonids, like trout, that seek to maintain a stationary feeding station against the current (Piccolo et al. 2014). Intra-specific differences in the consumption and/or exposure to microplastics have also been reported (exposure concentration: 4.1 mg/l; Nanninga et al. (2021)). Differences in personality traits, or consistent behavioural differences amongst individuals (Réale et al. 2007), may affect the extent of microplastics consumption, as bolder and more aggressive individuals often achieve greater foraging success relative to shyer and less aggressive individuals (i.e. Biro and Stamps (2008); Mittelbach et al. (2014)), therefore being more likely to consume microplastics (i.e. exposure concentration: 0.5 mg/l; Chen et al. (2022)). The negative physiological effects of microplastics result from a combination of physical damage, which varies with particle size and shape, oxidative stress and adverse changes to gut microbiota (Li et al. 2022; Xiong et al. 2023), as well as from translocation into different tissues (McIlwraith et al. 2021; Dong et al. 2023). However, many of the sub-lethal effects of plastics ingestion are driven largely by reductions in apparent food availability, which may also affect populations (Foley et al. 2018; Marn et al. 2020). In a recent modelling study, Marn et al. (2020) showed that, although current quantities of ingested plastic (exposure concentration: 3% of food) were insufficient to prevent sexual maturation in loggerhead turtles (*Caretta caretta*), plastics consumption was likely negatively impacting populations due to slower development and delayed sexual maturation. Moreover, ecotoxicological studies show that pollutants that alter behaviour often modify or interact with personality traits. For example, inter-individual differences were dramatically diminished in guppies (*Poecilia reticulata*) following long-term exposure to fluoxetine (exposure concentration: 40 ± 3 ng/l; Polverino et al. (2021)). Behavioural changes resulting from exposure to pollutants may also alter individual personality traits in fish (i.e. Brodin et al. (2014); Lopes et al. (2019)) in a manner that increases further contact with the pollutant, thus creating a positive feedback loop that greatly intensifies any negative effects (i.e. Jacquin et al. (2020)). Due to their neurotoxic effects (Xiong et al. 2023) and the changes in some personality traits observed following microplastics ingestion (exposure concentration: 100,000 particles/l for prey; Felismino (2023)), microplastics also have the potential to substantially affect inter-individual differences.

Mechanistic population modelling enables the scaling up of effects of microplastics consumption from the individual to the population-level. Agent Based Models (ABMs), in particular, are effective tools to evaluate the effects that emerge from behavioural changes at the individual level and upscale them to the population level (Grimm et al. 2017). As they are based on primary principles, ABMs are able to incorporate key ecological processes that are often non-linear, such as survival and body size, to make predictions in complex habitats (Forbes et al. 2008), including freshwater systems. ABMs simulate large-scale population dynamics from the bottom-up via adaptive, autonomous agents that interact with each other (i.e. competition, reproduction) and the environment (i.e. predators, physical environment) (Grimm et al. 2005). In summary, by representing the different types of behaviour of individual animals, ABMs can effectively incorporate behaviour effects on population dynamics (Macal 2016; McEntire and Maerz 2019). ABMs additionally offer a higher degree of experimental control relative to field, laboratory and archival studies; provide greater visibility of non-linear dynamics; and give increased clarity of the mechanisms involved (Jackson et al. 2017). Finally, as ABMs are not limited by the same practical or time constraints of real-world studies, the use of ABMs also enables the simultaneous exploration of a range of different risk scenarios (Forbes et al. 2008).

In this study, an existing individual-based model of stream-dwelling trout population dynamics (Railsback et al. 2023) was modified to predict how microplastics consumption affects fish abundance and body size at the population level. The effects of microplastics consumption were evaluated for different life stages (i.e. ages 0, 1, 2+) and different personality traits (i.e. bold/shy, dominant/subordinate and their interaction) under three different impact scenarios over a 10-year period, representing approximately 5–6 generations of trout. These three scenarios represent increasingly detrimental effects of microplastic consumption on trout: 1) reduced food intake (Foley et al. 2018), 2) reduced food intake and slow swimming when a given threshold of microplastics consumption is attained (i.e. Tongo and Erhunmwunse (2022)) and 3) reduced food intake, slow swimming and reduced foraging efficiency at high water velocities when the threshold of microplastics consumption is exceeded (i.e. Barboza et al. (2018); Tongo and Erhunmwunse (2022)). Microplastic concentrations of 0%, 1% and 3% of the drift food available in the water column were tested for each of the three scenarios as they represent realistic environmental concentrations (i.e. Silva-Cavalcanti et al. (2017); Thiele et al. (2021)). We then analysed body size and fish survival for different age classes per assigned personality trait to determine which age and combined personality traits were most sensitive to microplastics consumption; and what implications this had, if any, on body size and population abundance.

Material and methods

Agent-Based Model (ABM)

‘inSTREAM 7.3’: The ABM ‘inSTREAM 7.3’ (individual-based Stream Trout Environmental Assessment Model) is an individual-based model of stream trout, created for river management and research purposes to assess how changes in habitat characteristics (i.e. temperature, flow, turbidity, food production) and biological processes (i.e. competition, food intake, predation) affect trout populations (Railsback et al. 2021a; Railsback et al. 2023). Different versions of ‘inSTREAM’ have been adapted to evaluate the effects of habitat type and size on the reproductive success of anadromous salmonids (i.e. Railsback et al. (2015)), as well as to assess how trout populations are affected by climate change (Ayllón et al. 2019), oestrogen contamination from human contraceptives (Forbes et al. 2017; Forbes et al. 2019), contamination by the fungicide prochloraz (Hazlerigg et al. 2023), physical barriers, such as beaver dams (Harvey and Railsback 2021) and the combined effects of anthropogenic change and genetic evolution (Ayllón et al. 2016, 2018). The ‘inSTREAM 7.3’ model was used in the present study to simulate a population of rainbow trout living in a freshwater river exposed to the microplastics in stream drift and in sediments.

The version of the model used in this study represents a single reach of a river (184 m long, ~ 5–10 m wide), consisting of a grid of rectangular cells that represents the spatial environment (i.e. the “mainstem” reach; Harvey and Railsback (2021)). Within the reach, the flow, temperature and turbidity of the water change on a daily basis. The concentration of food and microplastics in the water column and benthos that are not depleted by foraging trout remains constant for the entire simulation period, a time span of 10 years; and the availability of both drift food and microplastics in the water column is proportional to flow, while the availability of food and microplastics in the sediments is proportional to habitat size and microplastics were present in the habitat for the duration of the simulation. All trout are represented as individual agents and are initially assigned to a particular rectangular cell, where they can consume food and microplastics and inhabit available shelters. Each rectangular cell represents a small unit of river habitat (~ 1–4 m^2) with a defined depth and velocity that vary daily with flow, as well as available spawning areas and shelters that provide refuge from high flow and predators. Spawning occurs stochastically when specific size, condition and habitat conditions (i.e. date, flow, temperature) are met for female trout. The different stages of the trout life cycle, from egg to adult, are all represented in the model by agents: initially by redds that contain different numbers of developing eggs, then by individual fish once they emerge from their redds. No effects of microplastics exposure on the developing eggs and larvae within the redds were modelled in this study, as exposure to microplastics has not been found to alter either embryo survival, the percentage of larvae that successfully hatch each day or larval growth for rainbow trout (Jakubowska et al. 2022). After emergence from the redds, all trout are assigned a length, weight, body condition, sex and two personality traits: dominance or relative competitive ability, represented by the size of their foraging territory (i.e. dominant, intermediate, subordinate), as well as shyness/boldness towards predators, represented by the degree to which hiding decreases their risk of predation (i.e. bold, average, shy). All fry are assigned an age of 0, while all fish, including juveniles (age 1) and adults (age 2+), age by one year at the beginning of every year (i.e. 1 January). As female trout must be at least 1 year old to be able to spawn, a 10-year simulation represents approximately 5 to 6 generations of trout.

During a 10-year simulation run, daily physical inputs (stream flow, temperature and turbidity) influence trout survival and body size by affecting the habitats that individual fish select and the activities they choose to engage in, which then determines their foraging success and predation risk. The accumulated decisions of thousands of individual trout then impact population metrics like abundance, via the survival and reproductive success of numerous individual trout, as well as mean body length, through the body condition and growth of many individual trout (Fig. 1). This model runs through four time steps every day, representing daytime, night-time and both crepuscular periods (i.e. dawn, dusk; Railsback et al. (2021b)). Following emergence from the redds, fish of all ages follow the same set of simple rules. At each time step, all fish decide which nearby habitat cell will maximise future fitness over a 60-day period, depending on which of three activities they engage in: hiding, drift feeding or search feeding and then move to the selected habitat and engage in the activity that will maximise their fitness. Larger fish are able to select from a larger radius of cells than smaller fish (Harvey and Railsback 2014) and are also given priority access to habitats to account for size hierarchies (i.e. Nakano (1995)). The “dominance” personality trait indirectly affects the position of a given fish within the size hierarchy, as the larger feeding territories of dominant and intermediate-dominant fish may result in higher growth rates and larger body sizes. Individual fish must trade off the risk of predation while foraging with the risk of mortality due to poor body condition and these trade-offs also drive habitat and activity selection. Fish reduce their mortality due to predation when they

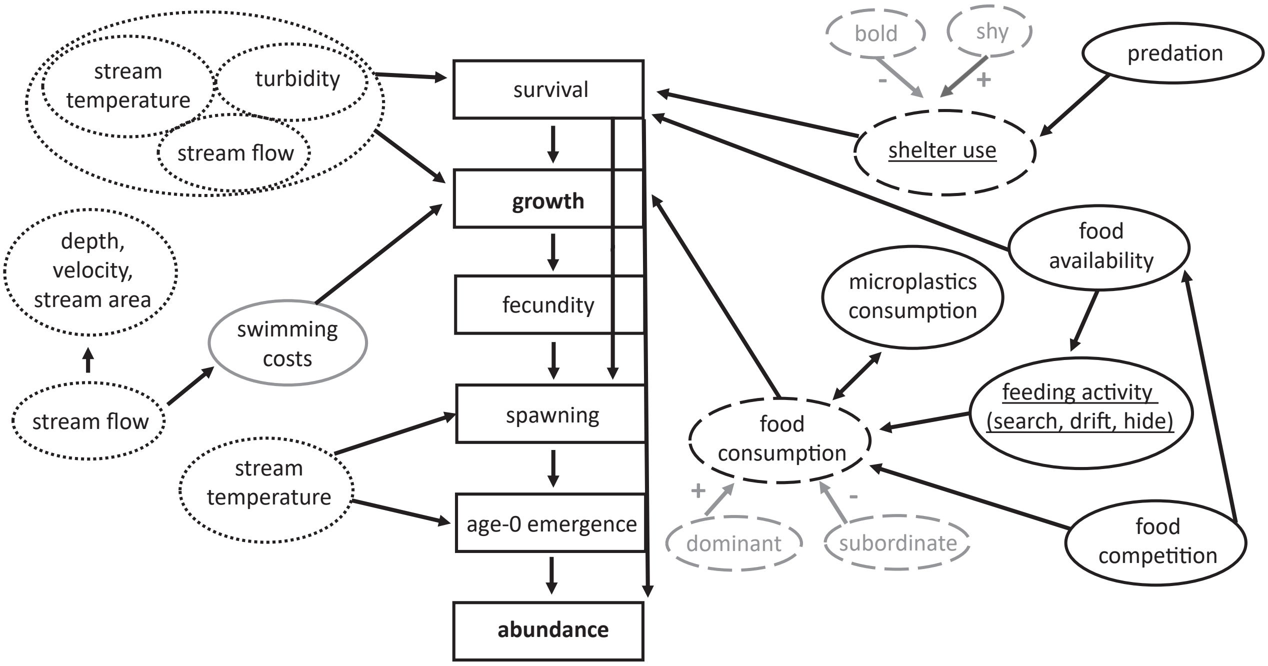

Figure 1. Flow diagram showing the key processes of inSTREAM7 and how different factors affect trout microplastics consumption, survival, growth and abundance. Legend: Dotted lines indicate the physical environment, dashed lines show personality traits (dominance, boldness/shyness), underlined text indicates trout behavioural choices and bold text indicates model outcomes.

hide, although they also increase their chances of starvation or disease by not consuming any food, while feeding fish face the opposite risks, as they are more exposed to terrestrial and aquatic predators (Railsback et al. 2020). Trout mortality is simulated by several survival sub-models, with each sub-model representing a different cause of mortality: high temperature, stranding, low condition which includes both starvation and disease, terrestrial predation and predation by piscivorous fish). The probability of survival for each individual fish is determined for each different source of mortality via “survival functions” and then a random Bernoulli trial is conducted to determine whether the fish survives each kind of mortality at each time step. These survival functions represent empirical knowledge (summarised by Railsback et al. (2023) and references therein) of how risk varies with relevant characteristics of individuals and their habitat, such as trout size and condition, light intensity, temperature, availability of hiding and escape cover and water depth and velocity. The survival functions for terrestrial and aquatic predation differ to reflect that terrestrial predators are less likely to target smaller fish, while piscivorous fish, including cannibal trout, tend to be more gape-limited and hence less risk to larger fish. Types of aggressive behaviour are not directly modelled in inSTREAM 7.3, but fish deplete the resources (i.e. food, shelter) within a given habitat in order of arrival so they become unavailable for other fish, with larger fish arriving before smaller fish (Railsback et al. 2023). Likewise, larger/older fish are able to displace smaller/younger fish from preferred habitats into less desirable habitats with faster water velocities or shallower depths. Fish remember their previous actions during the same day (i.e. three previous time steps) and use this memory to maximise survival over a 24-hr period, similar to what has been observed in wild populations (Railsback et al. 2020).

Simulations were run using the default, or ‘standard’ parameter values, except as noted. Standard parameter values were defined, based on a sensitivity analysis using the same simulated freshwater river habitat and were previously calibrated to obtain realistic long-term average results (as described by Railsback et al. (2023)).

Modifications to ‘inSTREAM 7.3’

To represent the effects of microplastic consumption on trout food consumption, swimming ability and foraging efficiency in our study, additional functions and modifications were made to the source code of ‘inStream 7.3’ using NetLogo (version 6.2.1; Wilensky (1999)). A pattern-oriented modelling approach was used to ensure realism (see Suppl. material 1: appendix S1).

