Received: 22 February 2023 | Accepted: 6 June 2023

DOI: 10.1111/jfb.15478

REGULAR PAPER

JOURNAL OF FISH BIOLOGY fsbi

The environmental impact of keeping a tropical aquarium in Northern Europe

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Abstract

Tropical fishkeeping is a popular practice in societies across the globe and involves recreating and sustaining an entire ecosystem in an aquarium within a domestic setting. The process invariably has an environmental impact, yet an assessment of this impact has previously been limited to the ecological consequences of harvesting fish from the wild or the release of non-native fish species. Provided here are the first estimates of carbon dioxide equivalent (CO_2eq) emissions produced from running a tropical aquarium across multiple countries in Northern Europe (France, Poland and the UK), along with water consumption. Estimates were produced *in silico* and are discussed in the context of freshwater and marine aquariums, calculated using example aquarium sizes of 50, 200 and 400 l. Using estimates from the UK, depending on size and running conditions, a tropical aquarium produces an estimated 85.3–635.2 kg of CO_2eq per year, equating to 1.6%–12.4% of the UK annual average household CO_2 emissions, and uses 156–31,200 l of water per year, equating to 0.2%–30.1% of the UK annual average household water usage. Despite this, comparison with the CO_2eq of an average-size dog (127–1592 kg of CO_2eq per year) or cat (121–251 kg of CO_2eq per year), estimated from meat consumption alone, demonstrates that ornamental fishkeeping can be a more environmentally conscious pet choice. In addition, the majority of CO_2eq produced from tropical fishkeeping is generated from the energy consumption of aquarium equipment and as more national electricity grids begin to decarbonize, this estimate should decrease.

KEYWORDS
aquarium, climate change, electricity, emissions, fishkeeping, water consumption

1 | INTRODUCTION

As we enter further into the Anthropocene, an epoch characterized by the environmental impact of human activities, the consequences of global warming are set to worsen (Arnell *et al*., 2019). The World Economic Forum (WEF)'s assessment of global risks ranked climate action failure, biodiversity loss and water crisis among their top five risks (World Economic Forum, 2020). The threat of climate change has been particularly transformative for aquatic ecosystems, so much so that in September 2020, 111 aquatic societies, representing 80,000 scientists globally, issued a statement outlining the dire situation aquatic ecosystems face under climate change and the need for immediate action (Bonar, 2021). In addition to climate change, aquatic ecosystems face a barrage of other anthropogenic pressures, including a conflict with growing human populations over water resources, with processes such as water abstraction (Benejam *et al.*, 2010) and damming (Barrella & Petrere, 2003) impacting the diversity of aquatic communities. This is a conflict that will only worsen under future climate change scenarios (Vicente-Serrano *et al.*, 2020). Trying to prevent these impacts is therefore a priority for those who value aquatic systems, many of whom demonstrate how much they value these environments by recreating them in their own homes in the form of aquariums. Yet paradoxically, keeping an aquarium could be contributing to the degradation of those very ecosystems they aim to recreate.

The adaptive behaviour of individuals has been highlighted as an important element in curbing the negative impacts of climate change (van Valkengoed & Steg, 2019), especially as many governments across the world have acted gradually in response to climate change and have not been transformative enough in their response to prevent irreversible climate thresholds from being crossed (Head *et al.*, 2014). Understanding how individual lifestyle choices contribute to climate change is therefore of great importance because without that information, action and adaptive behaviour cannot be achieved.

Ornamental fishkeeping has a rich history and is considered to be one of the most popular hobbies globally (Novák *et al.*, 2020). In the UK, 4 million households, or 14% of the population, own a pet fish (The Ornamental Aquatic Trade Association, 2020) and it is estimated that 70% of those that keep fish have a tropical freshwater aquarium (The Ornamental Aquatic Trade Association, 2012). With tropical fishkeeping being such a large and ubiquitous societal phenomenon, it is going to have environmental impact. The ecological impact of ornamental fish has, to some extent, been examined previously, including the risk of them being released into the wild and becoming invasive (Chang *et al.*, 2009; Gertzen *et al.*, 2008; Marra, 2019; Papavlasopoulou *et al.*, 2013), the impact their harvesting has on their home ecosystems (Friedlander, 2001; Gerstner *et al.*, 2006; Thornhill, 2012) as well as their beneficial role as a low-quantity, high-value fishery (Biondo & Burki, 2020; King, 2019; Teitelbaum *et al.*, 2010). However, despite the exploration of some ecological impacts of fishkeeping, there has been no assessment of the environmental impact of tropical fishkeeping in terms of carbon emissions and water usage.

Assessments into the carbon dioxide equivalent (CO_2eq) emissions of cats and dogs have been undertaken (MacKenzie & Cho, 2020; Martens *et al.*, 2019; Reijnders & Soret, 2003) and have produced results demonstrating that owning a cat or dog increases your environmental footprint through substantially increased CO_2eq emissions, mainly caused by their consumption of meat. The lack of such studies in fish means that many millions of fishkeepers worldwide do not know the possible impact that they are having on the environment. In the present study, the environmental impact of tropical aquariums, both freshwater and marine, is assessed through the lens of carbon emissions and water use, exploring energy demand (from heating, lighting and waterflow) as well as the carbon emissions linked with abiotic (water and salt) and biotic (livestock and feed) inputs. These estimates will provide an insight into how large an environmental impact fishkeeping is having, while also highlighting areas in which the environmental impact of fishkeeping can be minimized.

2 | MATERIALS AND METHODS

2.1 | Ethics statement

An ethical statement relating to animal welfare is not applicable in this instance because there were no animals used in this study.

