**Multiple Anthropogenic Stressors Reshape Evolutionary Processes in Galapagos: Marine
Pollution and Climate Change**

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Climate change and marine pollution are intertwined in the Galapagos' living laboratory, where unabated anthropogenic pollution is reshaping evolution in the Anthropocene.

In their comment “Evolution of the Galapagos in the Anthropocene” (27 April 2020), Salinas-de-León *et al.*¹ highlighted the significance of Galapagos to understand ecosystem resilience in the face of climate change, enabling effective socio-ecological co-evolution. The comment is timely and essential in the face of regional environmental changes across the Eastern Tropical Pacific. But to understand how evolutionary processes are influenced by global change in the Anthropocene, we need to consider the multiple anthropogenic stressors acting on populations (as described in references²⁻⁴).

This UNESCO World Heritage Site is vulnerable to cumulative anthropogenic pressures, including habitat loss, chemical and biological pollution, and overfishing⁵; all potential unnatural selection forces reshaping the evolutionary processes that inspired Darwin’s “On the Origin of Species” in 1859. Novel selection by pollution, where susceptibility to the pollutant depends on genetic characteristics of individuals, has been demonstrated experimentally for several common pollutants including metals and endocrine-disrupting chemicals (e.g., ref.⁶). Long term pollutant exposures can also induce gradual decreases in genetic diversity through multigenerational selection, reducing the standing genetic variation and altering physiological responses required to adapt to a second stressor (e.g. warming)²⁻⁴.

Hence, we contend that marine pollution is central to understanding impacts on evolutionary processes in Galapagos in the context of global change (Fig. 1), in addition to climate change impacts¹. Here, we highlight marine pollution affecting Galapagos and current steps being taken to find creative multidisciplinary solutions in the face of climate change.

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59 **Figure 1:** Key pathways of ocean pollution in Galapagos in the Anthropocene with summary
60 of potential impacts to health and fitness of marine species across anthropogenic marine
61 pollution types, including oil spills (hydrocarbons), chemical pollution by persistent organic
62 pollutants (POPs) and metals (e.g., methyl mercury, MeHg), biological pollution and
63 invasions (e.g., invasive species and pathogens) and ocean plastics/microplastics.
64 Photographs of (a) mitigation for an oil spill at San Cristóbal Island waters in December 2019
65 (photo credit: Daniela Alarcon-Ruales/Universidad San Francisco de Quito), (b) high
66 accumulation of floating litter and plastics in the Galapagos Marine Reserve, illustrating

ubiquitous marine debris in Rabida Island and interactions with Black striped Salema (*Xenocys jessie*), a planktivorous fish endemic to the Galapagos (c) a Galapagos sea lion juvenile (*Zalophus wolfebaeki*) entangled in plastic sheeting at San Cristóbal Island; and (d) a flightless cormorant (*Phalacrocorax harrisi*) with plastics incorporated in nest at Isabela Island (photo credits (b – d): Juan Pablo Muñoz-Pérez/Universidad San Francisco de Quito).

Oils spills and fossil fuel dependency

In the last three decades, oil and diesel spills have released at least 1,259,020 L of crude oil into the Galapagos environment. Burgeoning tourism and electric power generation are the major energy usage sectors for diesel consumption, with fishing and vehicle transportation consuming most of the gasoline⁵. While the 2001 Jessica oil spill, releasing 302,824 L of bunker fuel and 605,648 L of diesel oil, is a poignant reminder of urbanization and chronic chemical spills in Galapagos' coastal waters^{5, 7}, the most recent oil spill in December 2019 released >2,300 L of diesel. The long-term effects of toxic metabolites resulting from the volatilization reactions and dispersion of oil spills on endemic fauna are of serious concern (Fig. 1a). Marine iguanas (*Amblyrhynchus cristatus*), for instance, are very sensitive to adverse health effects when exposed even to low trace hydrocarbon pollution following spills, triggering stress hormones and compromising survival⁷.

Silent Spring in Galapagos

Oil spills are a highly visible example of marine pollution. Less obvious is the legacy of persistent organic pollutants (POPs), many of which were banned by the Stockholm Convention⁸, but have nonetheless been recently reported in apex predators and fish in Galapagos^{5, 9-13} (Fig. 1).