Effects of microplastic consumption scenarios

Scenario 1: Reduction in food consumption

Microplastics were added to both the water column and sediments in all three scenarios. The original “inSTREAM 7.3” included the concentrations of food available as either invertebrate drift-consumed while drift foraging or food consumed while search-feeding in the sediments, as the daily rate of available prey in grams. Microplastics were added as another type of food, represented by the parameter **micro-conc** and expressed as a percentage of the food available in the water column (i.e. drift food), with twice as many microplastics in the sediments (i.e. search food), in accordance with the observations in natural habitats (i.e. McNeish et al. (2018); Ma et al. (2019)). Microplastics concentrations of 0%, 1% and 3% of the available drift food in the habitat were evaluated in all scenarios. These concentrations reflect microplastics consumption of wild and commercial freshwater fish (i.e. Silva-Cavalcanti et al. (2017); Thiele et al. (2021)), except for the 3% concentration that represents a future scenario. Trout were not able to discriminate between real food and microplastics and were assumed not to show any preference for microplastic colour, shape or particle type. In all scenarios, microplastics are excreted regularly and do not build up in the bodies of the fish (i.e. Kim et al. (2020)); consequently, mortality and reductions in fitness that result from microplastics ingestion are driven by behavioural responses: the reduction in food consumption or changes in habitat use and activity choices. Scenario 1 represents a “best case scenario”, where the consumption of microplastics does not explicitly alter behaviour, but only reduces consumption of real food (i.e. Foley et al. (2018)). We represent this in the model by subtracting any ingested microplastics from the total food consumed. We also modified the memory function used to maximise fish survival over 24 hours by having remembered prey consumption as the sum of both prey and microplastics consumption. Consequently, fish make future decisions based on the assumption that the consumed microplastics do not differ from real food items, which results in fish consuming less food when microplastics concentration increases. At the population level, this is expected to be translated into shorter body lengths (i.e. smaller size), but not to significantly affect trout abundance.

Scenario 2: Reduction in swimming speed

In this scenario, fish are not able to swim as fast following microplastics consumption, which has been observed in laboratory studies (see below), but has not yet been evaluated under natural conditions; this is in addition to experiencing the reduced food consumption described for Scenario 1. Limited swimming ability can affect habitat choice and food intake, as fish become limited to foraging in low velocity habitats and are more likely to hide in shelter than to forage when water velocity is high. To account for these changes, a memory function, similar to the memory function used for food consumption, was added to keep track of the quantity of microplastics consumed by individual trout over the previous seven days. Consumption thresholds are based on laboratory findings from juvenile African freshwater catfish (*Clarias gariepinus*) exposed to microplastics and correspond to 5 mg (threshold 1) and 28 mg (threshold 2) of consumed microplastics for a mean body length of 17.28 cm (Tongo and Erhunmwunse 2022). However, trout reductions in swimming speed following the second threshold were less drastic than those of catfish, reflecting reductions in fish swimming speed observed in other studies (i.e. Mattsson et al. (2015)). These two thresholds (i.e. 0.29 mg and 1.6 mg of microplastics per cm body length, respectively) were then adapted to the different mean body lengths of the three age classes of salmonids in inSTREAM 7.3: age 0 (mean length: 5.18 cm; thresholds: 1.5 mg, 10 mg), age 1 (mean length: 9.33 cm; thresholds: 2.7 mg, 15 mg) and age 2+ (mean length: 21.08 cm; thresholds: 6.1 mg, 33 mg). If microplastics consumption exceeds the first threshold of 1.5, 2.7 or 6.1 mg per week for fry (age 0), juveniles (age 1) or adults (age 2+), respectively, then the parameter **trout-max-speed-B** is changed from 21 to 18, representing a 15% reduction in maximum speed (i.e. Tongo and Erhunmwunse (2022)). If the second consumption threshold of 10, 15 or 33 mg of microplastics is exceeded in a week by fry, juveniles or adults, respectively, the maximum sustainable swimming speed then decreases another 15%, for a total reduction of 30% (i.e. Tongo and Erhunmwunse (2022); Mattsson et al. (2015)) and the parameter **trout-max-speed-B** is further lowered to 14.1. These assumptions no doubt are simpler than reality, but reflect our empirical knowledge. As microplastics ingestion is associated with permanent histological damage (Peda et al. 2016; Yin et al. 2018) and neurotoxic effects (Ding et al. 2018), this change in maximum sustainable swimming speed is irreversible for individual fish. Scenario 2 reflects some observed effects of microplastics ingestion on swimming ability (i.e. Tongo and Erhunmwunse (2022)) and is less conservative than Scenario 1. Reductions in swimming speed are likely to result in lower fitness at the individual level, with foreseen decreases in fish abundance (i.e. increased mortality due to impaired foraging) and body length as microplastics concentration increases, due to reductions in both food consumption and swimming speed.

Scenario 3: Reduction in foraging efficiency

For Scenario 3, prey capture efficiency through drift foraging is also reduced in high velocity water flow, in addition to the reduction in swimming speed and food consumption that occurs in both previous scenarios. In inSTREAM 7.3, a decreasing logistic function is used to represent foraging success as a function of the ratio of stream velocity over the maximum sustainable swimming speed. The ability to capture prey at higher velocities is represented by the parameter **trout-capture-R1**, the ratio of stream velocity over the maximum sustainable swimming speed at which foraging success is 10%. Reductions in foraging efficiency in high velocity habitats will further impact fitness through habitat choice and food intake, as fish become even more limited to lower velocity habitats and more likely to hide than to forage. This parameter is lowered from 1.3 to 1.17 when the first microplastics consumption threshold is reached (i.e. 1.5, 2.7 or 6.1 mg per week for fry, juveniles or adults, respectively) and is further lowered to 1.0 when the second consumption threshold is reached (i.e. 10, 15 or 33 mg per week for fry, juveniles or adults, respectively). No further decreases in prey capture efficiency occurred after the second threshold. This change in parameter values is also permanent, even though consumed microplastics are regularly excreted and do not build up in the bodies of the fish, given that microplastics are always available for consumption. The change represents a reduction of the ability of trout to capture any prey when the velocity of their habitat exceeds their maximum sustainable swimming speed (Railsback et al. 2023). As the least conservative, Scenario 3 represents a combination of several observed behavioural effects that occur following microplastics ingestion (i.e. Barboza et al. (2018); Yin et al. (2018); Wang et al. (2021); Tongo and Erhunmwunse (2022)). Lower swimming speed and reduced foraging efficiency are both expected to limit the use of high-water velocity habitats and to increase the frequency of hiding activity, relative to drift or search foraging. Likewise, when trout do choose to feed, they will be less able to engage in drift feeding within the water column and are likely to engage in more search-feeding in the sediments. This response is likely to increase overall consumption of microplastics due to the higher concentrations of microplastics in the benthos. Reductions in foraging efficiency at high water velocities are likely to lower fitness more than in scenario 2, with predicted decreases in population abundance and body length, due to the combined effects of reduced food consumption, lower swimming speed and decreased foraging efficiency.

Incorporation of personality

We assigned two separate personality traits to each fish: dominance (i.e. increased access to food resources; Kaufmann (1983)) and shyness/boldness (i.e. tendency to risk predation; Réale et al. (2007)). Upon emergence, each fish was randomly assigned a dominance score (i.e. “dominant”, “intermediate” or “subordinate”) and a boldness score (i.e. “shy”, “average” or “bold”), represented numerically by the three parameters discussed below (Table 1). The dominance trait was represented by the parameter **react-dist-B**, i.e. the detection radius around fish while foraging, a proxy for territory size. Dominant fish are, thus, able to consume food over a larger area than subordinate fish and vice versa (e.g. Candolin and Voigt (2001)). Likewise, for shyness/boldness, the parameters **mort-terr-pred-hiding-factor** and **mort-fish-pred-hiding factor**, which account for terrestrial and fish predators, respectively, represent the degree to which hiding reduces predation, with shy fish benefitting more than bold fish (see Table 1). This personality trait alters habitat and activity choices, with shy fish hiding more often and foraging when risk is lower and bold fish

Table 1. Values of model parameters associated with the dominance and shyness/boldness personality traits, based on default values suggested for inSTREAM 7.3 (Railsback et al. 2023) and the achievement of realistic model outputs.

Model parameter	Personality trait	Levels	Parameter value
mort-terr-pred-hiding-factor	Shyness / Boldness	Shy	0.90
		Intermediate	0.80
		Bold	0.70
mort-fish-pred-hiding-factor	Shyness / Boldness	Shy	0.70
		Intermediate	0.60
		Bold	0.50
trout-react-dist-B	Dominance	Dominant	2.25
		Intermediate	2.00
		Subordinate	1.75

foraging more under high risk of predation. In the wild, shy fish are generally more likely to seek habitats that provide protection from predators, while bold fish are more likely to choose riskier habitats (e.g. Wilson et al. (1993); Hulthén et al. (2017)). A pattern-oriented model approach was used to ensure realistic personality traits (Suppl. material 1: appendix S1).

Both personality traits were incorporated into all three scenarios. All trout are expected to consume greater quantities of microplastics with higher concentrations of microplastics; however, as dominant trout are defined by a higher foraging success, they are expected to consume proportionally greater quantities of microplastics, relative to intermediate and, especially, to subordinate trout. Dominant trout are expected to reach the microplastics consumption thresholds that result in permanently lowered swimming speed and reduced foraging efficiency more frequently than intermediate or subordinate trout, especially the second microplastic-consumption thresholds. Consequently, a greater difference in fitness is expected for dominant trout in the presence of microplastics relative to intermediate and subordinate trout, regardless of their boldness.

Additionally, the trade-off between risk and reward may break down for bold trout when exposed to higher concentrations of microplastics, with reductions in foraging success (driven by lower swimming speed and/or less efficient prey capture) accompanied by no changes in predation risk. As a result, trout with average boldness may experience higher fitness relative to bold or shy trout at higher microplastics' concentrations. Shy individuals will spend less time foraging and spend more time hiding than trout with average boldness and especially bold trout, as a result of reduced swimming speed and impeded foraging efficiency. However, as trout that are both subordinate and shy tend to prioritise foraging less than the other combined personality traits, they are also expected to consume fewer microplastics and are, thus, less likely to be negatively harmed by microplastics ingestion, especially under Scenario 3. The same would apply to subordinate trout with average boldness, but to a lesser degree. Trout that are both dominant and bold, on the other hand, are more likely to be affected by microplastics as they tend to prioritise foraging more than the other combined personality traits and will, thus, be more likely to experience the negative effects of microplastic consumption relative to dominant trout that are also shy or trout with intermediate dominance, regardless of their level of boldness.

Model evaluation

The model was evaluated to determine if it reproduced patterns observed in real-life fish regarding personality and microplastics consumption. The literature was first searched for general patterns driven by the personality traits and microplastic concentrations and their associated assumptions, that were added to the model. We then evaluated these assumptions by how well the model reproduced those patterns. Here, we present the patterns found and how these patterns were defined in a statistically testable way (detailed below).

Personality traits

To confirm the realism of our modelled personality traits, we used a pattern-oriented modelling approach to evaluate the recreation of four real-world behavioural patterns: i) variable survival pattern: survival for different personality traits varies over time (Dingemanse and Réale 2013), ii) behavioural syndrome under predation pattern: increased predation selects for positive correlations between boldness and dominance (i.e. behavioural syndromes; Bell and Sih (2007)), iii) risk-reward with abundant food pattern: the shy-bold behavioural axis results from trade-offs between risk and reward that tend to break down when food is abundant, as fish have access to plentiful food regardless of risk-taking (Wilson et al. 1994; Seltmann et al. 2014) and iv) dominance in a competitive environment pattern: higher competition environments select for more dominant fish (i.e. Gilmour et al. (2005)). The personality patterns were verified using Scenario 1 (see below) in the absence of microplastics (0%), using data only from the latter 8 years of the simulations to ensure the results were independent of the initial conditions.

For the variable survival pattern (i.e. personality pattern i), the coefficient of variation (CV = (SD/mean) × 100)) was used to quantify variability in survival over time or the proportion of total abundance for the nine different combinations of the two personality traits within each age group. Generally, a coefficient of variation above 20% indicates substantial variability (i.e. Reed et al. (2002)). As personality traits were assigned to trout in equal numbers, differences in abundance reflect differential survival. Welch's t-tests were then used to assess the occurrence of the remaining three real-world behavioural patterns. For these patterns, one run of the 10-year simulation was used to represent each of the environmental conditions being compared (i.e. one simulation run for low predation vs. one simulation run for high predation), with data collected annually on the census day (i.e. Julian day: 266; only non-leap year values were used for simplicity) from the 3rd until the 10th year. For the behavioural syndrome under predation pattern (i.e. personality pattern ii), the proportional abundance of bold and dominant trout, shy and dominant trout and shy and subordinate trout were compared in a high and a low predation environment. These three combined personality traits were selected to facilitate comparison with the real-world study that reported this particular pattern (i.e. Bell and Sih (2007)). To compare high and low predation pressure, the minimum probability of surviving both terrestrial (i.e. reach-terr-pred-min) and fish predation (i.e. reach-fish-pred-min) in the riskiest combination of habitat and activity was lowered to 0.85 (i.e. high predation) and raised to 0.95 (i.e. low predation) from a standard value of 0.90 which represents a moderate quantity of predation for many stream environments (i.e. Railsback et al. (2023)). For the risk-reward with abundant food pattern (i.e. personality pattern iii), the proportional abundance of shy trout, bold trout and trout with average boldness (irrespective of dominance) was compared in an environment with either a standard or high availability of food (i.e. 150% standard), while for the dominance in competitive environments pattern (i.e. personality pattern iv), the proportional abundance of dominant trout (regardless of boldness) was assessed in a low and a high food competition environment (i.e. 80% standard, 120% standard, respectively).

Microplastic consumption

A pattern-oriented modelling approach was also used to evaluate the occurrence of three real-life patterns of microplastic consumption that are affected by life history and optimal foraging: i) larger fish consume more microplastics than smaller fish (Horton et al. 2018; McIlwraith et al. 2021), ii) consumption of microplastics is higher when environmental concentrations are higher (Silva-Cavalcanti et al. 2017; Jaafar et al. 2021) and iii) microplastic consumption is higher when food is more scarce (Aljaibachi and Callaghan 2018; Cheng et al. 2020). Patterns of microplastics consumption were also validated within the Scenario 1 environment, when fish experienced reductions only in food consumption, but no effects on swimming speed or foraging efficiency, using microplastics concentrations of 1% and 3%.

