Sustainable Horizons 3 (2022) 100023

Contents lists available at ScienceDirect

Sustainable Horizons

journal homepage: www.elsevier.com/locate/horiz

Perspective

Compound climate extreme events threaten migratory birds' conservation in western U.S.

Masoud Irannezhad[a,b,*], Mohadeseh S. Tahami[c], Behzad Ahmadi[d], Junguo Liu[b,e,*], Deliang Chen[f]

[a] Water, Energy and Environmental Engineering Research Unit, Faculty of Technology, University of Oulu, Oulu, Finland
[b] School of Environmental Science and Engineering, Southern University of Science and Technology (SUSTech), Shenzhen, China
[c] Department of Biological and Environmental Science, University of Jyväskylä, P.O. Box 35, Jyväskylä 40014, Finland
[d] WSP USA, Portland, OR, USA
[e] School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
[f] Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

ARTICLE INFO

Keywords:
North America
Migratory bird mortality
Snowstorm
Starvation
Sustainable development goals
Wildfires

ABSTRACT

In a warming world, more intense and frequent compound climate extreme events pose serious challenges to biodiversity and conservation on Earth as one of the 2030 United Nations' sustainable development goals (SDGs): "Life On Land" (SDG 15). In summer 2020, concurrent swelling wildfires and a sudden cold snap in the western U.S. killed a massive number of migratory birds. In August 2020, the hot and humid weather in response to the wildfire radiation and the oceanic evaporation could result in killing heat stress for migratory birds along the coastal shoreline, particularly in California. The heat and smoke of wildfires forced the migratory birds to abandon such feeding grounds towards inland regions, where water and food are naturally scarce, before being physiologically ready for their long-distance flyways. Then, a cold snap during 8–11 September in the Rocky Mountain states in the western U.S. urged those already weak migratory birds to fly southward before effectively recovering their physical and mental capabilities. This durable extreme starvation finally brought the skinny migrants low in the southwestern U.S. However, such ecological cascade effects of compound climate risks have rarely been acknowledged as a serious threat to migratory birds' conservation in both scientific literature and ecosystems' management practice. To improve our chances of saving birds' biodiversity on Earth, hence, conscious policies and sustained efforts must immediately be arranged through SDG 13 ("Climate Actions") based on scientific evidence and knowledge.

1. Mysterious migratory bird deaths 2020

During August-September 2020, hundreds of thousands of birds died in the western states of the United States (U.S.), including New Mexico, Colorado, Texas, Arizona, and Nebraska (Johnson, 2020a). The victims were mostly migratory species (e.g., swallows, sparrows, flycatchers, blackbirds, and warblers), while local birds like roadrunners, doves, and quail were rarely affected. Before their deaths, however, different strange behaviors, uncommon flight patterns, and stray or vagrant migratory birds were seen– becoming lethargic, dazed, sleepy, fearless, and congregating in groups. A primary scientific hypothesis involved two major climatic crises throughout the western U.S. during summer 2020 (Johnson, 2020b): (i) swelling wildfires (Pennisi, 2020) as one of the climate extreme events induced by concurrent droughts and heatwaves (Zscheischler et al., 2018) in the western states during recent years (Chinchar and Brink, 2020), and (ii) a sudden cold snap throughout the northwestern parts of U.S. in the early September 2020 (Wetson, 2020).

- Wildfires – With the most efficient terrestrial respiration system, birds are generally known as an environmental indicator of air quality and toxic gasses (Sanderfoot and Holloway, 2017). Thus, the impacts of inhaling wildfire smokes (i.e., absorbing more toxins) can cause serious respiratory distress, lung infection, and consequently suffocation in birds (Sanderfoot and Holloway, 2017). In particular, the heat and smoke of wildfires can force migratory birds to abandon their feeding grounds before having a chance to be physiologically ready for the long-distance flyways (Pennisi, 2020). Besides, low visibility during wildfires cannot only interrupt the