2.2 | Energy

The estimates of electrical energy use to heat an aquarium were calculated using the following equation:

$$Q = U \times A \times \Delta T \times t$$

where Q is the heat transfer rate in joules (J) and the estimate for the amount of electrical energy required to heat a tropical aquarium. The estimates of Q were divided by 3,600,000 to convert them to kWh. U is the heat transfer coefficient, with the value of 6 W/m^2K used for a single pane of glass (Gläser, 2008). A is the surface area of a cube aquarium of the given volume in m^2, and for the aquariums used here A was 0.8143 m^2 (50 l), 2.052 m^2 (200 l) and 3.257 m^2 (400 l). In the absence of data on the volumes of the aquariums owned by the public, the aquarium volumes for each of the scenarios were based on the volume filtering range of a popular aquarium supplier. ΔT is the temperature difference between the water and its surroundings in Kelvin (K). It is recommended that a tropical marine aquarium should be kept between 24 and 28°C (Bulk Reef Supply, 2016), with similar temperature guidelines given for tropical freshwater aquariums (Aqueon, 2023) as some fish, such as discus, require temperatures up to 30°C. Given an average room temperature of 20°C (Yohanis & Mondol, 2010), ΔT was therefore set at 4 and 10 K. Finally, t is the time in seconds, which in the examples used here was 1 year (rounded to 31,540,000 s).

When calculating the energy use for aquarium lighting, a range of 8–12 h was used, based on recommendations to fishkeepers, with 12 h of light being the maximum daylight on the equator, and live corals and plants surviving on the lower estimate of 8 h of light (Gay, 2023a). Energy use estimates also considered the number of lighting units required for the different aquarium sizes. A larger aquarium will require more lighting units, which was reflected in the 50, 200 and 400 l aquarium scenarios factoring in one, two and three lighting units, respectively. Lighting units were based on typical 30 W light-emitting diodes (LEDs) aquarium lights, consuming 30 W per hour, which are suitable for fish, planted and coral aquariums. Lights of this description are common in tropical fishkeeping and include models such as the Fluval AquaSky LED 2.0 (30 W), the Fluval Plant 3.0 LED (32 W), the HIPARGERO LED Aquarium Light (30 W) and the Arcadia Blade Slim LED Aquarium Light (26 W), although lower and higher wattage lights are available.

Energy use estimates for water flow were based on the following scenarios: a 5 W internal filter for the 50 l aquarium, a 12 W internal filter for the 200 l aquarium and a 55 W sump pump for the 400 l aquarium, as well as a 1.2 W aerator for the 50 l aquarium, a 4.5 W aerator for the 200 l aquarium and a 18 W protein skimmer for the 400 l aquarium, and, finally, a 4 W circulation pump in the 200 l aquarium and a 7 W circulation pump in the 400 l aquarium. The combined wattage sums to 6.2, 20.5 and 37 W for the 50, 200 and 400 l aquariums, respectively. Estimates were also based on continuous use as water flow is rarely intermittent. The scenarios outlined here are typical of many aquarium set-ups, with internal filters being a more popular choice in smaller aquariums and larger aquariums often containing a sump due to the greater turnover of water required. It is recognized, however, that these are some scenarios to demonstrate the increased wattage required for larger tanks, but other set-ups will be present in the real world.

In the process of calculating the energy consumption required to heat an aquarium, several assumptions were made. The first is that there is a consistent energy differential between the aquarium and the room it is in, although in most instances the aquarium will warm the room, thus reducing the temperature difference and therefore also reducing the energy required. The second assumption is that the room temperature remains at 20°C, although there will be instances where the central heating in a home will not be running, such as during the night or when the house is empty, and therefore the temperature differentials experienced in temperate climates, especially in winter, can be much greater. It can also be the case that room temperature will exceed 20°C in a temperate climate in the summer. The third assumption is that the heat transfer coefficient between the aquarium and the room is based solely on that of a single pane of glass, but aquariums are also often in cabinets, which will reduce the heat transfer coefficient from that of glass alone. The fourth assumption is that estimates are based on the surface area of a cube, whereas many aquariums are rectangular, which will increase their surface area and thus increase the amount of heat lost. Many saltwater aquariums also have a sump system, which involves water being drained from the main aquarium and pumped through another smaller aquarium, often containing filter media, which will increase the loss of heat and thus increase energy demand. The fifth assumption is that heater efficiency is 100%, but in a real system not all electrical energy units are transferred to units of heat. Finally, heat given off other equipment such as lights, UV clarifiers and pumps will also heat the water to some extent and therefore reduce energy consumption.

Once the energy requirements were calculated they were converted into CO_2eq using the 2022 CO_2eq estimates per kWh for France, Poland and the UK (Nowtricity, 2023) in conjunction with CO_2eq time series estimates between 2000 and 2022 (Ember, 2023) and predicted CO_2eq for 2040 (Ian Tiseo, 2023).

Energy consumption from a real-world system came from a 380 l marine aquarium containing a sump and running the following equipment: one heater, two 30 W LED lights, one 8 W LED light, one protein skimmer, one return pump, two wavemakers and one UV sterilization unit. The lights were on a 9 h cycle, apart from the 8 W LED light, which was run constantly in the refugium, and the heater was set at 24°C. Energy use was measured using a Tapo smart plug. Measurements were taken over a 15-day period in February 2023.

2.3 | Abiotic inputs

The first abiotic input assessed was water consumption. Estimates of recommended water change frequency and quantity for an aquarium differ between sources, but range from 6% to 25% of the aquarium volume per week (Maidenhead Aquatics, 2023; Tetra, 2023), and this range was used for the water consumption estimates here. A second water estimate was also included, based on the use of a reverse osmosis (RO) system, where for every 1 l of RO water, the system produces around 5 l of reject water (US Environmental Protection Agency, 2023). To calculate the amount of RO reject water, water consumption was therefore multiplied by five. To calculate the CO_2eq for water consumption, the UK conversion factor of 149 kg of CO_2eq per million litres (UK Government, 2022) was used.