To determine whether larger fish consume more microplastics than smaller fish (i.e. microplastics consumption pattern i), a linear model was constructed with the quantity of microplastics consumed as the response variable and body size (small, large), microplastics concentration (1%, 3%) and age (0, 1, 2+) as the predictor variables. Fish of each age group were classified as small or large based on their body length relative to the mean body length for their corresponding age group. Small fish were shorter than one standard deviation below the mean body length for their age category, while large fish were longer than one standard deviation above the mean body length. Welch's t-tests were then used to assess if higher microplastics consumption occurs when environmental concentrations are also higher (i.e. microplastics consumption pattern ii). Overall microplastics consumption of trout was compared with the lowest (i.e. 1%) and highest (i.e. 3%) microplastics concentrations, with data collected as above, with one simulation run for each of these two concentrations of microplastics. Finally, another linear model was constructed to examine if microplastics consumption is higher when food is more scarce (i.e. microplastics consumption pattern iii). Microplastics consumption, scaled to the total quantity of available food, was the response variable, while the quantity of available food (standard quantity, half the standard quantity), the concentration of microplastics and trout age were the predictor variables.

Data analysis

Microplastic consumption scenarios

To evaluate the effects of the three different scenarios on fish biomass at the population level, data from several annual censuses conducted for each of the 10-year simulations were used, with only the last 8 years of the simulation considered to ensure results were independent from initial conditions (Railsback et al. 2023). Data on the entire population were surveyed in autumn (i.e. Julian day: 266). For each population census, we collected data on fish length and abundance from each age group (ages 0, 1 and 2+), for each combination of the personality traits. As correlations between behavioural traits (i.e. behavioural syndromes; Sih et al. (2004)) are not ubiquitous in nature and are highly context dependent (Dingemanse et al. 2007), we included all possible combinations of the two different personality traits. Ten replicate simulations were conducted per each microplastics concentration for each of the three scenarios, giving a total of 90 model runs, 30 per scenario.

Results from model simulations were analysed using linear mixed-effect models, using the 'lme4' package in R (Bates et al. 2015; R Core Team 2021), with p-values obtained via the 'lmerTest' package (Kuznetsova et al. 2017). When values were significant, post-hoc Tukey HSD tests were conducted using the 'multcomp' package (Hothorn et al. 2008) to identify which groups were significantly different. Trout microplastics consumption, as well as length and abundance at the population level, were the three independent response variables of the linear mixed-effect models, while the run number of the simulation (numeric, 1–30) was set as the random effect. The fixed effects included microplastics concentration (categorical, 0%, 1%, 3%), trout age (categorical, 0, 1, 2+), personality (categorical, dominant-bold, dominant-average, dominant-shy, intermediate-bold, intermediate-average, intermediate-shy, subordinate-bold, subordinate-average, subordinate-shy) and year (continuous, 3–10). As length and abundance vary for the different age groups and personality traits, we looked for any significant interactions with microplastics concentration. We initially tested for three-way interactions between microplastics concentration, age and personality; and two-way interactions between: microplastics concentration and year, microplastics concentration and age and microplastics concentration and personality.

Mortality at age 1 and age 2 was determined by subtracting the abundance of fish from each age group at the end of the year (i.e. Julian Day 365), from the abundance at the beginning of the year (i.e. Julian Day 1, when all fish age by 1 year). As the simulation begins and ends in September, the first calculations for mortality used data from Julian Day 1 on the 3rd year and Julian Day 365 on the 4th year (i.e. year 4 mortality), while the final mortality calculations used data from Julian Day 1 on the 9th year and Julian Day 365 on the 10th year (i.e. year 10 mortality). The number of fish of each age class on Julian day 1 was used to determine recruitment. As personality traits are assigned to emerging fish in equal numbers in May and June, mortality for age 0 fish was not explicitly determined, but was rather inferred through fry abundance.

Sensitivity analysis

A sensitivity analysis (summarised in Suppl. material 1: appendix S2) was conducted to assess the relative effects of the stream and trout parameters modified in this study (Suppl. material 1: table S1) on population biomass (i.e. a single population-level measure that accounts for both abundance and body length). The results of a sensitivity analysis for the remaining parameters that were not modified in this study are available in the user manual (see Railsback et al. (2023)). Parameters were varied one-by-one to evaluate their effects on trout biomass after 10 years. Parameters not being tested were set at their default values (i.e. Suppl. material 1: table S1). A range of parameter values close to the default value were evaluated (as summarised in Suppl. material 1: S1). These values were based on empirical evidence to ensure realism (i.e. Cunningham (2007); Railsback et al. (2009); Railsback et al. (2023)). The relationships between the modified parameters and fish biomass were plotted to determine their direction and to identify which parameters exert the strongest impacts on population biomass, as determined by the largest absolute value of the slope across the range of values observed in our study (Suppl. material 1: fig. S1). Parameter values were standardised and then scaled from 0 to 1, with 0 representing the lowest value tested, 0.5 representing the middle value (usually the default value) and 1 representing the highest value tested (*sensu* Cunningham (2007)). To ensure results were independent from initial conditions, only data from the last five years (i.e. years 5–10) of the 10-year simulations were analysed. The absolute value of the “scaled slope” of population biomass over the full range of scaled parameter values was then used to rank each of the parameters according to their effects on the model’s outputs (i.e. trout biomass).

Results

Model evaluation

Four patterns were used to verify whether our personality parameterisation reproduced known, real-world responses. For the variable survival pattern, both personality traits and all age groups exhibited substantial variability in survival over the simulation run (Suppl. material 1: fig. S2A). Due to the particularly high mortality characteristic of the fry stage (Elliott 1994), CV’s for age-0 fish are substantially lower than for the other age groups. Although all personality traits exhibited substantial variability (i.e. > 20%), dominant trout (regardless of boldness) showed the lowest variability in survival, followed by intermediate-dominant trout for age 1 and age 2+ (regardless of boldness). Conversely, subordinate trout (regardless of boldness), as well as shy and average-bold trout (regardless of dominance), showed similar variability in survival, with substantially higher variability for age 2+, relative to age 1. For the behavioural syndrome under predation pattern, the proportion of trout that were both bold and dominant was greater under higher relative to lower predation (Welch’s t-test, t = 3.90, df = 177.14, p = 0.00013), while the proportion of trout that were both shy and dominant was smaller when predation was higher than when it was lower (Welch’s t-test, t = -2.98, df = 193.61, p = 0.0033). However, the proportion of trout that were both shy and subordinate did not differ under the two predation regimes (Welch’s t-test, t = 0.60, df = 146.24, p-value = 0.55). For the risk-reward with abundant food pattern, dominant fish that were also bold or shy were proportionally less abundant when food was abundant than when only a standard amount of food was available (Suppl. material 1: fig. S2B). For the dominance in competitive environments pattern, a greater proportion of dominants (regardless of boldness) were found in the high competition environment with less available food, relative to the low competition environment with greater food availability (Welch’s t-test, t = 4.11, p < 0.0001).

In comparing model predictions of microplastics consumption with real-world patterns, larger fish consumed more microplastics than smaller fish within the same age category (LM, $F_{2,288} = 26.73$, p < 0.0001). As well, more microplastics were consumed by all fish when microplastics concentrations in the environment were higher (1% vs. 3% microplastics, Welch's t-test, t = -3.78, df = 154.7, p-value = 0.0002). Relative microplastics consumption was also higher when food was more scarce, when microplastics consumption was scaled to account for food availability (LMM, $F_{1.720} = 5.18$, p = 0.023).

Effects of microplastic consumption

Microplastics consumption

Microplastics consumption was also affected by significant interactions between age, personality and microplastics concentration in all three scenarios (LMMs, all p's < 0.00001; Fig. 2). Across all scenarios, age 2+ fish consumed substantially more microplastics than all other age groups. Dominant fish (regardless of boldness) consumed substantially more microplastics than the other personality types at microplastics concentrations of 3%, in all scenarios (Fig. 2), but this tendency was highest under Scenario 2 (Fig. 2B) and lowest in Scenario 3 (Fig. 2C). In contrast, subordinate and shy fish consumed the fewest microplastics in Scenario 1 (Fig. 2A) and Scenario 2 (Fig. 2B), while subordinate fish with average-boldness consumed the fewest microplastics in Scenario 3 (Fig. 2).

As well, significant interactions were found amongst trout age, microplastics concentration and simulation year. A decrease in microplastics consumption over time was observed for age-2+ fish at concentrations of 3% under Scenario 1 (LMM, $F_{4,5987} = 5.81$, p = 0.00012; Fig. 3A) and Scenario 2 (LMM, $F_{4,5989} = 14.79$, p < 0.00001; Fig. 3B), but not for Scenario 3 (LMM, $F_{3,8077} = 0.11$, p = 0.96; Fig. 3C), where microplastics consumption remained unchanged over simulation year.

Body size

Fish body size, as represented by body length, was significantly affected by interactions amongst age, personality and microplastics concentration, for all three scenarios (LMMs, all p's < 0.00001; Fig. 4). For all scenarios, only the body size of age-2+ fish was affected by microplastics consumption (LMM, all other p's > 0.7). Overall, body size was highest for dominant fish across all scenarios (Tukey's HSD, dominant vs. intermediate or subordinate, p's < 0.001) and also tended to be higher for intermediate-dominant fish than for subordinate fish, regardless of boldness (Tukey's HSD, intermediate vs. subordinate, p's < 0.001).

In Scenario 1, body length of dominant and bold age-2+ fish was negatively affected at microplastics concentrations of 3% (Tukey's HSD, 1% vs. 3% microplastics, z = -3.36, p = 0.0022, 0% vs. 3% microplastics, z = -2.83, p = 0.013, Fig. 4A). In Scenario 2, body size of subordinate and shy age-0 fish was negatively affected by microplastics concentrations of 3% (Tukey's HSD, 0% vs. 3% microplastics, z = -2.62, p = 0.024; Fig. 4B), while in Scenario 3, body size of age-2+ dominant fish was negatively affected by microplastics concentrations of 3% (Tukey's HSD, 1% vs. 3% microplastics, z = -2.35, p = 0.049, 0% vs. 3% microplastics, z = -3.60, p < 0.001; Fig. 4C).

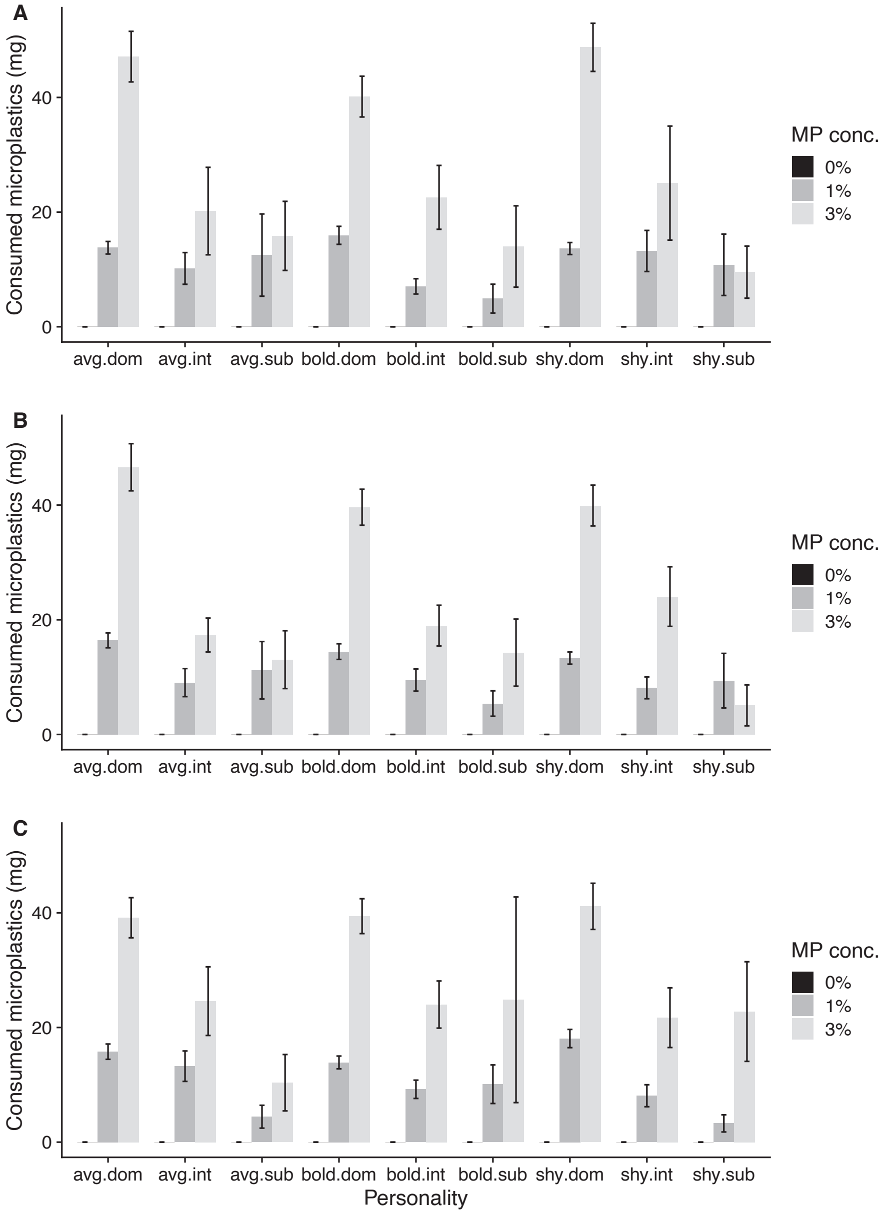

Figure 2. Mean weekly microplastics consumption (± 95% C.I.s) of age 2+ rainbow trout with different combinations of personality traits (shy, average, bold; dominant, intermediate, subordinate) at different microplastic (MP) concentrations (0%, 1%, 3%) for each scenario: **A** reduction in food consumption, **B** reduction in swimming speed and **C** reduction in foraging ability. Legend: sub = subordinate, avg = average-boldness, dom = dominant, int = intermediate-dominance.

Interactions between age and simulation year were significant for all three scenarios (LMMs, all p's < 0.00001), as body size of age-2+ fish decreased over time in a similar manner in each of the scenarios (Fig. 5). No significant interactions between year and microplastics concentration were detected for any scenario (LMMs, all p's > 0.42). Interactions between trout age, microplastics concentration and simulation year were not significant for any scenario (LMMs, all p's > 0.15).