Two decades before Rachel Carson's Silent Spring in 1962, the Galapagos Islands were a strategic location for US navy/military forces during World War II^{5, 9, 10}. The pesticide dichlorodiphenyltrichloroethane (DDT) was used to eliminate black rats (*Rattus rattus*)

introduced during this military presence^{9, 10}. The legacy of DDT still lingers, illustrated by the biomagnification of DDT in the Galapagos sea lion (*Zalophus worlbebaeki*) food chain¹¹. DDT mean concentrations in male pups ranged from 293 µg/kg in 2005 to 533 µg/kg in 2008, indicating a 45% increase⁹⁻¹¹. DDT concentrations in some Galapagos sea lions also exceeded the DDT-antiandrogenic toxic effect (i.e., causing feminization) of 6,890 µg/kg⁹. Not only were the Galapagos sea lions contaminated by DDT, but also the Galapagos fur seals (*Arctocephalus galapagoensis*) and several fish species (i.e., mullet, *Mugil curema*; thread herring, *Ophistonema berlangai*). Several other POPs such as polychlorinated biphenyls (PCBs) and organochlorine pesticides (i.e., dieldrin, mirex, chlordanes and beta-hexachlorocyclohexane [β -HCH]) were also detected in these marine species¹⁰⁻¹². Despite the evolutionary adaptation responsible for genetic resistance of the malaria mosquito (*Anopheles*) to DDT, its use is still allowed by the World Health Organization to control malaria in tropical countries (e.g., Ecuador) where the disease is endemic⁹⁻¹¹. A relatively less harmful, pyrethroid-based insecticide to combat the dengue mosquito (*Aedes aegypti*) was recently applied in Galapagos⁵.

Several POPs (e.g., PCBs, DDTs) can compromise the immune and endocrine systems, impacting the capacity of animals to combat disease and to successfully reproduce, especially relevant during periods of nutritional and environmental stressors in stochastic environments^{5, 9-12} (Fig. 1). For instance, Galapagos sea lions from human-impacted rookeries showed altered immune function compared to those from more remote sites, highlighting health risk implications for individual fitness, colony stability and emerging infectious diseases^{5, 10}. The interplay of pollutants and climate change could be exceptionally severe in periods of emerging diseases, food shortage and nutritional stress during the strongest El Niño Southern Oscillation (ENSO) events^{5, 10, 13}, i.e., climate change-induced vulnerability and sensitivity to pollution leading to exacerbation of toxicity, bioaccumulation and biomagnification in food webs¹³, as mass die-off occurs and populations frequently reach the tipping points of extinction.

Akin to POPs, methylmercury, the main biomagnifying mercury form found in marine fishes, was detected in yellowfin tuna (*Thunnus albacares*) from Galapagos' waters¹⁰ (Fig. 1). Methylmercury is formed in high quantities in Oxygen Minimum Zones (OMZ), in which upwellings are the main cause of oxygen decrease¹⁴, like those occurring in Galapagos.

Plastic pollution

Galapagos' coastlines have remained virtually unchanged since Darwin's visit except for some urbanized islands and plastic pollution^{5, 10, 15, 16}. The Galapagos National Park Directorate report over eight tons of plastic removed from remote beaches over just a few weeks in 2019 with at least 31 marine species adversely affected by entanglement or ingestion (Fig. 1b-d; J.P. Muñoz, pers. obs). In addition, plastics can act as vectors of chemical contaminants (e.g., POPs) with the potential to desorb chemicals once ingested with subsequent health implications on organisms¹⁷. Like climate change, plastic pollution is difficult to solve and can become a 'wicked problem' due to the large number of people and opinions involved, the large economic burden and the interconnected nature of these problems with other challenges¹⁸. Substantial efforts to clean Galapagos shorelines, investigate biodiversity impacts and devise strict regulations to ban single-use plastics are underway, while an international research effort has been mobilised to use creative and multi-disciplinary approaches to co-design effective solutions¹⁵.

Towards an Effective Management Plan for the Galapagos Future

Effective enforcement of regulatory controls has contributed to local pollutant sources on Galapagos remaining low compared to global sources^{5, 9-11, 15}. To allow this success to continue, it is imperative to formulate an effective preventive management plan in compliance with national and international laws to ensure the continuance of evolutionary process in the Galapagos Marine Reserve and terrestrial ecosystems of the Galapagos National Park. This

approach is advocated by the United Nations-Sustainable Development Goals (Goal 14: Life Below Water).

In an era of Blue Economy, a road map of sustainability should be created for Galapagos. Investing in a smart transition to a carbon-free economy and net-zero greenhouse gas emissions is critical. This could aim to divorce the constant dependence of materials and fuel transported to Galapagos' human centres from Ecuador's mainland coast (i.e., continentalization).

There is only one Galapagos, and it is not too late to safeguard its unique biodiversity and protect the irreplaceable evolutionary processes that inspired Darwin for generations to come.

Acknowledgements

The first author thanks the Nippon Foundation (Ocean Litter Project) for providing research funding. We thank the Galapagos National Park (GNP) for the trust granted; and the Galapagos Science Center (GSC) and Galapagos Conservation Trust (GCT) for supporting research.

Author contributions

All authors contributed to the development, synthesis of information and manuscript preparation.

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