In addition to water, another abiotic input to marine aquariums is salt. During water changes, salt must be added to the new freshwater to maintain a specific gravity of 1.012–1.025 (Barrington, 2021; Gay, 2023b). The amount of salt required was calculated using the parameters of a water temperature of 26°C, salt mix impurity of 5 and target specific gravity of 1.025, along with the water volumes calculated previously based on 6%–25% water change per week (Arain, 2023). The CO_2eq associated with the freight of salt was then calculated based on a leading marine salt supplier who acquired their salt from the Red Sea. The supplier pumps seawater into evaporation lagoons where the salt is later extracted and then shipped to aquariums globally. A crude calculation of shipment-incurred CO_2eq was then calculated based on the emissions incurred for ship freight from the Red Sea Gateway Terminal (Jeddah), Saudi Arabia to London, UK, of 0.03 kg of CO_2 per kg of freight (Carbon Care, 2023).

2.4 | Biotic inputs

Estimating the CO_2eq from biotic inputs begins with the transport of the ornamental fish. The blue-green chromis (*Chromis viridis*) was used as an example. The blue-green chromis is one of the most popular ornamental marine fish and is heavily imported from South-East Asia, such as Indonesia (Biondo, 2017; Rhyne *et al*., 2012). If fish were transported from Jakarta's Soekarno-Hatta International Airport to London Heathrow, UK (not including transport to and from the airport), a 5 kg package will accumulate an estimated 50.93 kg of CO_2eq (Freightos, 2022). The addition of livestock does not reoccur in a properly operated aquarium, and so the CO_2eq incurred should be spread over the lifetime of the livestock. Blue-green chromis have a life expectancy in captivity of around 10 years (Yang, 2020), therefore the estimate of CO_2eq for the blue-green chromis should be divided by 10.

As well as livestock, feed is another biotic input into aquariums. Understanding the impact of fish feed is difficult because it is so diverse (*e.g*., flake, pellets, live, frozen), coming from multiple sources (*e.g*., fish meal, invertebrates and algae) and given at different frequencies and quantities depending on species, aquarium size and user. Estimates of CO_2eq produced by fish feed are probably best characterized in food production aquaculture, where 1.69 kg of CO_2eq is attributed to the production of 1 kg of fish meal, the main component in many ornamental fish feeds (Thévenot *et al*., 2018). For this study, it was assumed that in a year 100, 50 and 30 g of fish feed would be adequate for the 400, 200 and 50 l aquariums, respectively, based on the weight of commercially available fish feed packages and personal experience.

3 | RESULTS

3.1 | Energy

Heating water to a tropical level in a temperate environment resulted in the largest consumption of electrical energy when compared to lighting and water flow, as reflected in its CO_2eq emissions (Table 1). Aquarium size also impacted the amount of electrical energy a set-up used due to varying demands for heating, lighting and water flow (Figure 1). How the aquarium was operated, in terms of temperature and light regime, also substantially impacted the amount of energy used, even when it was operating within the suggested parameters of 24–30°C water temperature and 8–12 h of light. A real-world example of energy consumption from a marine aquarium is also given (Supporting Information Figure S1), demonstrating the validity of the estimates used here, with a peak energy consumption over a 15-day period of 4.34 kWh per day. The mean energy consumption over this 15-day period was 4.05 kWh per day, which equates to 1479.44 kWh per year, which is within the 1271.7–2430 kWh estimated energy range provided here for the 400 l aquarium (Table 1). Finally, the CO_2eq for heating an aquarium was compared over three northern European countries. This not only demonstrates the nonlinear increase in CO_2eq as aquarium size increases, but also that the impact of heating an aquarium varies between countries due to differing levels of decarbonization in their electricity grids. In addition, the production of CO_2eq per kWh of energy generated has also changed over time in these countries (Figures 1 and 2).

3.2 | Abiotic inputs

CO_2eq emissions from abiotic inputs were a lot smaller than those from the energy demands of aquarium equipment, including water and salt inputs for marine aquariums. However, water consumption was highly variable in terms of tank size, use of RO and the quantity of water included in weekly water changes (6%–25%) (Table 1). The freight of marine salt taken from the Red Sea contributed a small amount of CO_2eq emissions when compared to the CO_2eq produced from the energy demands of aquarium equipment, but it was still larger than the CO_2eq emissions attributed to the supply of water.

TABLE 1 Use of energy, water (tap water and reject RO water), salt, livestock and feed with associated kilograms of CO_2eq per year (kg CO_2eq/year) for small (50 l), medium (200 l) and large 400 l aquariums

Parameter	Range	Small (50 l)	Medium (200 l)	Large (400 l)
Energy				
Temperature (kWh/year)	24–30°C	171.2–428.1	431.5–1078.7	684.8–1712.1
Light (kWh/year)	8–12 h	87.6–131.4	175.2–262.8	262.8–394.2
Waterflow (kWh/year)	Constant	54.3	179.6	324.1
Total (kWh/year)		**313.1–613.8**	**786.3–1521.1**	**1271.7–2430**
Total (kg CO_2eq/year)		**79.8–156.5**	**200.5–387.9**	**324.3–619.8**
Abiotic inputs				
Water (l/year)	6%–25% water change per week	156–650	624–2600	1248–5200
Total (kg CO_2eq/year)		**0.02–0.10**	**0.09–0.39**	**0.19–0.77**
Reject RO water (l/year)	6%–25% water change per week	780–3250	3120–13,000	6240–26,000
Total (kg CO_2eq/year)		**0.12–0.48**	**0.46–1.94**	**0.93–3.87**
Salt (kg/year)	Specific gravity 1.025	6.26–26.1	25.05–104.39	50.11–208.78
Total (kg CO_2eq/year)		**0.19–0.78**	**0.75–3.13**	**1.50–6.26**
Biotic inputs				
Livestock		–	–	–
Total (kg CO_2eq/year)		**5.1**	**5.1**	**5.1**
Feed (kg/year)	Constant	0.03	0.05	0.10
Total (kg CO_2eq/year)		**0.04**	**0.08**	**0.17**
Grand total emissions				
Total (kg CO_2eq/year) (using RO and salt)		**85.3–162.9**	**206.9–398.1**	**332.0–635.2**

Note: CO_2eq estimates are based on electricity consumption in the UK. RO, reverse osmosis. Bold entries are all totals.