Mortality

Patterns of recruitment and mortality appear to reflect general patterns of abundance, with higher mortality and higher survival experienced by fish that were more abundant (Suppl. material 1: fig. S3). Although mortality was highest for

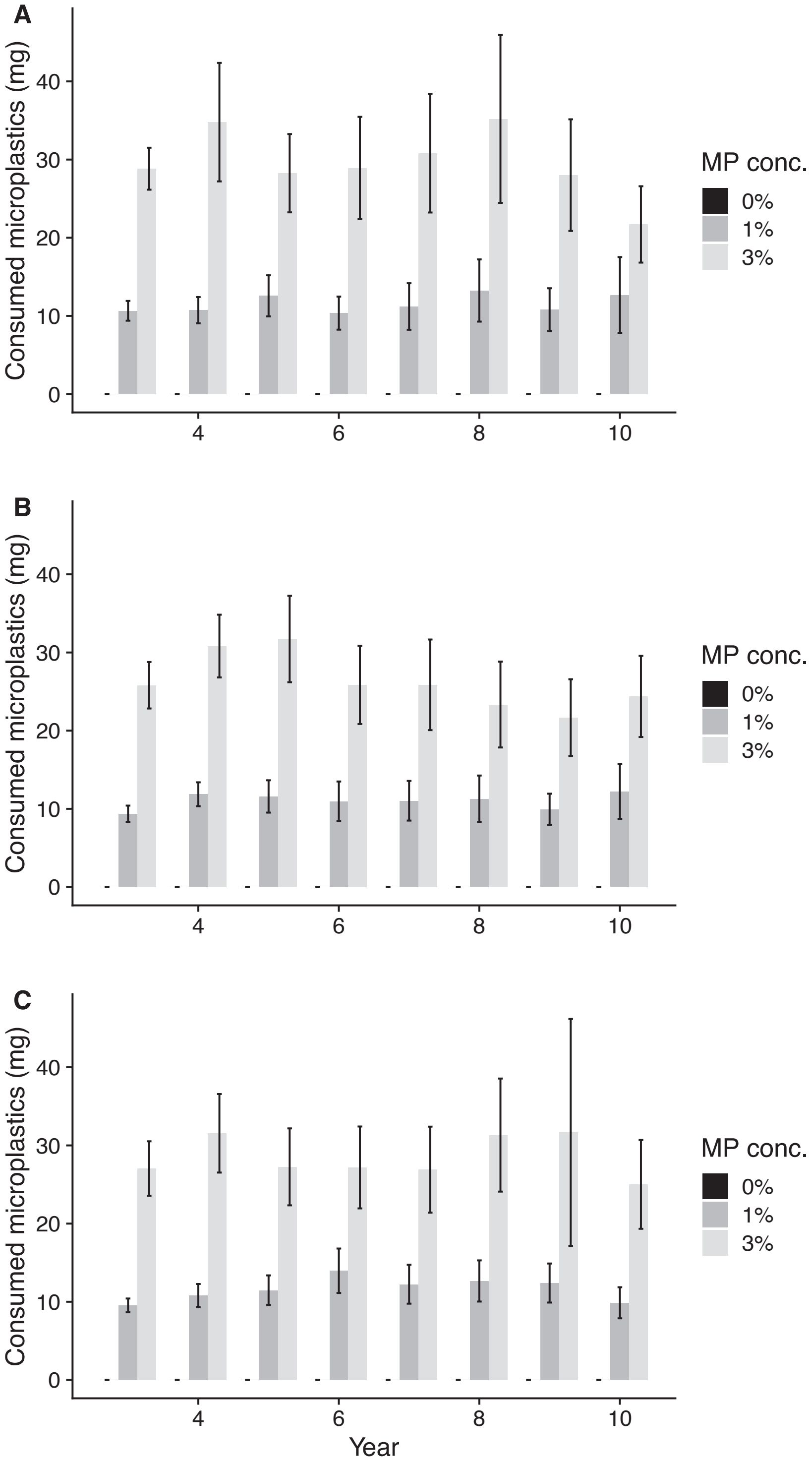

Figure 3. Mean weekly microplastics consumption (± 95% C.I.s) of age 2+ rainbow trout over time, at different microplastic (MP) concentrations (0%, 1%, 3%) for each scenario: **A** reduction in food consumption, B reduction in swimming speed and **C** reduction in foraging ability.

bold and dominant fish, they were the most abundant in all scenarios and were also recruited and survived in greater numbers, than the other dominant fish, as well as to fish with intermediate dominance and especially subordinate fish, regardless of boldness (Suppl. material 1: fig. S4). Overall patterns of recruitment and mortality were similar over simulation year and for the three effects of microplastics consumption scenarios (Suppl. material 1: fig. S4).

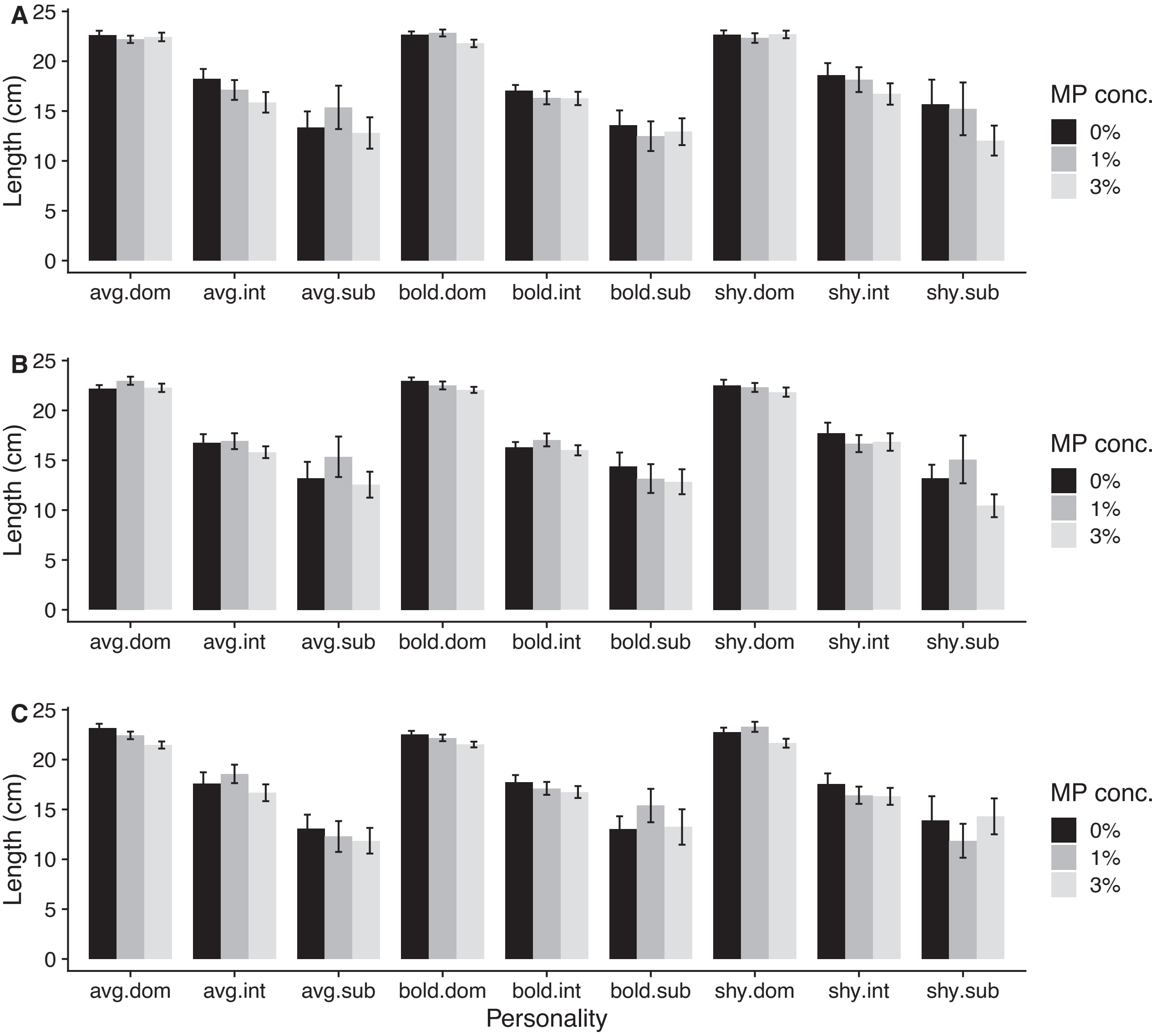

Figure 4. Mean body length (± 95% C.I.s) of age 2+ rainbow trout with different combinations of personality traits (shy, average, bold; dominant, intermediate, subordinate) at different microplastics (MP) concentrations (0%, 1%, 3%), for each scenario: **A** reduction in food consumption, **B** reduction in swimming speed and **C** reduction in foraging ability. Legend: sub = subordinate, avg = average-boldness, dom = dominant, int = intermediate-dominance.

Abundance

Abundance was affected by interactions between age and personality for all three scenarios (LMMs, all p's < 0.00001). Abundance differed amongst the different personality traits, but only for age-0 fish (Fig. 6). In essence, dominant and bold age-0 fish tended to be the most abundant in all scenarios, while subordinate and shy age-0 fish tended to be the least abundant within this cohort.

Similarly, microplastics' concentration significantly interacted with age in all three scenarios, but only affected abundance in age-0 fish (LMMs, all p's < 0.01; Fig. 6). There was lower abundance of age-0 fish in the presence than absence of microplastics (Fig. 6). Similarly, in Scenario 3, the abundance of dominant and bold age-0 fish was significantly lower in the presence than absence of microplastics (Fig. 6C).

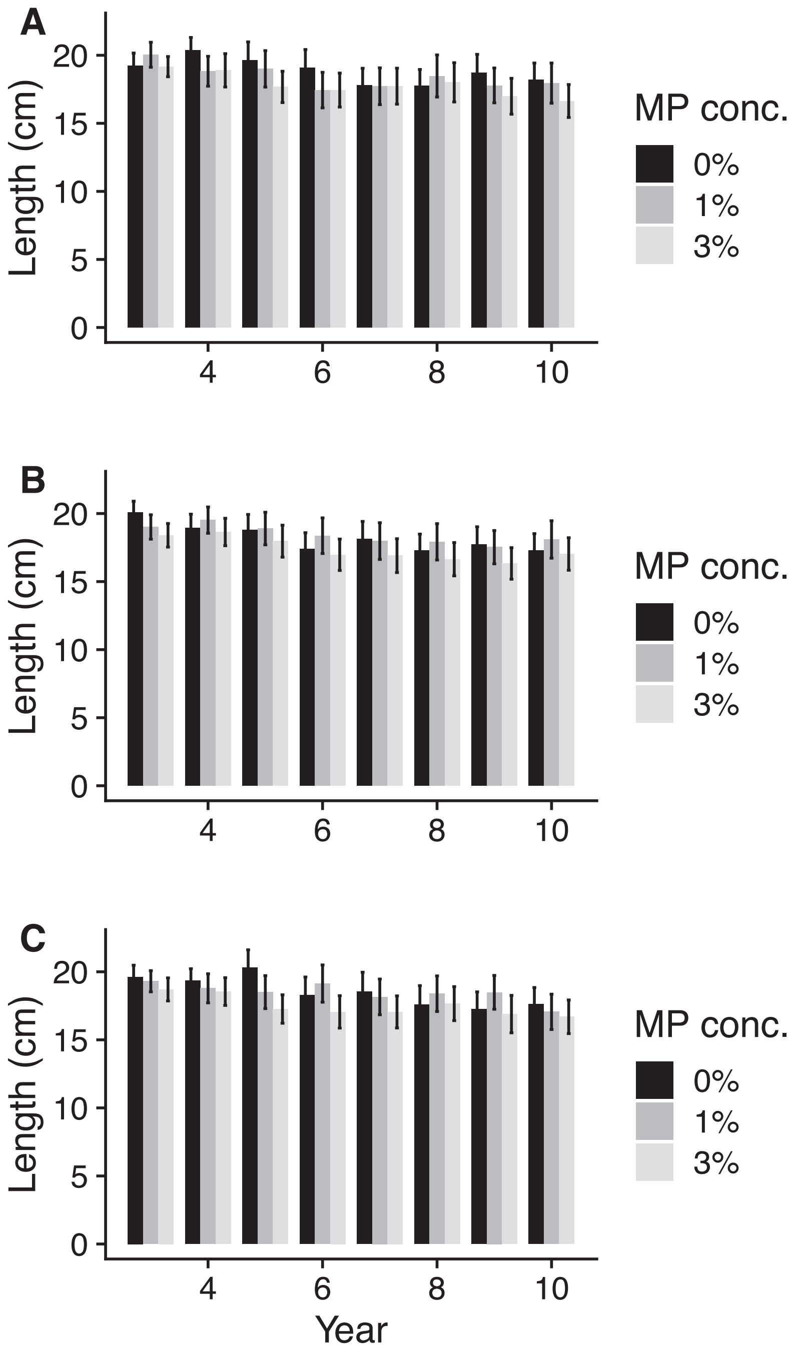

Figure 5. Mean body length (± 95% C.I.s) of age 2+ rainbow trout over time, at different microplastics (MP) concentrations (0%, 1%, 3%) for each scenario: **A** reduction in food consumption, **B** reduction in swimming speed and **C** reduction in foraging ability.

