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PERSPECTIVE

Ozone pollution threatens bird populations to collapse: an imminent ecological threat?

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Abstract While bird populations are declining, the factors associated with this decline are unclear. Based on laboratory experiments, air pollution has long been recognized as a factor causing oxidative stress and adversely affecting bird health. Recently, studies employing an epidemiological approach have reported significant declines in avian populations in Central Europe and the United States due to air pollution, and ozone in particular. We advocate that urgent actions are needed to mitigate these effects, which threaten biodiversity and environmental health, and propose a series of measures which can enlighten the path toward mitigating air pollution effects on avian populations.

Keywords Air pollution · Biosecurity · Bird population · Biodiversity · Ornithology · Ozone risk

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Introduction

Worldwide ground-level ozone (O_3) exposures display a multi-fold increase, e.g. about 35 – 50 nmol mol^{-1} average O_3 concentration in the northern hemisphere, compared to the pre-industrial levels (Agathokleous et al. 2020). This increase is attributed to anthropogenic inputs that change the balance between volatile organic compounds (VOCs) and nitrogen oxides (NO_x) (O_3 precursors) under ideal weather conditions (e.g., temperature, sunlight). Due to its complex chemistry and the influence of natural emitters of VOCs (e.g. vegetation) even when NO_x are decreased, mediation of O_3 pollution is challenging and expected to persist for several decades to come (Agathokleous et al. 2020).

Bird populations are declining but the driving factors are unclear (Lehikoinen et al. 2019), and air pollution has long been considered as a potential factor (Sanderfoot and Holloway 2017). Specifically, an abundance of controlled and in situ studies show that birds experience adverse effects upon a variety of air pollutants including O_3, carbon monoxide (CO), heavy metals, smoke, sulfur dioxide (SO_2), and mixtures of emissions (Sanderfoot and Holloway 2017), of which O_3 exposures are predominant at high elevations (Sicard et al. 2016). When exposed to toxic levels of such air pollutants, birds undergo oxidative stress and allocate resources/energy to scavenge harmful reactive chemical species and detoxify (Sanderfoot and Holloway 2017) (Fig. 1). As the stress elevates, birds experience distress of the respiratory system, immunosuppression, illness, behavioral alterations, and potentially impaired reproductive success (Sanderfoot and Holloway 2017).

While ongoing O_3 pollution is well-known to adversely affect human health and vegetation (Otu-Larbi et al. 2020; Sicard et al. 2020; Holm and Balmes 2022), new studies employing a thorough, epidemiological-like approach

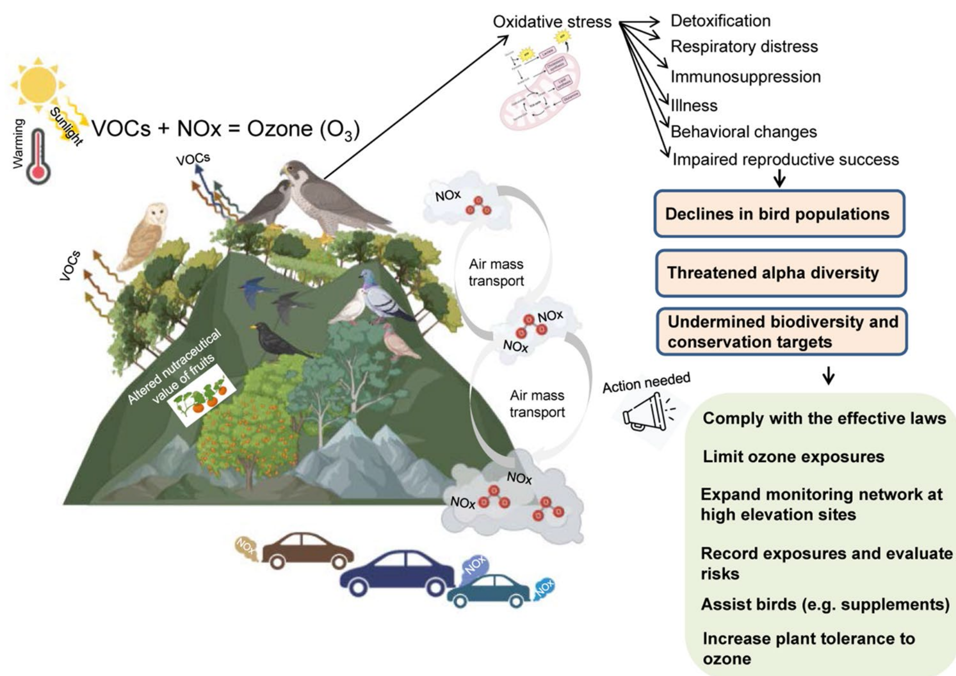

Fig. 1 Tropospheric ozone (O_3) pollution threatens bird populations. VOCs: volatile organic compounds; NO_x: nitrogen oxides