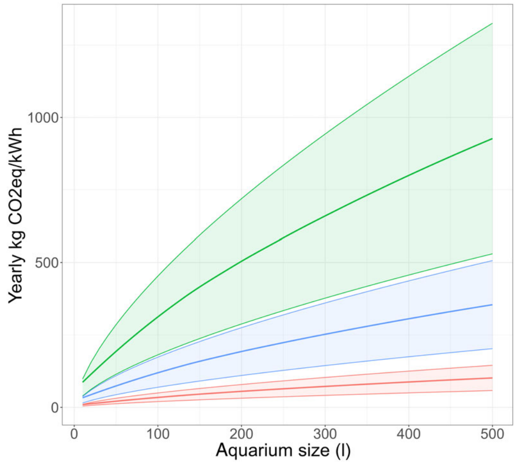

FIGURE 1 Carbon dioxide equivalent (CO_2eq) produced per kWh yearly in the process of heating different sized aquariums in three northern European countries whose electricity grids have gone through varying levels of decarbonization. Bold lines are estimates for heating aquarium water at 7°C above room temperature, upper and lower bounds are for heating aquarium water 10°C and 4°C above room temperature, respectively. ▤, France; ▤, Poland; ▤, UK

3.3 | Biotic inputs

The CO_2eq produced from biotic inputs primarily came from the air-freight of the livestock in the aquarium, with feed producing much smaller CO_2eq (Table 1). However, when compared to the CO_2eq produced from the energy demands of aquarium equipment, the CO_2eq associated with both livestock and feed was small (Table 1).

4 | DISCUSSION

The aim of this work was to identify the environmental impact of keeping ornamental tropical fish in an aquarium through *in silico* experimentation, focusing on common environmental metrics such as CO_2eq and water use. Such an assessment has not been previously undertaken and this work therefore provides a valuable insight into the practice of tropical fishkeeping. Such insights are vital in reducing environmental impact into the future and trying to mitigate the anthropogenic pressures that are causing mass ecological degradation across the globe, including climate change and overexploitation of water resources. The examples used here focused on northern Europe and common aquarium set-ups, and assessed the impact of the energy needed to run an aquarium, as well as biotic and abiotic inputs.

4.1 | Energy

Despite the assumptions used to produce energy consumption estimates, these estimates were remarkably close to real-world examples from the UK (Supporting Information Figure S1) and therefore provide a good framework for assessing energy consumption. Energy use in a tropical aquarium in the form of electricity was highlighted as the main source of CO_2eq and thus environmental impact, with heat being the largest consumer, which can be expected when trying to sustain a miniature tropical ecosystem in a glass box in a nontropical domestic environment. Despite the high energy usage of heating tropical aquarium water, the process of heating that water does have the possible beneficial side effect of acting as an electric radiator, providing a secondary benefit of heating a space, with electrification of home heating highlighted as a low-carbon solution in climate change action plans (Carroll *et al*., 2020).

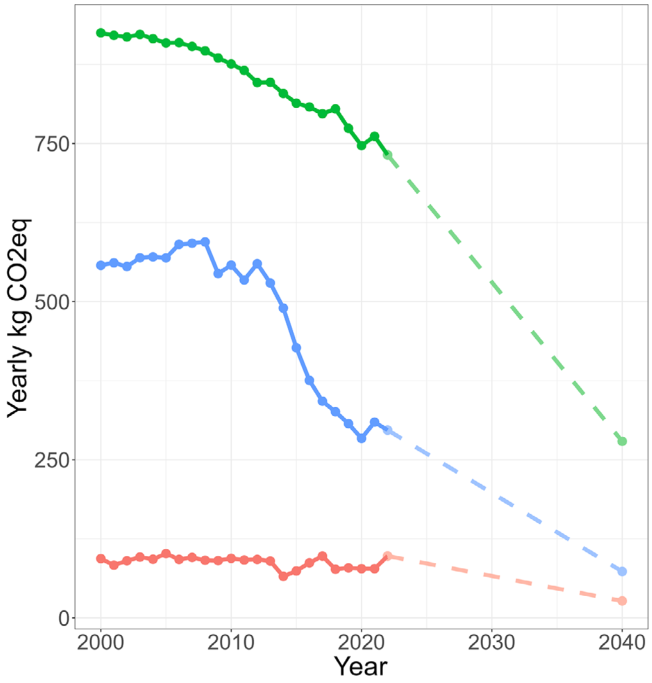

FIGURE 2 Carbon dioxide equivalent (CO_2eq) produced yearly in the running of a 200 l aquarium (heating, lighting and waterflow; mean of estimates found in Table 1) between 2000 and 2022 in three northern European countries. Energy usage is based on current aquarium equipment. ●, France; ●, France (predicted); ●, Poland; ●, Poland (predicted); ●, UK; ●, UK (predicted)

Lighting, out of all the aquarium equipment, is likely to be on for the shortest period, yet despite this, and depending on the aquarium set-up, it can be the second-largest consumer of electrical energy (Table 1). Here, scenarios were constructed based on light units suitable for corals and planted aquariums, as well as the associated recommended lighting periods. However, the length of light, intensity of that light, and the number of lighting units added to an aquarium can depend on several factors, including aesthetics, algal growth, but mainly whether or not the aquarium contains photosynthetic organisms (*e.g*., plants or coral). For example, the energy requirements would be far less for a fish-only aquarium, as the intensity of light could be lower and light periods could be shorter without detrimental impact. Over the last decade there has been a positive shift in the aquarium light market away from halogen lights and towards the lower-energy LED light equivalents used in the scenarios here.