Interactions between trout age, microplastics concentration and year were significant in Scenario 1 (LMM, $F_{4,6411} = 3.09$, $p = 0.015$; Fig. 7A), but not in Scenario 2 (LMM, $F_{4,6363} = 1.54$, $p = 0. 19$; Fig. 7B) or in Scenario 3 (LMM, $F_{4,6363} = 1.71$, $p = 0.15$; Fig. 7C) since abundance did not differ over the years for the three concentrations of microplastics. In Scenario 1, abundance of age-0 fish was lower in years 6 and 9 with 3% microplastics compared to 0% or 1% microplastics, but was higher in the presence than absence of microplastics in year 10. However, interactions between trout age and year were significant in Scenario 2 (LMM, $F_{2,6417} = 4.63$, $p = 0.0098$) and in Scenario 3 (LMM, $F_{2,6417} = 5.97$, $p = 0.0026$), with consistently

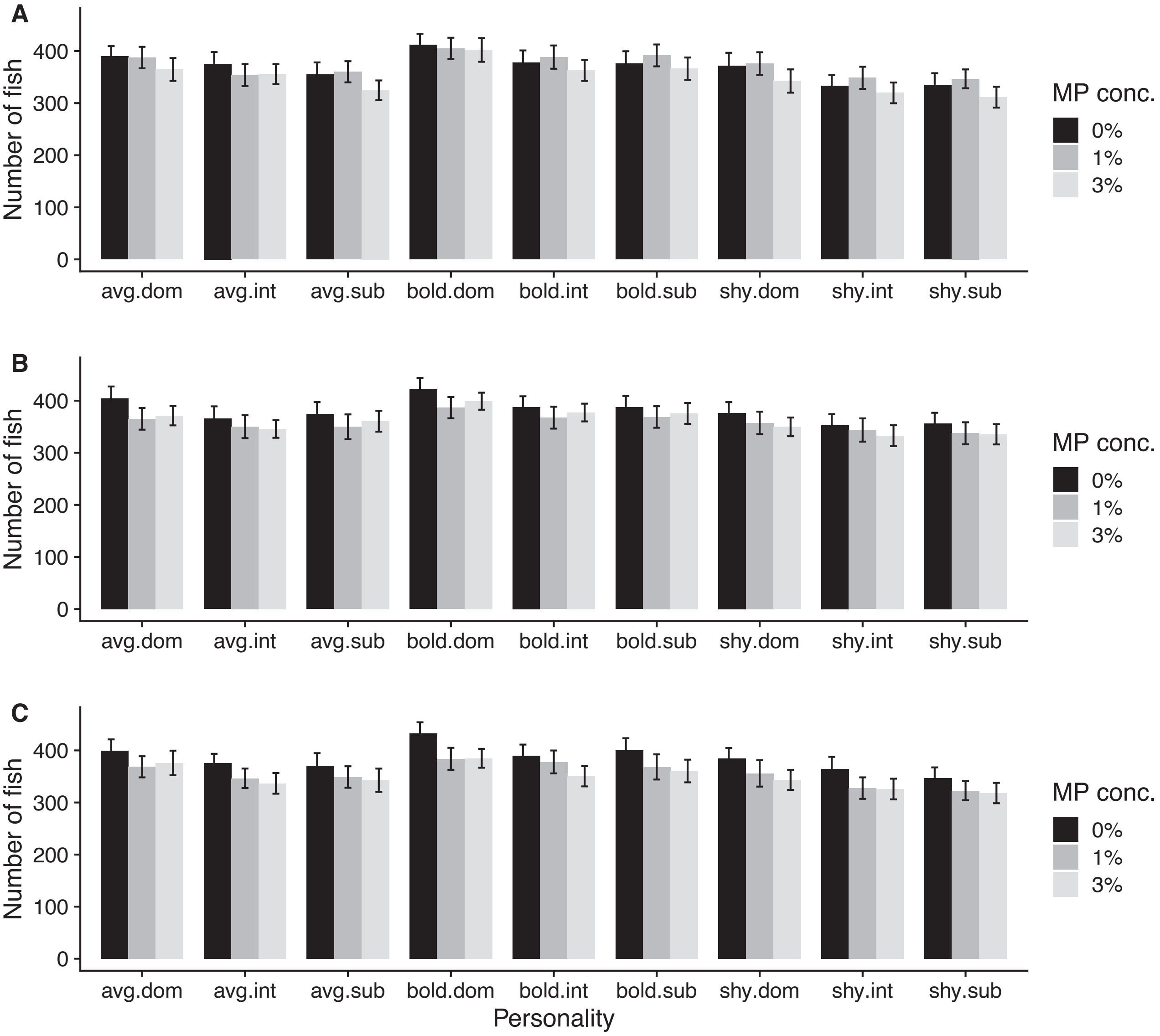

Figure 6. Abundance of age-0 rainbow trout (± 95% C.I.s) with different combinations of personality traits (shy, average, bold; dominant, intermediate, subordinate) at different microplastics (MP) concentrations (0%, 1%, 3%) for each scenario: **A** reduction in food consumption, **B** reduction in swimming speed and **C** reduction in foraging ability. Legend: sub = subordinate, avg = average-boldness, dom = dominant, int = intermediate-dominance.

higher abundance for age-0 fish than the other ages across all years (Fig. 7B, C). No significant three-way interactions were found amongst age, personality and microplastics concentration (LMM, all p's > 0.97) or between personality and microplastics concentration (LMM, all p's > 0.18) for any of the scenarios.

Sensitivity analysis

The effects of the tested parameters on population biomass are represented numerically by the magnitude of the scaled slope (summarised in Suppl. material 1: table S1). Population biomass was strongly and positively affected by reaction distance (e.g. trout-react-dist-B; scaled slope = -27.84), a proxy for territory size while foraging (i.e. dominance; Suppl. material 1: fig. S1A), followed by maximum sustainable swimming speed (e.g. max_speed_B; scenario 2; scaled slope = 8.72; Suppl. material 1: fig. S1B) and prey capture efficiency (e.g.

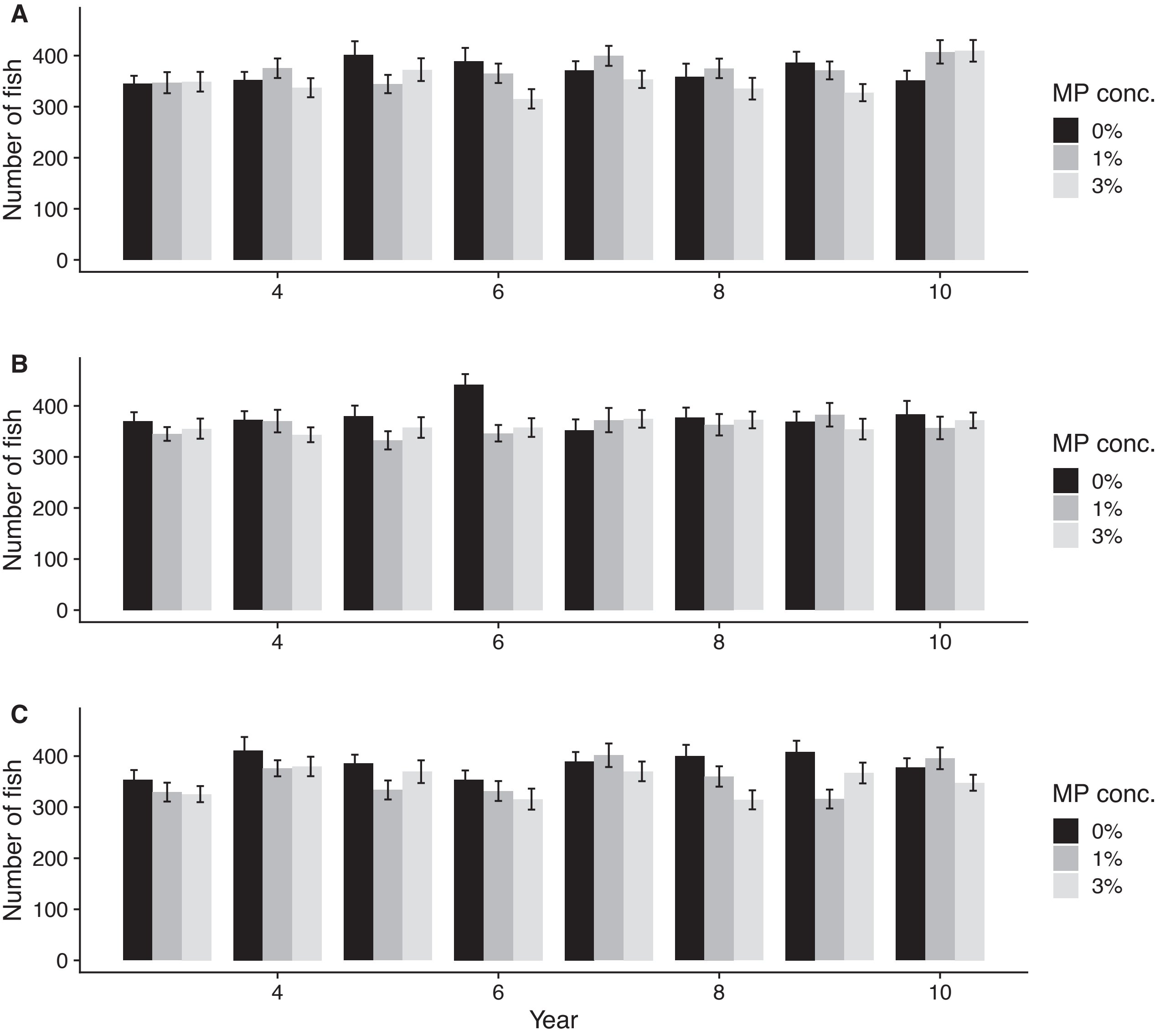

Figure 7. Abundance of age-0 rainbow trout (± 95% C.I.s) over time, at different microplastic (MP) concentrations (0%, 1%, 3%) for each scenario: **A** reduction in food consumption, **B** reduction in swimming speed and **C** reduction in foraging ability.

trout-capture-R1; Scenario 3; scaled slope = 6.19; Suppl. material 1: fig. S1C). All three of these parameters directly affect drift foraging ability. Microplastics concentration (e.g., micro-conc) exerted a moderate, negative effect on population biomass (scaled slope = -2.96; Suppl. material 1: fig. S1D), while the hiding factors for terrestrial and fish predation (i.e. shyness/boldness) exerted only slightly negative effects on population biomass that were stronger for fish predators (scaled slope = -1.76; Suppl. material 1: fig. S1E) than for terrestrial predators (scaled slope = -0.66; Suppl. material 1: fig. S1F).

Discussion

Microplastics consumption impacted trout abundance and fish body size through behavioural changes, namely, changes in swimming and foraging ability (i.e. prey capture efficiency), but only for certain personality traits. Overall, dominant trout were the most affected by microplastics consumption at all life stages, especially bold and dominant trout, as predicted. Only the body length of bold and dominant adults in Scenario 2 and dominant adults in Scenario 3 and the abundance of bold and dominant fry in Scenario 3, were impacted by microplastics consumption. These impacts were likely driven by the overall greater foraging success of trout with these personality traits, which results in the consumption of substantially greater quantities of microplastics, especially when higher concentrations of microplastics are present in the environment, according to predictions. However, the reduction in adult microplastics consumption in both Scenario 2 and Scenario 3 likely indicates a negative feedback loop, with the negative impacts of microplastics consumption on swimming and foraging behaviour also reducing the ability of adult fish to forage on microplastics.

However, dominance was not the only personality trait negatively affected by microplastics consumption. Contrary to predictions, the body size of adult fish that were both subordinate and shy was negatively affected by microplastics consumption, but only at the highest concentration of microplastics. This trend appears to be driven by fewer older and larger adult fish with these personality traits. These results suggest that both survival and reproductive success of shy and subordinate adults are likely to be negatively affected by high concentrations of microplastics, since larger fish are generally less vulnerable to gape-limited predators (Lundvall et al. 1999), are better competitors for mates and more effective at nest defence (i.e. Van den Berghe and Gross (1989); Hixon et al. (2014); Koch and Narum (2021)) and reproductive value scales with body size (i.e. Van den Berghe and Gross (1986); Tentelier et al. (2016); Auld et al. (2019)). As the body size of adult fish that were either subordinate or shy was unaffected by microplastics consumption in the three scenarios, it is likely that fish with this particular combination of traits are especially vulnerable to reduced swimming speed, perhaps because these risk-averse and subordinate fish are unable to consume sufficient food to compensate for the energy deficits experienced after consuming microplastics (i.e. Foley et al. (2018)). Likewise, subordinate and shy fish may also be more likely to engage in less risky search-feeding in the sediments at night, rather than more risky drift feeding in daytime; they are likely to consequently increase ingestion of microplastics due to the higher microplastics concentrations in the sediments relative to the water column (Ma et al. 2019). Although bold behaviour seemed to mediate the costs of lower swimming speed, the effects of shyness/boldness on microplastics consumption were more subtle than the effects of dominance, in agreement with the results of the sensitivity analysis (see above).

Our results suggest that individuals within a population of stream salmonids are not likely to suffer equally from microplastics ingestion. The much higher consumption of microplastics by dominant trout shows that the effects of microplastics consumption are not uniform across individuals. Similar to our findings, large individual differences in microplastics ingestion have been observed amongst juvenile spiny chromis damselfish (0–2000 particles per individual; *Acanthochromis polyacanthus*; Critchell and Hoogenboom (2018)) and amongst juvenile Ambon damselfish (1–33 particles per individual; *Pomacentrus amboinensis*; McCormick et al. (2020); but see Vidal et al. (2021)), while Gilthead seabream (*Sparus aurata*) showed repeatable individual differences in microplastic consumption (0–290 particles per individual; Nanninga et al. (2021)). Much of this individual variation may be driven by personality, with personality traits associated with feeding behaviour especially likely to affect individual microplastics consumption (i.e. Nanninga et al. (2021)), as seen in the dominant fish in this study. Analogous to our findings, higher overall feeding activity was also positively associated with greater microplastics consumption in zebrafish (*Danio rerio*; Chen et al. (2022)), while personality was associated with microplastic consumption for juvenile anemonefish (*Amphiprion ocellaris*), with most microplastics consumed by active fish that were more consistent in their behaviour over time (Nanninga et al. 2020). Microplastics consumption appears to select against different behavioural traits, depending on which physiological and behavioural changes occur following ingestion. Similar to our findings, differences in microplastics consumption were reported to impact individual gilthead seabream differently (*S. aurata*), as fish became less active in response to a threat stimulus after consuming microplastics and these changes were more pronounced in fish that consumed more microplastics (Nanninga et al. 2021). If ingestion of microplastics merely reduced food consumption, only fish that are both dominant and bold will be selected against, while if microplastics ingestion led to decreased swimming ability at high water velocity, fish that are both subordinate and shy will be at a disadvantage. Although subordinate and shy fish are less likely to consume as many microplastics as the other personality types due to their lower foraging success, this lower inherent foraging success may make them more vulnerable to any further reductions in their foraging ability. However, when foraging efficiency was impeded following microplastics consumption, all dominant fish, regardless of boldness, were negatively affected. However, dominant fish also appeared to experience a negative feedback loop under this scenario, since consumption of microplastics decreased over time due to greater reductions in their foraging efficiency relative to other personality types. It appears that the behavioural type that would experience the greatest adaptive advantage in the absence of microplastics is also the one most negatively affected by microplastics consumption. Even with the negative feedback loops in the latter two scenarios that reduce their consumption of microplastics, dominant trout lose their characteristic foraging advantage. The outcome of these disproportionate impacts on dominant fish could be increased selection for less competitive trout with lower foraging success (i.e. intermediate dominance and bold), as these fish consume fewer microplastics, which may also promote greater overall variability in personality traits that determine foraging success. However, this hypothesis remains to be tested. Within a range of realistic microplastics concentrations, consumption does not appear to exert a strong impact on trout populations on its own.