have reported significant related declines in birds populations in the United States and Central Europe (Liang et al. 2020; Reif et al. 2023), now demonstrating the real-world impacts of air pollution on avian populations and further supporting the expectations based on stress biology and the toxicological literature (Sanderfoot and Holloway 2017). For example, an analysis of 25-year data from a Central European mountain range (Giant Mountains, Czech), which also considered the impact of weather conditions, revealed that O_3 exposure had a significant negative effect on the population growth rates of upland bird species in the alpine zone above treeline (Reif et al. 2023). The effect was non-significant across all species, and the O_3 risks become higher along an altitudinal gradient (Reif et al. 2023). A further analysis of data from the United States revealed an estimated averted loss of approximately 20% (1.5 billion birds) of current total bird populations due to improvements of air quality in the last four decades (Liang et al. 2020). Massive deaths of birds, facilitated by emissions of primary pollutants boosting O_3 formation, threaten diminishing alpha diversity, and undermine biodiversity and conservation targets (Agathokleous et al. 2020) and, thus, must be averted.

In accordance with the Convention on Biological Diversity (https://www.un.org/en/observances/biological-diversity-day/conventio), more actions are needed to aid a sustainable future. Immediate actions by individual countries and unions are needed to comply with the effective laws. Existing laws include the European Council Directive 2009/147/EC on the conservation of wild birds (aka Birds Directive) and the Migratory Bird Treaty Act of 1918, a US's federal law and convention with countries like Canada, Mexico, Japan, and Soviet Union.

A solution to mediate the ongoing decline in bird populations is to limit O_3 exposure, especially at high elevation areas where O_3 levels are higher, creating ideal conditions for chronic high exposures of birds (Lelieveld and Dentener 2000; Agathokleous et al. 2023; Reif et al. 2023). Limiting O_3 precursor emissions in urban areas could lead to lower transport of O_3 and its precursors to high-elevation areas, and weakened O_3 exposures (Cristofanelli et al. 2021; Rizos et al. 2022; Wang et al. 2022). However, this countermeasure alone may not be expected to suffice, since local O_3 formation is largely regulated by the VOCs-to-NO_x ratio (Calatayud et al. 2023; Guo et al. 2023; Latha et al. 2023; Lee et al. 2023; Lu et al. 2023). Hence, while NO_x can be decreased by regulating primary air pollutant emissions, VOCs are mostly biogenic and increase with climate warming (Bourtsoukidis et al. 2012), and, under ideal conditions, reduction of anthropogenic precursor emissions could increase O_3 exposures (Querol et al. 2021; Calatayud et al. 2023). Importantly, at high-elevation areas, there is a considerable input from stratospheric O_3, further increasing O_3 exposures (Li et al. 2018; Hu et al. 2022). Hence, limiting O_3 exposures is challenging, policies to reduce air pollution are often unsuccessful to decrease O_3 exposures, and decreasing O_3 precursor emissions overall without accounting for atmospheric chemistry reactions may fail to decrease O_3 exposures. More measures are needed besides aiming at merely decreasing pollutant emissions.

There are many technologies allowing for monitoring of O_3 and other air pollutant concentrations, some of which are low-cost (Idrees and Zheng 2020; Saitanis et al. 2020). Due to lack of electricity and difficulty to access, there is lack of monitoring stations on mountainous forests and especially at high-elevation areas. This is a fundamental issue because O_3 risk assessments and exposure standards are mainly based on urban and suburban stations, while high heterogeneity and insufficiency of monitoring stations to represent air pollutant exposures still exists in large areas of the world (De Marco et al. 2022). However, technological advances, such as the use of solar panels, provide an opportunity to develop and expand monitoring networks to record exposures (Paoletti et al. 2019) and evaluate risks to wildlife. Hence, to limit O_3 exposures on mountainous forests, it is essential to greatly expand the coverage of air pollution monitoring stations across such areas.

Another solution is a holistic approach to increase bird health. High chronic O_3 exposures cause oxidative stress in birds (Sanderfoot and Holloway 2017) while decreasing yield and alter the nutritional quality of plant edible products (Hoshika et al. 2022; Sahoo et al. 2023). The nutraceutical quality of fruits may increase in some tolerant plants but it may decrease in susceptible plants, suggesting bird species-specific risks depending on their feeding behavior. Local programs are needed to assist birds such as by providing antioxidant supplements during feedings and watering, especially in urban areas where supervised citizens can support such actions. Moreover, further developments are needed to increase the tolerance of plants to O_3 such as via bioengineering and by applying approved plant protectants that alleviate O_3 stress; however, the applications of such approaches in the real-world require extensive assessments to determine whether they may pose a threat to biosecurity, including ecological health as well as the health of animals that may consume such bioengineered products or products treated with synthetic chemicals. If such holistic measures are not taken, the global populations of birds are at risk of collapse and biodiversity threatened.

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