The final source of energy demand explored here was water flow, which incorporates filtration and aeration. Water flow is important in both freshwater and marine aquariums for oxygenation, circulation and waste management. Filtration is intrinsically linked with water flow in an aquarium, as it normally involves water passing over different types of mechanical, biological and chemical filtration either in an internal filter or in a sump. Aeration plays a key role in oxygenation in freshwater and marine aquariums, and also in the removal of waste, especially in marine aquariums, in the form of protein skimmers. Unlike heating and lighting in an aquarium, equipment relating to water flow typically runs continuously, which contributes to its relatively high, and often unappreciated, demand for energy (Table 1).

4.2 | Abiotic inputs

Energy is not the only resource used in a tropical aquarium, with water also being vital. To prevent the build up of fish waste and its by-products, such as ammonia, nitrates and nitrites, water from the aquarium must be regularly replaced with new water, a process referred to as a water change. Unconditioned tap water is not recommended for aquarium water changes due to the presence of additives such as chlorine, and also impurities such as ammonia, nitrates, phosphates and heavy metals, which can be detrimental to fish and invertebrates. Water from an RO system is the gold standard, in which tap water is forced through a series of filters and a membrane to remove impurities. This practice is largely used with marine fishkeeping, and not freshwater tropical fishkeeping, where instead of RO, tap water is often just conditioned with a declinator. Most RO systems produce reject water in the filtering process, which causes a large inflation of water consumption (Table 1). Increased water consumption not only uses up a valuable resource, but also contributes to CO_2eq, as it takes energy to supply households with water. In marine aquariums, aquarium-grade salt must be added to any freshwater which enters the aquarium, and as aquarium size and water change volumes get larger, more salt is required. However, because salt will be transported by sea rather than by air, the CO_2eq associated with its transport is relatively low (Table 1), even when it originates from areas such as the Red Sea.

4.3 | Biotic inputs

The final set of inputs into an aquarium are biotic, with the most fundamental of these being the ornamental fish themselves. In the UK, 90% of ornamental marine fish are wild caught from the tropics (The Ornamental Aquatic Trade Association, 2020) due to the difficulties of captive breeding, and this has CO_2eq emissions associated with their transport. Indonesia is as a major exporter of ornamental marine fish to Europe, having exported 3,353,983 kg of ornamental marine fish between 2015 and 2019 (Akmal *et al*., 2020), but other hotspots include Sri Lanka and the Philippines (Biondo, 2017). The blue-green chromis was used as an example of the CO_2eq emissions that can be accumulated by the transport of fish, but this is a marine fish and the supply of freshwater fish is very different. Only 5% of ornamental freshwater fish are wild caught, in stark contrast with ornamental marine fish, but they make up 77% of air freight compared to the 23% of marine fish, with many captive-bred freshwater fish imported from the tropics (The Ornamental Aquatic Trade Association, 2020). Some of the largest exporters of ornamental freshwater fish include Singapore, Israel, Japan and Indonesia (The Ornamental Aquatic Trade Association, 2018). Imports from these countries accumulate substantial freight airmiles. For example, a 5 kg package containing some of the UK's most sold fish, guppies (The Ornamental Aquatic Trade Association, 2020), sent from Singapore Changi Airport to London Heathrow will accumulate an estimated 60.38 kg of CO_2eq (Freightos, 2022), even more than the wild-caught blue-green chromis example given earlier. In addition to this, the lifespan of a guppy is far lower, at only 1–2 years (Page, 2021), and therefore the lifetime carbon emissions are greater.

A consistent livestock CO_2eq amount is assumed across different aquarium sizes, as if all fish had been shipped together (Table 1). However, it could be that larger tanks contain a greater diversity of fish from multiple different locations across the globe and could therefore have a higher associated CO_2eq, but this has not been assessed. Having a better understanding of the CO_2eq linked with aquarium fish is an area that requires greater research, as it is likely more heavily stocked aquariums will incur larger CO_2eq, as would more diverse communities of fish within an aquarium. In addition to this, CO_2eq emissions from parts of the supply chain other than transport will also increase the estimated CO_2eq, but currently this area lacks research. Not only this, but consumers often do not know where their livestock originates from, and this lack of information means that they cannot make informed decisions based on environmental impact.

4.4 | Minimizing environmental impacts

Other sectors similar to ornamental fishkeeping, such as aquaponics, have previously demonstrated sustainable practices to minimize the environmental impacts of their operations, focusing on energy, water and feed (Love *et al*., 2014), but such principles have not been strongly advocated in the fishkeeping hobby. At a local level, investment in renewable electricity in homes, such as solar photovoltaics (PV), is a solution to reducing the impact of tropical fishkeeping. A typical 350 W solar panel will produce 256 kWh/year on average in northern European countries such as the UK (Howell, 2023). Using the upper estimate of energy consumption of a 200 l aquarium (1521.1 kWh/year), six solar panels would be needed to offset this energy demand. Using lifecycle assessments of solar PV, which estimate 0.037 kg of CO_2eq/year for a roof-mounted solar PV system (Gibon, 2022), this would reduce CO_2eq from 387.9 kg/year using the grid to 56.3 kg/year, an 85% decrease. A well-insulated house will also reduce the temperature differential between the aquarium and the room it is kept in, which will reduce the energy demand required to heat the aquarium. Changes in fishkeeping practices can also cut emissions, such as keeping the aquarium at the minimum suggested temperature and light threshold. Even placing water flow equipment on timers to have short breaks in their usage could reduce emissions, with alternatives including locally sourced aquarium plants for oxygenation.