However, our model is limited by its lack of consideration of multiple interacting stressors, neurotoxic effects (i.e. increased susceptibility to predation, altered sensory perception, reduced food detection) and changes in personality, as personality traits were fixed in this study. Currently, the model is conservative, but can be further modified in future iterations to accommodate these factors. As well, future versions of the model would also benefit from salmonid-specific parameters on the effects of microplastics consumption on swimming and foraging ability to further improve realism, as the certainty of ABMs increases with greater data availability. Microplastics pollution represents an additional stressor for salmonid populations that are already under strain from the combined negative effects of climate change (Beechie et al. 2013; Jones et al. 2020), habitat destruction (Herbold et al. 2018; Finn et al. 2021), invasive species (Kovach et al. 2015; Marsden et al. 2019) and disease (Ma et al. 2018; Bailey et al. 2021; James et al. 2021). Salmonid populations are also vulnerable to additive effects from these stressors (i.e. Rahel et al. (2008); Lennox et al. (2020); Ros et al. (2022)) and would require further investigation.

The results from the sensitivity analysis demonstrated that the impacts of microplastics consumption on trout populations can be determined via its effects on both swimming ability and the efficiency of prey capture, factors which largely determine foraging success for salmonids. For instance, the variable, “reaction distance for prey” represents the area over which fish capture food when drift feeding, a proxy of territory size (i.e. Grant et al. (1989)) that corresponds to dominance status. Although its standard parameter values are based on empirical data on food detection distance, it is also affected by dominance, with the feeding areas of less-dominant individuals limited by aggressive interactions with conspecifics as well as by the food detection distance. If foraging success is negatively affected by microplastics consumption, salmonid populations are likely to be adversely affected by smaller quantities of microplastics, whereas substantial quantities of microplastics in the environment are likely to have negligible effects on populations of salmonids if foraging behaviour is only weakly affected by ingested microplastics. Moreover, although factors that impact risk-taking behaviour through vulnerability to predation are far less influential on salmonid populations than factors that directly impact foraging efficiency, this finding may not extend to high predation habitats, which may favour shy fish over bold.

More empirical research is needed to determine salmon-specific parameters of microplastics consumption and to identify the precise behavioural changes in swimming and foraging behaviour that may occur when different quantities of microplastics are consumed by stream-dwelling salmonids, such as changes in station-holding ability (i.e. resistance), reductions of swimming speed, alterations in foraging efficiency during drift foraging or increased reliance on benthic rather than drift foraging. These findings would be particularly insightful, given that other environmental factors, including sedimentation (i.e. Sweka et al. (2003); Zamor et al. (2007); Becker et al. (2016)), behavioural deficits due to domestication (i.e. Larsson et al. (2011)) and pollutants (i.e. Giaquinto et al. (2017); Soler et al. (2021)), can also negatively affect the health of stream-dwelling fish by impeding foraging efficiency, so the impacts of microplastics consumption can further exacerbate the effects of stressors that salmonids are already currently facing. As the majority of studies do not consider the differential impact of environmental stressors on fish behavioural types (for an exception, see Sloman et al. (2003)), more research is needed to confirm whether such disruptions in foraging efficiency tend to disproportionally affect dominant competitors in general, as was observed in the present study.

The effects of microplastics consumption can vary widely between species and were reflected in the three scenarios explored in this study. For most animals, microplastics consumption leads to a reduced intake of real food items only (Foley et al. 2018), in agreement with the results of Scenario 1. Species of fish that showed reduced food consumption following microplastics consumption, but no effects on swimming performance or foraging success, include barramundi (*Lates calcarifer*; exposure concentration: 100 particles/l; Guven et al. (2018)), convict surgeonfish (*Acanthurus triostegus*; 5000 particles/l; Jacob et al. (2019)) and juvenile spiny chromis (*Acanthochromis polyacanthus*; 0.021–0.1 mg/l; Critchell and Hoogenboom (2018)). Impaired swimming behaviour following microplastics consumption, as simulated by the second scenario, was observed in zebrafish (*D. rerio*), which began swimming hyperactively after ingesting microplastics (exposure concentration: 1 mg/l; Chen et al. (2020)) and in Ambon damselfish (*Pomacentrus amboinensis*), which were more active and bold following microplastics ingestion, likely due to increased nutritional stress (exposure concentration: 167 particles/l; McCormick et al. (2020)). Similar impairments in swimming behaviour were also observed in Crucian carp (*Carassius carassius*) fed nanoplastics (plastic particles < 1 μm), which swam more slowly, became less active and had a smaller foraging area relative to fish that did not consume nanoplastics (exposure concentration: 130 mg per feeding; Mattsson et al. (2015)). European sea bass individuals (*D. labrax*) also swam more slowly and were more lethargic following microplastics ingestion and became less effective at swimming in faster water currents (exposure concentration: 0.26–0.69 mg/l; Barboza et al. (2018)). Similar to the reduced foraging efficiency modelled in the third scenario, impeded foraging success following microplastics consumption was also observed in the common goby (*Pomatoschistus microps*; exposure concentration: 0.184 mg/l; Ferreira et al. (2016)) and in juvenile African freshwater catfish, due to impairments in swimming ability (*Clarias gariepinus*; exposure concentration: 0.5–2.0 g/l; Tongo and Erhunmwunse (2022)). Finally, although fish often exhibit behavioural changes following direct ingestion of microplastics, as modelled in this study, these behavioural changes may not be observed if microplastics are present within the bodies of prey rather than in the water column, as Krefft's frillgobies (*Bathygobius kreffti*) showed no changes to their bold and exploratory behaviour after consuming beach hoppers (*Platorchestia smithi*) previously exposed to microplastics (exposure concentration: 0.5–2.0 g/l; Tosetto et al. (2017)). More research is needed to effectively predict the impacts of microplastics consumption for salmonids in particular and how this may vary due to their source.

The ubiquitous presence of microplastics in aquatic habitats is generally viewed as a major threat to biodiversity (Galloway and Lewis 2016; Rochman 2018; Hu et al. 2019; Reid et al. 2019; Choudhury et al. 2022). However, although many laboratory and field studies explore the often negative individual-level effects of microplastics consumption on fish (i.e. De Sá et al. (2015); Jabeen et al. (2018); McCormick et al. (2020); Romano et al. (2020); Seeley et al. (2023)), the predicted population level impacts of microplastics consumption in freshwater ecosystems are often speculative and lack definitive proof (Cunningham et al. 2020). Although negative impacts on feeding, behaviour and growth are commonly observed following microplastics ingestion (Salerno et al. 2021), more research is needed on the population- and ecosystem-level impacts of microplastics (Parker et al. 2021; Wootton et al. 2021). For example, a recent meta-analysis of the effects of plastic consumption on air-breathing marine megafauna, such as marine mammals, seabirds and sea turtles, did not find a single study within the last 50 years that reported any direct population level effects of plastic pollution, as virtually all included studies reported the effects of plastic pollution on individual animals (Senko et al. 2020). Likewise, another meta-analysis on the effects of microplastics consumption on fish functional traits, which shape population dynamics and ecosystem functioning (Sibly et al. 2012), found that, in general, microplastics consumption negatively impacted fish feeding, behaviour and growth, but different life stages were differentially affected; juveniles tended to be more susceptible to these impacts, while adults tended to be more resistant (Salerno et al. 2021). These findings mirror the results observed in this study, with abundances of fry negatively affected by microplastics consumption, while, for adults, only their body size was impeded. Although the long-term structure and function of aquatic ecosystems is expected to be negatively impacted by the fish microplastics consumption, more direct and long-term research on population and ecosystem level effects is needed to confirm these predictions for real-life aquatic systems (Salerno et al. 2021). The present study contributes to fill this knowledge gap by developing a model that allows the simulation of realistic microplastic exposure scenarios (i.e. Hossain and Olden (2022)) for stream-dwelling salmonid populations.

Conclusions

The implications of the present study are that researchers studying and predicting the effects of microplastics should characterise fish behavioural types and incorporate these traits in their analyses to improve their understanding and predictive ability. This study found that microplastics consumption over 5–6 generations is not likely to pose a significant threat to healthy populations of stream-dwelling salmonids, like rainbow trout, via alterations to behaviour such as swimming and foraging. However, traits of dominant individuals of all ages such as body size will be disproportionally affected by the direct, negative effects of microplastics due to their much higher consumption rates. Microplastics consumption represents an additional impact for wild salmonid populations and more research is needed to assess the combined effects of multiple stressors alongside microplastic ingestion. As many studies report contrasting or neutral impacts of microplastics consumption on fish, only relatively mild impacts of microplastics ingestion were explored in this study, representative of currently available knowledge. This modelling study highlights the impacts of microplastics consumption on salmonids in freshwater stream environments and how these impacts can be mediated by personality differences. The inSTREAM model developed in the present study can be further used to explore the combined effects of multiple stressors, neurotoxic effects and changes in personality traits, on the effects of microplastics consumption on populations of stream-dwelling salmonids.

Acknowledgements

The authors are grateful to Katie Facecchia, Jenna Quinn, and Istafa Sufı for helpful discussion.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

Review and/or approval by an ethics committee was not needed for this study because this is a simulation study using ABMs and no live animals were used.

Funding

This work was supported by Mitacs [IT26178]; ***rare*** Charitable Research Reserve [IT26178]; and the Natural Sciences and Engineering Research Council (NSERC) of Canada [06768].

Author contributions

Conceptualization: KC. Data curation: KC. Formal analysis: KC. Funding acquisition: CS, KC. Investigation: KC, SR. Methodology: CS, KC, SR. Resources: SR, CS. Software: KC, SR. Supervision: CS. Validation: KC. Visualization: KC. Writing – original draft: KC. Writing – review and editing: KC, CS, SR.

Author ORCIDs

Kathleen D. W. Church https://orcid.org/0000-0002-7096-6869
Steven F. Railsback https://orcid.org/0000-0002-5923-9847
Christina A. D. Semeniuk https://orcid.org/0000-0001-5115-9853

Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

References

Auld HL, Noakes DLG, Banks MA (2019) Advancing mate choice studies in salmonids. Reviews in Fish Biology and Fisheries 29(2): 249–276. https://doi.org/10.1007/s11160-019-09551-5

Ayllón D, Railsback SF, Vincenzi S, Groeneveld J, Almodóvar A, Grimm V (2016) InSTREAM-Gen: Modelling eco-evolutionary dynamics of trout populations under anthropogenic environmental change. Ecological Modelling 326: 36–53. https://doi.org/10.1016/j.ecolmodel.2015.07.026

Ayllón D, Railsback SF, Almodóvar A, Nicola GG, Vincenzi S, Elvira B, Grimm V (2018) Eco-evolutionary responses to recreational fishing under different harvest regulations. Ecology and Evolution 8(19): 9600–9613. https://doi.org/10.1002/ece3.4270

Ayllón D, Nicola GG, Elvira B, Almodóvar A (2019) Optimal harvest regulations under conflicting tradeoffs between conservation and recreational fishery objectives. Fisheries Research 216: 47–58. https://doi.org/10.1016/j.fishres.2019.03.021

Bailey C, Strepparava N, Ros A, Wahli T, Schmidt-Posthaus H, Segner H, Tafalla C (2021) It's a hard knock life for some: Heterogeneity in infection life history of salmonids influences parasite disease outcomes. Journal of Animal Ecology 90(11): 2573–2593. https://doi.org/10.1111/1365-2656.13562

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1): 1–48. https://doi.org/10.18637/jss.v067.i01

Barboza LGA, Vieira LR, Guilhermino L (2018) Single and combined effects of microplastics and mercury on juveniles of the European seabass (*Dicentrarchus labrax*): changes in behavioural responses and reduction of swimming velocity and resistance time. Environmental Pollution 236: 1014–1019. https://doi.org/10.1016/j.envpol.2017.12.082

Becker LS, Brooks EM, Gabor CR (2016) Effects of turbidity on foraging behavior in the endangered fountain darter (*Etheostoma fonticola*). The American Midland Naturalist 175(1): 55–63. https://doi.org/10.1674/amid-175-01-55-63.1

Beechie T, Imaki H, Greene J, Wade A, Wu H, Pess G, Roni P, Kimball J, Stanford J, Kiffney P, Mantua N (2013) Restoring salmon habitat for a changing climate. River Research and Applications 29(8): 939–960. https://doi.org/10.1002/rra.2590

Biro PA, Stamps JA (2008) Are animal personality traits linked to life-history productivity? Trends in Ecology & Evolution 23(7): 361–368. https://doi.org/10.1016/j.tree.2008.04.003

Brodin T, Piovano S, Fick J, Klaminder J, Heynen M, Jonsson M (2014) Ecological effects of pharmaceuticals in aquatic systems—impacts through behavioural alterations. Philosophical Transactions of the Royal Society B: Biological Sciences 369(1656): 20130580. https://doi.org/10.1098/rstb.2013.0580

Candolin U, Voigt HR (2001) Correlation between male size and territory quality: consequence of male competition or predation susceptibility? Oikos 95(2): 225–230. https://doi.org/10.1034/j.1600-0706.2001.950204.x

Chen Q, Lackmann C, Wang W, Seiler TB, Hollert H, Shi H (2020) Microplastics lead to hyperactive swimming behaviour in adult zebrafish. Aquatic Toxicology 224: 105521. https://doi.org/10.1016/j.aquatox.2020.105521

Chen Y, Li W, Xiang L, Mi X, Duan M, Wu C (2022) Fish personality affects their exposure to microplastics. Ecotoxicology and Environmental Safety 233: 113301. https://doi.org/10.1016/j.ecoenv.2022.113301

Choudhury M, Sharma A, Pervez A, Upadhyay P, Dutta J (2022) Growing menace of microplastics in and around the coastal ecosystem. In: Madhav S, Nazneen S, Singh P (Eds) Coastal Ecosystems. Coastal Research Library, Springer, Cham, vol. 38, 117–137. https://doi.org/10.1007/978-3-030-84255-0_6

Collard F, Gasperi J, Gabrielsen GW, Tassin B (2019) Plastic particle ingestion by wild freshwater fish: a critical review. Environmental Science & Technology 53(22): 12974–12988. https://doi.org/10.1021/acs.est.9b03083

Critchell K, Hoogenboom MO (2018) Effects of microplastic exposure on the body condition and behaviour of planktivorous reef fish (*Acanthochromis polyacanthus*). PLOS ONE 13(3): e0193308. https://doi.org/10.1371/journal.pone.0193308

Cunningham EM, Kiriakoulakis K, Dick JT, Kregting L, Schuchert P, Sigwart JD (2020) Driven by speculation, not by impact-the effects of plastic on fish species. Journal of Fish Biology 96(6): 1294–1297. https://doi.org/10.1111/jfb.14303

Cunningham P (2007) A sensitivity analysis of an individual-based trout model. Master's Thesis, Humboldt State University, Arcada, California.

De Sá LC, Luís LG, Guilhermino L (2015) Effects of microplastics on juveniles of the common goby (*Pomatoschistus microps*): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. Environmental Pollution 196: 359–362. https://doi.org/10.1016/j.envpol.2014.10.026

Ding J, Zhang S, Razanajatovo RM, Zou H, Zhu W (2018) Accumulation, tissue distribution, and biochemical effects of polystyrene microplastics in the freshwater fish red tilapia (*Oreochromis niloticus*). Environmental Pollution 238: 1–9. https://doi.org/10.1016/j.envpol.2018.03.001

Dingemanse NJ, Wright J, Kazem AJ, Thomas DK, Hickling R, Dawnay N (2007) Behavioural syndromes differ predictably between 12 populations of three-spined stickleback. Journal of Animal Ecology 76: 1128–1138. https://doi.org/10.1111/j.1365-2656.2007.01284.x

Elliott JM (1994) Quantitative Ecology and the Brown Trout. Oxford Series in Ecology and Evolution. Oxford University Press, Oxford, UK, 286 pp. https://doi.org/10.1093/oso/9780198546788.001.0001

Felismino MEL (2023) The effects of polyethylene microplastics on the growth, behaviour and cognition of juvenile convict cichlids. Doctoral dissertation, Concordia University.

Ferreira P, Fonte E, Soares ME, Carvalho F, Guilhermino L (2016) Effects of multi-stressors on juveniles of the marine fish *Pomatoschistus microps*: gold nanoparticles, microplastics and temperature. Aquatic Toxicology 170: 89–103. https://doi.org/10.1016/j.aquatox.2015.11.011

Finn RJ, Chalifour L, Gergel SE, Hinch SG, Scott DC, Martin TG (2021) Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower Fraser River. Ecosphere 12(7): e03646. https://doi.org/10.1002/ecs2.3646

Foley CJ, Feiner ZS, Malinich, TD, Höök TO (2018) A meta-analysis of the effects of exposure to microplastics on fish and aquatic invertebrates. Science of the Total Environment 631: 550–559. https://doi.org/10.1016/j.scitotenv.2018.03.046

Forbes VE, Calow P, Sibly RM (2008) The extrapolation problem and how population modeling can help. Environmental Toxicology and Chemistry: An International Journal 27(10): 1987–1994. https://doi.org/10.1897/08-029.1

Forbes VE, Salice C, Birnir B, Bruins R, Calow P, Ducrot V, Galic N, Garber K, Harvey B, Jager Y, Kanarek A, Pastorok R, Railsback S, Rebarber R, Thorbek P (2017) A framework for predicting impacts on ecosystem services from (sub)organismal responses to chemicals. Environmental Toxicology and Chemistry 36(4): 845–859. https://doi.org/10.1002/etc.3720

Forbes VE, Railsback S, Accolla C, Birnir B, Bruins RJ, Ducrot V, Galic N, Garber K, Harvey BC, Jager HI, Kanarek A, Pastorok R, Rebarber R, Thorbek P, Salice CJ (2019) Predicting impacts of chemicals from organisms to ecosystem service delivery: A case study of endocrine disruptor effects on trout. Science of the Total Environment 649: 949–959. https://doi.org/10.1016/j.scitotenv.2018.08.344

Galloway TS, Lewis CN (2016) Marine microplastics spell big problems for future generations. Proceedings of the National Academy of Sciences 113(9): 2331–2333. https://doi.org/10.1073/pnas.1600715113

Giaquinto PC, de Sá MB, Sugihara VS, Gonçalves BB, Delício HC, Barki A (2017) Effects of glyphosate-based herbicide sub-lethal concentrations on fish feeding behavior. Bulletin of Environmental Contamination and Toxicology 98(4): 460–464. https://doi.org/10.1007/s00128-017-2037-2

Grant JW, Noakes DL, Jonas KM (1989) Spatial distribution of defence and foraging in young-of-the-year Brook Charr, *Salvelinus fontinalis*. The Journal of Animal Ecology 58(3): 773–784. https://doi.org/10.2307/5123

Grimm V, Revilla E, Berger U, Jeltsch F, Mooij WM, Railsback SF, Thulke H-H, Weiner J, Wiegand T, DeAngelis DL (2005) Pattern-oriented modeling of agent-based complex systems: lessons from ecology. Science 310(5750): 987–991. https://doi.org/10.1126/science.1116681

Grimm V, Ayllón D, Railsback SF (2017) Next-generation individual-based models integrate biodiversity and ecosystems: yes we can, and yes we must. Ecosystems 20(2): 229–236. https://doi.org/10.1007/s10021-016-0071-2

Guven O, Bach L, Munk P, Dinh KV, Mariani P, Nielsen TG (2018) Microplastic does not magnify the acute effect of PAH pyrene on predatory performance of a tropical fish (*Lates calcarifer*). Aquatic Toxicology 198: 287–293. https://doi.org/10.1016/j.aquatox.2018.03.011

Harvey BC, Railsback SF (2014) Feeding modes in stream salmonid population models: is drift feeding the whole story? Environmental Biology of Fishes 97(5): 615–625. https://doi.org/10.1007/s10641-013-0186-7

Harvey BC, Railsback SF (2021) "All fish, all the time": a good general objective for fish passage projects? Fisheries 46: 119–124. https://doi.org/10.1002/fsh.10549

Hazlerigg CR, Mintram KS, Tyler CR, Weltje L, Thorbek P (2023) Harnessing modelling for assessing the population relevance of exposure to endocrine active chemicals. Environmental Toxicology and Chemistry 42(7): 1624–1640. https://doi.org/10.1002/etc.5640

Herbold, B, Carlson SM, Henery R, Johnson RC, Mantua N, McClure M, Moyle PB, Sommer T (2018) Managing for salmon resilience in California's variable and changing climate. San Francisco Estuary and Watershed Science 16(2): 1–23. https://doi.org/10.15447/sfews.2018v16iss2art3

Hixon MA, Johnson DW, Sogard SM (2014) BOFFFFs: on the importance of conserving old-growth age structure in fishery populations. ICES Journal of Marine Science 71(8): 2171–2185. https://doi.org/10.1093/icesjms/fst200

Hossain MA, Olden JD (2022) Global meta-analysis reveals diverse effects of microplastics on freshwater and marine fishes. Fish and Fisheries 23(6): 1439–1454. https://doi.org/10.1111/faf.12701

Hothorn T, Bretz F, Westfall P (2008) Simultaneous Inference in General Parametric Models. Biometrical Journal 50(3): 346–363. https://doi.org/10.1002/bimj.200810425

Hu D, Shen M, Zhang Y, Li H, Zeng G (2019) Microplastics and nanoplastics: would they affect global biodiversity change? Environmental Science and Pollution Research 26: 19997–20002. https://doi.org/10.1007/s11356-019-05414-5

Hulthén K, Chapman BB, Nilsson PA, Hansson LA, Skov C, Brodersen J, Vinterstare J, Brönmark C (2017) A predation cost to bold fish in the wild. Scientific Reports 7(1): 1–5. https://doi.org/10.1038/s41598-017-01270-w

Hurley RR, Woodward JC, Rothwell JJ (2017) Ingestion of microplastics by freshwater tubifex worms. Environmental Science & Technology 51(21): 12844–12851. https://doi.org/10.1021/acs.est.7b03567

Jabeen K, Li B, Chen Q, Su L, Wu C, Hollert H, Shi H (2018) Effects of virgin microplastics on goldfish (*Carassius auratus*). Chemosphere 213: 323–332. https://doi.org/10.1016/j.chemosphere.2018.09.031

Jackson JC, Rand D, Lewis K, Norton MI, Gray K (2017) Agent-based modeling: A guide for social psychologists. Social Psychological and Personality Science 8(4): 387–395. https://doi.org/10.1177/1948550617691100

Jacob H, Gilson A, Lanctôt C, Besson M, Metian M, Lecchini D (2019) No effect of polystyrene microplastics on foraging activity and survival in a post-larvae coral-reef fish, *Acanthurus triostegus*. Bulletin of Environmental Contamination and Toxicology 102(4): 457–461. https://doi.org/10.1007/s00128-019-02587-0

Jacquin L, Petitjean Q, Côte J, Laffaille P, Jean S (2020) Effects of pollution on fish behavior, personality, and cognition: some research perspectives. Frontiers in Ecology and Evolution 8: 86. https://doi.org/10.3389/fevo.2020.00086

Jakubowska M, Białowąs M, Stankevičiūtė M, Chomiczewska A, Jonko-Sobuś K, Pažusienė J, Hallmann A, Bučaitė A, Urban-Malinga B (2022) Effects of different types of primary microplastics on early life stages of rainbow trout (*Oncorhynchus mykiss*). Science of the Total Environment 808: 151909. https://doi.org/10.1016/j.scitotenv.2021.151909

James CT, Veillard MF, Martens AM, Pila EA, Turnbull A, Hanington P, Luek A, Alexander J, Nehring RB (2021) Whirling disease in the Crowsnest River: an emerging threat to wild salmonids in Alberta. Canadian Journal of Fisheries and Aquatic Sciences 78(12): 1855–1868. https://doi.org/10.1139/cjfas-2020-0484

Jones LA, Schoen ER, Shaftel R, Cunningham CJ, Mauger S, Rinella DJ, St. Saviour A (2020) Watershed-scale climate influences productivity of Chinook salmon populations across southcentral Alaska. Global Change Biology 26(9): 4919–4936. https://doi.org/10.1111/gcb.15155

Kaufmann JH (1983) On the definitions and functions of dominance and territoriality. Biological Reviews 58(1): 1–20. https://doi.org/10.1111/j.1469-185X.1983.tb00379.x

Kim J, Poirier DG, Helm PA, Bayoumi M, Rochman CM (2020) No evidence of spherical microplastics (10–300 μm) translocation in adult rainbow trout (*Oncorhynchus *mykiss*) after a two-week dietary exposure. PLOS ONE 15(9): e0239128. https://doi.org/10.1371/journal.pone.0239128

Koch IJ, Narum SR (2021) An evaluation of the potential factors affecting lifetime reproductive success in salmonids. Evolutionary Applications 14(8): 1929–1957. https://doi.org/10.1111/eva.13263

Kovach RP, Muhlfeld CC, Boyer MC, Lowe WH, Allendorf FW, Luikart G (2015) Dispersal and selection mediate hybridization between a native and invasive species. Proceedings of the Royal Society B: Biological Sciences 282(1799): 20142454. https://doi.org/10.1098/rspb.2014.2454

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: Tests in Linear Mixed Effects Models. Journal of Statistical Software 82(13): 1–26. https://doi.org/10.18637/jss.v082.i13

Larsson S, Linnansaari T, Vatanen S, Serrano I, Haikonen A (2011) Feeding of wild and hatchery reared Atlantic salmon (*Salmo salar* L.) smolts during downstream migration. Environmental Biology of Fishes 92(3): 361–369. https://doi.org/10.1007/s10641-011-9846-7

Lennox RJ, Bravener GA, Lin HY, Madenjian CP, Muir AM, Remucal, CK, Robinson KF, Rous AM, Siefkes MJ, Wilkie MP, Zielinski DP, Cooke SJ (2020) Potential changes to the biology and challenges to the management of invasive sea lamprey *Petromyzon marinus* in the Laurentian Great Lakes due to climate change. Global Change Biology 26(3): 1118–1137. https://doi.org/10.1111/gcb.14957

Li J, Liu H, Chen JP (2018) Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. Water Research 137: 362–374. https://doi.org/10.1016/j.watres.2017.12.056

Lopes JVSR, Young RJ, de Azevedo CS (2019) Effects of the neutral household detergent on the behaviour and personality of guppy *Poecilia reticulata* (Peters, 1859) (Osteichthyes: Poeciliidae). Acta Ethologica 22(2): 113–123. https://doi.org/10.1007/s10211-019-00313-x

Lundvall D, Svanbäck R, Persson L, Byström P (1999) Size-dependent predation in piscivores: interactions between predator foraging and prey avoidance abilities. Canadian Journal of Fisheries and Aquatic Sciences 56(7): 1285–1292. https://doi.org/10.1139/f99-058

Luo W, Su L, Craig NJ, Du F, Wu C, Shi H (2019) Comparison of microplastic pollution in different water bodies from urban creeks to coastal waters. Environmental Pollution 246: 174–182. https://doi.org/10.1016/j.envpol.2018.11.081

Ma J, Bruce TJ, Sudheesh PS, Knupp C, Loch TP, Faisal M, Cain KD (2018) Assessment of cross-protection to heterologous strains of *Flavobacterium psychrophilum* following vaccination with a live-attenuated coldwater disease immersion vaccine. Journal of Fish Diseases 42(1): 75–84. https://doi.org/10.1111/jfd.12902

Ma P, Wei Wang M, Liu H, Feng Chen Y, Xia J (2019) Research on ecotoxicology of microplastics on freshwater aquatic organisms. Environmental Pollutants and Bioavailability 31(1): 131–137. https://doi.org/10.1080/26395940.2019.1580151

Macal CM (2016) Everything you need to know about agent-based modelling and simulation. Journal of Simulation 10: 144–156. https://doi.org/10.1057/jos.2016.7

Marn N, Jusup M, Kooijman SA, Klanjscek T (2020) Quantifying impacts of plastic debris on marine wildlife identifies ecological breakpoints. Ecology Letters 23(10): 1479–1487. https://doi.org/10.1111/ele.13574

Marsden JE, Siefkes MJ (2019) Control of invasive sea lamprey in the Great Lakes, Lake Champlain, and Finger Lakes of New York. In: Docker MS (Ed.) Lampreys: biology, conservation and control. Springer, Dordrecht, 411–479. https://doi.org/10.1007/978-94-024-1684-8_5

Mattsson K, Ekvall MT, Hansson LA, Linse S, Malmendal A, Cedervall T (2015) Altered behavior, physiology, and metabolism in fish exposed to polystyrene nanoparticles. Environmental Science & Technology 49(1): 553–561. https://doi.org/10.1021/es5053655

McCormick MI, Chivers DP, Ferrari MC, Blandford MI, Nanninga GB, Richardson C, Fakan EP, Vamvounis G, Gulizia AM, Allan BJM (2020) Microplastic exposure interacts with habitat degradation to affect behaviour and survival of juvenile fish in the field. Proceedings of the Royal Society B 287(1937): 20201947. https://doi.org/10.1098/rspb.2020.1947