Many freshwater fish are captively bred and the captive breeding of marine fish is a growing sector (The Ornamental Aquatic Trade Association, 2020), but this is not an indication that the air miles associated with fishkeeping could decrease, as most captively bred are still imported from the tropics. Reductions in CO_2eq can be achieved by buying fish from local breeders, rather than importing them. Indeed, a recent study found that almost 90% of hobbyists surveyed had bred fish (Pountney, 2023), primarily freshwater, which demonstrates that utilizing networks of other local hobbyists can provide a environmentally friendly alternative to imported fish. If fish are going to be imported, such as marine fish that are not easily bred by hobbyists, better packaging can allow for reductions in CO_2eq as most of the freight weight is water rather than livestock (The Ornamental Aquatic Trade Association, 2021).

To reduce the high water demand, tropical fishkeepers can keep track of important water parameters such as pH, ammonia and nitrates using inexpensive commercial kits that can inform the frequency and quantity of water change required, and not just relying on arbitrary guides, which may often be excessive. Rather than using the gold standard of RO purified water, for some less-sensitive freshwater tropical fish tap water conditioned with chemicals to remove impurities such as phosphates may be suitable, thus avoiding large volumes of reject water, which can make up over 80% of the total water consumption in such a system. The suitability of this method will depend on local water quality. The demand for water from an aquarium will also have the greatest impact when water resources in a region are low, such as summer droughts, and so another environmentally conscious choice would be to reduce the volume of water changes during the summer months.

Storing and utilizing the greywater produced from an aquarium is another solution to reduce waste. For freshwater tropical aquariums, this is far easier, as water from the aquarium can be repurposed for garden irrigation or flushing toilets. The same is also true of reject water produced from an RO system, which has even greater utility because it has not been in contact with the aquarium and the biological communities within it, making it suitable for applications such as in washing machines or dishwashers.

4.5 | Contextualization

Based on these estimates for heating, lighting and water movement in aquariums, it is possible to calculate total electrical energy consumption (Table 1), highlighting that energy requirements increase with aquarium size and by aquarium operation scenarios. The estimates given here, based on the UK, show that a tropical aquarium's emissions can range from 85.3 to 162.9 kg of CO_2eq per year for a 50 l aquarium and 206.9–398.1 kg of CO_2eq per year for a 200 l aquarium to 332.0–635.2 kg of CO_2eq per year for a 400 l aquarium. To put this into perspective, an average-size dog is responsible for 127–1592 kg of CO_2eq per year based on their consumption of meat alone (Martens *et al*., 2019), let alone other documented emissions such as drives to local parks (MacKenzie & Cho, 2020). Similarly, based on meat consumption alone, cats are responsible for 121–251 kg of CO_2eq per year (Martens *et al*., 2019). This demonstrates that fish can be a more environmentally conscious pet option than cats and dogs. The tropical fishkeeping CO_2eq estimates calculated in this study would account for 1.6%–12.4% of the UK annual mean household CO2 emissions (5110 kg) (Büchs & Schnepf, 2013), which highlights that the practice can still substantially contribute to carbon emissions. However, the main source of CO_2eq from keeping tropical fish comes from the electricity required to heat, light and move water in the aquarium, and this is a far easier element to decarbonize than emissions from meat production in the case of cats and dogs. For example, the UK continues to decarbonize its electricity grid, thus emissions produced by tropical fishkeeping will substantially reduce in the future (Figure 2). It should also be highlighted that the impact of keeping tropical fish will vary between countries due to the varying extent of decarbonization of national electricity grids (Figure 1), and so keeping tropical fish in France is less impactful than keeping them in the UK or Poland, for example.

The estimates provided here also show that water is another resource that is used in large quantities for tropical fishkeeping, using 156–3900, 624–15,600 and 1248–31,200 l per year for a 50, 200 and 400 l aquariums, respectively, giving an overall water usage range of 156–31,200 l per year. The per household consumption of water in the UK is 103,660 l per year (Abu-Bakar *et al*., 2021), therefore an aquarium could use 0.2%–30.1% of total water use. This is a large proportion of household water consumption, especially as drought events are expected to increase across Europe and other regions of the world under almost all climate change scenarios (Grillakis, 2019), as typified by the 2022 summer drought in Europe, which widely affected river discharges, making water an increasingly valuable and scarce commodity not only for drinking but also for the generation of hydroelectric power, power plant cooling systems and crop yields (European Comission, 2022). In addition, the consumption of water generates wastewater and in the UK, like many countries, wastewater systems are over capacity due to growing populations (Manning *et al*., 2016) and a variable climate (Hughes *et al*., 2021). Additional sources of wastewater can increase the pressure on mechanisms such as combined sewer overflows, making the release of untreated wastewater into rivers and the sea more likely, thus generating a negative environmental impact.

4.6 | Summary

Overall, these results show that ornamental fishkeeping can have low environmental impacts when it comes to energy and water consumption when compared to other pets such as cats and dogs, especially when you consider that an entire ecosystem is being created and sustained within living spaces. However, the environmental impacts can also be substantial depending on aquarium size, how it is run and even what country it is in. There are thus still improvements that can be made to ensure the environmental sustainability of the hobby, which will continue to improve as national energy grids start to decarbonize. Reducing the environmental impact of high water consumption will not come easily and will require ingenuity at the level of the individual.

AUTHOR CONTRIBUTIONS

Concept, writing and analysis was conducted by William Bernard Perry.

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REFERENCES

Abu-Bakar, H., Williams, L., & Hallett, S. H. (2021). Quantifying the impact of the COVID-19 lockdown on household water consumption patterns in England. *NPJ Clean Water*, *4*(1), 1–9.

Akmal, S. G., Zámečníková-Wanma, B. P. D., Prabowo, R. E., Khatami, A. M., Novák, J., Petrtýl, M., … Thebaud, O. (2020). Marine ornamental trade in Indonesia. *Aquatic Living Resources*, *33*, 25.

Aquatics, M. (2023). How often and much do I need to change my aquarium water and clean my filter? https://www.fishkeeper.co.uk/faq/how-often-and-much-do-i-need-to-change-my-aquarium-water-and-clean-my-filter/ (accessed Feb 9, 2023).

Aqueon. (2023). Water Temperature and Fish Health. https://www.aqueon.com/articles/fish-tanks-and-water-temperature#:~:text=Tropical_fish%2C_for_example%2C_do,tropical-and-cold-water-realms (accessed Feb 10, 2023).

Arain, H. M. (2023). Direct Salt Addition Calculator. https://www.hamzasreef.com/Contents/Calculators/DirectSaltCalculator.php (accessed Feb 11, 2023).

Arnell, N. W., Lowe, J. A., Challinor, A. J., & Osborn, T. J. (2019). Global and regional impacts of climate change at different levels of global temperature increase. *Climatic Change*, *155*, 377–391.

Barrella, W., & Petrere, M. (2003). Fish community alterations due to pollution and damming in Tietê and Paranapanema rivers (Brazil). *River Research and Applications*, *19*, 59–76.

Barrington, K. (2021). Salinity Requirements in a Saltwater Aquarium. https://www.ratemyfishtank.com/blog/salinity-requirements-in-a-saltwater-aquarium (accessed Feb 11, 2023).

Benejam, L., Angermeier, P. L., Munné, A., & García-Berthou, E. (2010). Assessing effects of water abstraction on fish assemblages in Mediterranean streams. *Freshwater Biology*, *55*, 628–642.

Biondo, M. V. (2017). Quantifying the trade in marine ornamental fishes into Switzerland and an estimation of imports from the European Union. *Global Ecology and Conservation*, *11*, 95–105.

Biondo, M. V., & Burki, R. P. (2020). A systematic review of the ornamental fish trade with emphasis on coral reef fishes—An impossible task. *Animals*, *10*, 2014.

Bonar, S. A. (2021). More than 100 aquatic-science societies sound climate alarm. *Nature*, *589*, 352.

Bulk Reef Supply. (2016). Week 8: Tank temperature. Finding a way to trust your heater. 52 Weeks of Reefing #BRS160. https://www.bulkreefsupply.com/content/post/week-8-tank-temperature (accessed Feb 9, 2023).

Büchs, M., & Schnepf, S. V. (2013). Who emits most? Associations between socio-economic factors and UK households' home energy, transport, indirect and total CO2 emissions. *Ecological Economics*, *90*, 114–123.

Care, C. (2023). CO2 Emissions Calculator. https://www.carboncare.org/en/co2-emissions-calculator.html (accessed Feb 11, 2023).

Carroll, P., Chesser, M., & Lyons, P. (2020). Air source heat pumps field studies: A systematic literature review. *Renewable and Sustainable Energy Reviews*, *134*, 110275.

Chang, A. L., Grossman, J. D., Spezio, T. S., Weiskel, H. W., Blum, J. C., Burt, J. W., … Grosholz, E. D. (2009). Tackling aquatic invasions: Risks and opportunities for the aquarium fish industry. *Biological Invasions*, *11*, 773–785.

Ember. (2023). Yearly electricity data. https://ember-climate.org/data-catalogue/yearly-electricity-data/ (accessed Apr 24, 2023).

European Comission. (2022). Drought in Europe August 2022. GDO Analytical Report.

Freightos. (2022). Air Freight CO2 Emissions Calculator, WebCargo. https://www.webcargo.co/knowledge-base/tools/freight-co2-emissions-calculator/ (accessed Feb 10, 2023).

Friedlander, A. M. (2001). Essential fish habitat and the effective design of marine reserves: Application for marine ornamental fishes. *Aquarium Sciences and Conservation*, *3*, 135–150.

Gay, J. (2023a). How long should aquarium lights be on for? https://www.swelluk.com/help-guides/how-long-should-aquarium-lights-be-on-for/ (accessed Feb 15, 2023).

Gay, J. (2023b). How much salt per litre for a marine aquarium? Help Guides. https://www.swelluk.com/help-guides/how-much-salt-per-litre-for-a-marine-aquarium/ (accessed Feb 11, 2023).

Gerstner, C. L., Ortega, H., Sanchez, H., & Graham, D. L. (2006). Effects of the freshwater aquarium trade on wild fish populations in differentially-fished areas of the Peruvian Amazon. *Journal of Fish Biology*, *68*, 862–875.

Gertzen, E., Familiar, O., & Leung, B. (2008). Quantifying invasion pathways: Fish introductions from the aquarium trade. *Canadian Journal of Fisheries and Aquatic Sciences*, *65*, 1265–1273.

Gläser, H. J. (2008). History of the development and industrial production of low thermal emissivity coatings for high heat insulating glass units. *Applied Optics*, *47*, C193–C199.

Gibon, T., Menacho, T. Á. H. & Guiton, M. (2022). *Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources*. United Nations Economic Commission for Europe. https://www.un–ilibrary.org/content/books/9789210014854/read

Grillakis, M. G. (2019). Increase in severe and extreme soil moisture droughts for Europe under climate change. *Science of the Total Environment*, *660*, 1245–1255.

Head, L., Adams, M., Mcgregor, H. V., & Toole, S. (2014). Climate change and Australia. *Wiley Interdisciplinary Reviews: Climate Change*, *5*, 175–197.

Howell, B. (2023). Solar Panel Output: How Much Electricity Do They Produce? https://www.theecoexperts.co.uk/solar-panels/electricity-power-output (accessed Apr 26, 2023).

Hughes, J., Cowper-Heays, K., Olesson, E., Bell, R., & Stroombergen, A. (2021). Impacts and implications of climate change on wastewater systems: A New Zealand perspective. *Climate Risk Management*, *31*, 100262.

King, T. A. (2019). Wild caught ornamental fish: A perspective from the UK ornamental aquatic industry on the sustainability of aquatic organisms and livelihoods. *Journal of Fish Biology*, *94*, 925–936.