McEntire KD, Maerz JC (2019) Integrating ecophysiological and agent-based models to simulate how behavior moderates salamander sensitivity to climate. Frontiers in Ecology and Evolution 7: 22. https://doi.org/10.3389/fevo.2019.00022

McNeish RE, Kim LH, Barrett HA, Mason SA, Kelly JJ, Hoellein TJ (2018) Microplastic in riverine fish is connected to species traits. Scientific Reports 8(1): 1–12. https://doi.org/10.1038/s41598-018-29980-9

Melvin SD, Wilson SP (2013) The utility of behavioral studies for aquatic toxicology testing: a meta-analysis. Chemosphere 93(10): 2217–2223. https://doi.org/10.1016/j.chemosphere.2013.07.036

Mittelbach GG, Ballew NG, Kjelvik MK (2014) Fish behavioral types and their ecological consequences. Canadian Journal of Fisheries and Aquatic Sciences 71(6): 927–944. https://doi.org/10.1139/cjfas-2013-0558

Nakano S (1995) Competitive interactions for foraging microhabitats in a size-structured interspecific dominance hierarchy of two sympatric stream salmonids in a natural habitat. Canadian Journal of Zoology 73(10): 1845–1854. https://doi.org/10.1139/z95-217

Nanninga GB, Scott A, Manica A (2020) Microplastic ingestion rates are phenotype-dependent in juvenile anemonefish. Environmental Pollution 259: 113855. https://doi.org/10.1016/j.envpol.2019.113855

Nanninga GB, Pertzelan A, Kiflawi M, Holzman R, Plakolm I, Manica A (2021) Treatment-level impacts of microplastic exposure may be confounded by variation in individual-level responses in juvenile fish. Journal of Hazardous Materials 416: 126059. https://doi.org/10.1016/j.jhazmat.2021.126059

O'Connor JD, Murphy S, Lally HT, O'Connor I, Nash R, O'Sullivan J, Bruen M, Heerey L, Koelmans AA, Cullagh A, Cullagh D, Mahon AM (2020) Microplastics in brown trout (*Salmo trutta* Linnaeus, 1758) from an Irish riverine system. Environmental Pollution 267: 115572. https://doi.org/10.1016/j.envpol.2020.115572

O'Connor JD, Lally HT, Mahon AM, O'Connor I, Nash R, O'Sullivan JJ, Bruen M, Heerey L, Koelmans AA, Marnell F, Murphy S (2022) Microplastics in Eurasian otter (*Lutra lutra*) spraints and their potential as a biomonitoring tool in freshwater systems. Ecosphere 13(7): e3955. https://doi.org/10.1002/ecs2.3955

Parker B, Andreou D, Green ID, Britton JR (2021) Microplastics in freshwater fishes: Occurrence, impacts and future perspectives. Fish and Fisheries 22(3): 467–488. https://doi.org/10.1111/faf.12528

Peda C, Caccamo L, Fossi MC, Gai F, Andaloro F, Genovese L, Perdichizzi A, Romeo T, Maricchiolo G (2016) Intestinal alterations in European sea bass *Dicentrarchus labrax* (Linnaeus, 1758) exposed to microplastics: preliminary results. Environmental Pollution 212 : 251–256. https://doi.org/10.1016/j.envpol.2016.01.083

Piccolo JJ, Frank BM, Hayes JW (2014) Food and space revisited: The role of drift-feeding theory in predicting the distribution, growth, and abundance of stream salmonids.

Environmental Biology of Fishes 97(5): 475–488. https://doi.org/10.1007/s10641-014-0222-2

Polverino G, Martin JM, Bertram MG, Soman VR, Tan H, Brand JA, Mason RT, Wong BB (2021) Psychoactive pollution suppresses individual differences in fish behaviour. Proceedings of the Royal Society B 288(1944): 20202294. https://doi.org/10.1098/rspb.2020.2294

R Core Team (2021) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rahel FJ, Bierwagen B, Taniguchi Y (2008) Managing aquatic species of conservation concern in the face of climate change and invasive species. Conservation Biology 22(3): 551–561. https://doi.org/10.1111/j.1523-1739.2008.00953.x

Railsback SF, Harvey BC, Jackson SK, Lamberson RH (2009) InSTREAM: the individual-based stream trout research and environmental assessment model. General Technical Report PSW-GTR-218. Albany, CA: US Department of Agriculture, Forest Service, Pacific Southwest Research Station, 254 pp, 218. https://doi.org/10.2737/PSW-GTR-218

Railsback SF, Harvey BC, White JL (2015) Effects of spatial extent on modeled relations between habitat and anadromous salmonid spawning success. Transactions of the American Fisheries Society 144(6): 1220–1236. https://doi.org/10.1080/00028487.2015.1079553

Railsback SF, Harvey BC, Ayllón D (2020) Contingent trade-off decisions with feedbacks in cyclical environments: testing alternative theories. Behavioral Ecology 31(5): 1192–1206. https://doi.org/10.1093/beheco/araa070

Railsback SF, Ayllón D, Harvey BC (2021a) InSTREAM 7: Instream flow assessment and management model for stream trout. River Research and Applications 37(9): 1294–1302. https://doi.org/10.1002/rra.3845

Railsback SF, Harvey BC, Ayllón D (2021b) Importance of the daily light cycle in population–habitat relations: a simulation study. Transactions of the American Fisheries Society 150(1): 130–143. https://doi.org/10.1002/tafs.10283

Railsback SF, Harvey BC, Ayllón D (2023) InSTREAM 7 user manual: model description, software guide, and application guide. General Technical Report, USDA Forest Service, Pacific Southwest Research Station, Albany, California. https://doi.org/10.2737/PSW-GTR-276

Réale D, Reader SM, Sol D, McDougall PT, Dingemanse NJ (2007) Integrating animal temperament within ecology and evolution. Biological Reviews 82(2): 291–318. https://doi.org/10.1111/j.1469-185X.2007.00010.x

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PT, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ (2019) Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews 94(3): 849–873. https://doi.org/10.1111/brv.12480

Rochman CM (2018) Microplastics research—from sink to source. Science 360(6384): 28–29. https://doi.org/10.1126/science.aar7734

Romano N, Renukdas N, Fischer H, Shrivastava J, Baruah K, Egnew N, Sinha AK (2020) Differential modulation of oxidative stress, antioxidant defense, histomorphology, ion-regulation and growth marker gene expression in goldfish (*Carassius auratus*) following exposure to different dose of virgin microplastics. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 238: 108862. https://doi.org/10.1016/j.cbpc.2020.108862

Ros A, Schmidt-Posthaus H, Brinker A (2022) Mitigating human impacts including climate change on proliferative kidney disease in salmonids of running waters. Journal of Fish Diseases 45(4): 497–521. https://doi.org/10.1111/jfd.13585

Salerno M, Berlino M, Mangano MC, Sarà G (2021) Microplastics and the functional traits of fishes: A global meta-analysis. Global Change Biology 27(12): 2645–2655. https://doi.org/10.1111/gcb.15570

Scott GR, Sloman KA (2004) The effects of environmental pollutants on complex fish behaviour: integrating behavioural and physiological indicators of toxicity. Aquatic Toxicology 68(4): 369–392. https://doi.org/10.1016/j.aquatox.2004.03.016

Seeley ME, Hale RC, Zwollo P, Vogelbein W, Verry G, Wargo AR (2023) Microplastics exacerbate virus-mediated mortality in fish. Science of The Total Environment 866: 161191. https://doi.org/10.1016/j.scitotenv.2022.161191

Senko JF, Nelms SE, Reavis JL, Witherington B, Godley BJ, Wallace BP (2020) Understanding individual and population-level effects of plastic pollution on marine megafauna. Endangered Species Research 43: 234–252. https://doi.org/10.3354/esr01064

Sibly RM, Brown JH, Kodric-Brown A (2012) Metabolic ecology: A Scaling approach. John Wiley & Sons, 375 pp. https://doi.org/10.1002/9781119968535

Sih A, Bell AM, Johnson JC, Ziemba RE (2004) Behavioral syndromes: an integrative overview. The Quarterly Review of Biology 79(3): 241–277. https://doi.org/10.1086/422893

Silva-Cavalcanti JS, Silva JDB, de França EJ, de Araújo MCB, Gusmao F (2017) Microplastics ingestion by a common tropical freshwater fishing resource. Environmental Pollution 221: 218–226. https://doi.org/10.1016/j.envpol.2016.11.068

Sloman KA, Morgan TP, McDonald DG, Wood CM (2003) Socially-induced changes in sodium regulation affect the uptake of water-borne copper and silver in the rainbow trout, *Oncorhynchus mykiss*. Comparative Biochemistry and Physiology Part C: Toxicology & Pharmacology 135(4): 393–403. https://doi.org/10.1016/S1532-0456(03)00139-X

Soler P, Faria M, Barata C, García-Galea E, Lorente B, Vinyoles D (2021) Improving water quality does not guarantee fish health: Effects of ammonia pollution on the behaviour of wild-caught pre-exposed fish. PLOS ONE 16(8): e0243404. https://doi.org/10.1371/journal.pone.0243404

Steer M, Cole M, Thompson RC, Lindeque PK (2017) Microplastic ingestion in fish larvae in the western English Channel. Environmental Pollution 226: 250–259. https://doi.org/10.1016/j.envpol.2017.03.062

Sweka JA, Hartman KJ (2003) Reduction of reactive distance and foraging success in smallmouth bass, *Micropterus dolomieu*, exposed to elevated turbidity levels. Environmental Biology of Fishes 67(4): 341–347. https://doi.org/10.1023/A:1025835031366

Tentelier C, Lepais O, Larranaga N, Manicki A, Lange F, Rives J (2016) Sexual selection leads to a tenfold difference in reproductive success of alternative reproductive tactics in male Atlantic salmon. The Science of Nature 103: 1–13. https://doi.org/10.1007/s00114-016-1372-1

Thiele CJ, Hudson MD, Russell AE, Saluveer M, Sidaoui-Haddad G (2021) Microplastics in fish and fishmeal: an emerging environmental challenge? Scientific Reports 11(1): 1–12. https://doi.org/10.1038/s41598-021-81499-8

Thompson RC, Moore CJ, Vom Saal FS, Swan SH (2009) Plastics, the environment and human health: current consensus and future trends. Philosophical Transactions of the Royal Society B: Biological Sciences 364(1526): 2153–2166. https://doi.org/10.1098/rstb.2009.0053

Tongo I, Erhunmwunse NO (2022) Effects of ingestion of polyethylene microplastics on survival rate, opercular respiration rate and swimming performance of African catfish (*Clarias gariepinus*). Journal of Hazardous Materials 423: 127237. https://doi.org/10.1016/j.jhazmat.2021.127237

Tosetto L, Williamson JE, Brown C (2017) Trophic transfer of microplastics does not affect fish personality. Animal Behaviour 123: 159–167. https://doi.org/10.1016/j.anbehav.2016.10.035

Van den Berghe EP, Gross MR (1986) Length of breeding life of coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Zoology 64(7): 1482–1486. https://doi.org/10.1139/z86-221

Van den Berghe EP, Gross MR (1989) Natural selection resulting from female breeding competition in a Pacific salmon (coho: *Oncorhynchus kisutch*). Evolution 43(1): 125–140. https://doi.org/10.1111/j.1558-5646.1989.tb04212.x

Vidal C, Lozoya JP, Tesitore G, Goyenola G, Teixeira-de-Mello F (2021) Incidence of Watershed Land Use on the Consumption of Meso and Microplastics by Fish Communities in Uruguayan Lowland Streams. Water 13(11): 1575. https://doi.org/10.3390/w13111575

Wang T, Hu M, Xu G, Shi H, Leung JY, Wang Y (2021) Microplastic accumulation via trophic transfer: can a predatory crab counter the adverse effects of microplastics by body defence? Science of The Total Environment 754: 142099. https://doi.org/10.1016/j.scitotenv.2020.142099

Wilensky U (1999) NetLogo. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. http://ccl.northwestern.edu/netlogo

Wilson DS, Coleman K, Clark AB, Biederman L (1993) Shy-bold continuum in pumpkinseed sunfish (*Lepomis gibbosus*): An ecological study of a psychological trait. Journal of Comparative Psychology 107(3): 250. https://doi.org/10.1037/0735-7036.107.3.250

Wong B, Candolin U (2015) Behavioral responses to changing environments. Behavioral Ecology 26(3): 665–673. https://doi.org/10.1093/beheco/aru183

Wootton N, Reis-Santos P, Gillanders BM (2021) Microplastic in fish–A global synthesis. Reviews in Fish Biology and Fisheries 31: 753–771. https://doi.org/10.1007/s11160-021-09684-6

Xiong F, Liu J, Xu K, Huang J, Wang D, Li F, Wang S, Zhang J, Pu Y, Sun R (2023) Microplastics induce neurotoxicity in aquatic animals at environmentally realistic concentrations: A meta-analysis. Environmental Pollution 318: 120939. https://doi.org/10.1016/j.envpol.2022.120939

Yin L, Chen B, Xia B, Shi X, Qu K (2018) Polystyrene microplastics alter the behavior, energy reserve and nutritional composition of marine jacopever (*Sebastes schlegelii*). Journal of Hazardous Materials 360: 97–105. https://doi.org/10.1016/j.jhazmat.2018.07.110

Zamor RM, Grossman GD (2007) Turbidity affects foraging success of drift-feeding rosyside dace. Transactions of the American Fisheries Society 136(1): 167–176. https://doi.org/10.1577/T05-316.1

Supplementary material 1

Supplementary data

Authors: Kathleen D. W. Church, Steven F. Railsback, Christina A. D. Semeniuk

Data type: docx

Explanation note: **table S1**: Sensitivity analysis for stream and trout parameters altered in inSTREAM7, to evaluate the effect of each parameter on fish biomass, which accounts for abundance and body length. **figure S1**: Results of the sensitivity analysis for parameters altered in inSTREAM 7, and their effects on trout biomass, which accounts for abundance and body length. **figure S2**: The existence of real-life behavioural patterns were recreated using pattern oriented modelling. **figure S3**: Recruitment and mortality (± 95% C.I.s) for fish of age 1 (A, C, E) and 2 (B, D, F) nine different combinations of personality traits for the three microplastics consumption scenarios. figure S4: Recruitment and mortality over time (± 95% C.I.s) for fish of age 1 (A, C, E) and 2 (B, D, F) for the three microplastic consumption scenario. **appendix S1**: Methods and Results. **appendix S2**: Sensitivity analysis.

Link: https://doi.org/10.3897/ibe.1.137398.suppl1