Love, D. C., Fry, J. P., Genello, L., Hill, E. S., Frederick, J. A., Li, X., & Semmens, K. (2014). An international survey of aquaponics practitioners. *PLoS One*, *9*, e102662.

MacKenzie, D., & Cho, H. (2020). Travel demand and emissions from driving dogs to dog parks. *Transportation Research Record*, *2674*, 291–296.

Manning, L. J., Graham, D. W., & Hall, J. W. (2016). Wastewater systems assessment. In *The Future of National Infrastructure: A System-of-Systems Approach* (pp. 134–157). Cambridge: Cambridge University Press.

Marra, P. P. (2019). The ecological cost of pets. *Current Biology*, *29*, R955–R956.

Martens, P., Su, B., & Deblomme, S. (2019). The ecological paw print of companion dogs and cats. *Bioscience*, *69*, 467–474.

Novák, J., Kalous, L., & Patoka, J. (2020). Modern ornamental aquaculture in Europe: Early history of freshwater fish imports. *Reviews in Aquaculture*, *12*, 2042–2060.

Nowtricity. (2023). CO2 emissions per kWh. https://www.nowtricity.com/ (accessed Apr 24, 2023).

Page, A. (2021). How Long Do Guppies Live? Facts About Life Expectancy. https://www.tankarium.com/how-long-do-guppies-live/ (accessed Feb 12, 2023).

Papavlasopoulou, I., Vardakas, L., Perdikaris, C., Kommatas, D., & Paschos, I. (2013). Ornamental fish in pet stores in Greece: A threat to biodiversity? *Mediterranean Marine Science*, *15*, 126–134.

Pountney, S. M. (2023). Survey indicates large proportion of fishkeeping hobbyists engaged in producing ornamental fish. *Aquaculture Reports*, *29*, 101503.

Reijnders, L., & Soret, S. (2003). Quantification of the environmental impact of different dietary protein choices. *American Journal of Clinical Nutrition*, *78*, 664S–668S.

Rhyne, A. L., Tlusty, M. F., Schofield, P. J., Kaufman, L., Morris, J. A., & Bruckner, A. W. (2012). Revealing the appetite of the marine aquarium fish trade: The volume and biodiversity of fish imported into the United States. *PLoS One*, *7*, e35808.

Teitelbaum, A., Yeeting, B., Kinch, J., & Ponia, B. (2010). Aquarium trade in the Pacific. *SPC Live Reef Fish Information Bulletin*, *19*, 6.

Tetra. (2023). How often should I change the water in my aquarium? https://www.tetra-fish.com/ask-tetra/faqs/aquarium/fish-tank-maintenance-tips/how-often-should-i-change-the-water-in-my-aquarium.aspx (accessed Feb 9, 2023).

The Ornamental Aquatic Trade Association. (2012). *Customer Profile Survey Results Winter* 2011/2012.

The Ornamental Aquatic Trade Association. (2018). EU Ornamental Fish Import & Export Statistics 2017 (Third Countries & Intra-EU Community trade). https://www.google.com/search?client=firefox-b-d&q=EU+Ornamental+Fish+Import+%26+Export+Statistics+2017+%28Third+Countries+%26+Intra-EU+Community+trade%29 (accessed Feb 10, 2023).

The Ornamental Aquatic Trade Association. (2020). Fishing for facts: an introduction to the UK ornamental fish trade. https://ornamentalfish.org/what-we-do/represent-the-industry/fishing-for-facts/ (accessed Feb 10, 2023).

The Ornamental Aquatic Trade Association. (2021). *Looking to the future*.

Thornhill, D. J. (2012). Ecological impacts and practices of the coral reef wildlife trade. *Defenders of Wildlife*, *187*, 137–141.

Thévenot, A., Rivera, J. L., Wilfart, A., Maillard, F., Hassouna, M., Senga-Kiesse, T., … Aubin, J. (2018). Mealworm meal for animal feed: Environmental assessment and sensitivity analysis to guide future prospects. *Journal of Cleaner Production*, *170*, 1260–1267.

Tiseo, I. (2023). Power sector carbon intensity outlook 2050. https://www.statista.com/statistics/1189677/carbon-intensity-outlook-of-great-britain/#:~:text=The_carbon_intensity_of_Great,kilowatt-hour_of_electricity_generated (accessed Apr 24, 2023).

UK Government. (2022). Greenhouse gas reporting: conversion factors 2022. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022 (accessed Feb 10, 2023).

US Environmental Protection Agency. (2023). Point-of-Use Reverse Osmosis Systems. https://www.epa.gov/watersense/point-use-reverse-osmosis-systems#:~:text=While_RO_systems-can-improve,every_gallon_of_permeate_produced (accessed Feb 10, 2023).

van Valkengoed, A. M., & Steg, L. (2019). Meta-analyses of factors motivating climate change adaptation behaviour. *Nature Climate Change*, *9*(2), 158–163.

Vicente-Serrano, S. M., Quiring, S. M., Peña-Gallardo, M., Yuan, S., & Domínguez-Castro, F. (2020). A review of environmental droughts: Increased risk under global warming? *Earth-Science Reviews*, *201*, 102953.

World Economic Forum. (2020). Global Risk Report. https://www.weforum.org/reports/the-global-risks-report-2020 (accessed Feb 16, 2023).

Yang, A. (2020). Blue Green Chromis Care: The Complete Guide. https://www.aquariumsource.com/blue-green-chromis/#:~:text=Lifespan,only_possible_with_proper_care (accessed Feb 12, 2023).

Yohanis, Y. G., & Mondol, J. D. (2010). Annual variations of temperature in a sample of UK dwellings. *Applied Energy*, *87*, 681–690.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Perry, W. B. (2023). The environmental impact of keeping a tropical aquarium in Northern Europe. *Journal of Fish Biology*, 1–9. https://doi.org/10.1111/jfb.15478