* Corresponding authors at: School of Environmental Science and Engineering, Southern University of Science and Technology (SUSTech), Shenzhen, China.
E-mail addresses: masoud.irannezhad@oulu.fi (M. Irannezhad), liujg@sustech.edu.cn (J. Liu).

https://doi.org/10.1016/j.horiz.2022.100023
Received 20 July 2022; Received in revised form 7 August 2022; Accepted 12 August 2022

navigation of different migratory bird species but also intensify their potential struggles with successfully detecting food and water sources (Haider et al., 2019). Moreover, the wildfires can change the avian behaviors of migratory birds, from spontaneous to homing activities (Sanderfoot and Holloway, 2017). Hence, the wildfires can potentially derive variations in the existence, availability, and mortality of birds, particularly different migratory species.

- Cold snaps – Birds are warm-blooded, with an average normal body temperature of about 41 °C (e.g., Clark and Rothery, 2008). Therefore, a sudden drop in surface air temperature (SAT) can profoundly impact the life and behavior of birds (e.g., Møller et al., 2010). For staying warm in such cold snaps, birds have evolved different behavioral strategies by increasing or decreasing their activity (e.g., Cohen et al., 2020), like shivering, fluffing feathers, roosting, cuddling, and tucking feet, heads and bills. These responsive tactics, however, cannot be affordable for long because birds need to forage food as their most critical challenge for surviving on consecutive cold days (e.g., Maggini and Bairlein, 2013). Alternatively, precipitation during freezing SATs can cause thick snow cover, destroy habitat, block food sources, and consequently death in birds. This is particularly true for migratory species that are (i) inherently unable to endure the cold weather conditions, (ii) already stressed from their long journey, and (iii) possibly running out of time for finding available nourishments (e.g., Krause et al., 2016). Snowstorms can also disorient the naive migratory birds by reducing visibility (Alerstam, 1990), and thus increase the risk of their mortality (Newton, 2007).

2. Theoretical analysis versus laboratory test results

Employing citizen scientist observations and different geospatial models, Yang et al. (2021) investigated the roles of different environmental and climatic factors in the unprecedented migratory bird die-off in 2020 throughout the western U.S. Their results indicated more (fewer) dead birds close to wildfires in western states (California) during August (September), statistically significant positive correlations between bird mortality and air quality, an increasing number of bird deaths in urban areas, and no substantial effects of snow cover on such a massive loss of migratory birds. Accordingly, Yang et al. (2021) concluded that the urban air quality was very likely degraded by the heavy forest wildfires, causing respiratory illness and consequently death in birds. Contrarily, however, the laboratory scientists in the U.S. Geological Survey National Wildlife Center reported no evidence of smoke poisoning in the dead migratory bird bodies collected, cataloged, and sent by the New Mexico Department of Game and Fish in early September 2020 (New Mexico Department of Game and Fish, 2020). Such a contradiction is because Yang et al. (2021) applied the dead bird observations reported on the citizen science platform (Johnson, 2020a). Hence, the detection of dead bird bodies was regionally clustered in urban areas as the primary movement radius of most citizens in the summer of 2020, particularly under the emergence of Covid-19 and wildfire air pollution in the western US (Archer et al., 2020). Besides, such a citizen-based dataset rarely includes bird death records in areas with high snow cover thickness because people do not tend to travel during heavy snowstorms. Accordingly, there is also high uncertainty about the conclusion of Yang et al. (2021) on the role of snow cover in migratory bird mortality throughout the western U.S. during the summer of 2020.

Although the biologists in the U.S. Geological Survey National Wildlife Center unexpectedly ruled out the wildfire smoke as a cause of migratory bird deaths in the western U.S. in summer 2020, other laboratory test results curiously indicated: (i) no foodstuffs in the stomachs and intestines; (ii) kidney failure; (iii) significant depletion of fat deposits as the stored energy for migration; and (iv) shrunken large breast muscles controlling the wings of birds (New Mexico Department of Game and Fish, 2020). These observations confirmed the single abnormal evidence shared nearly by all the dead migratory birds: physical exertion without enough nourishment for recovery (Johnson, 2020b). This left the begging question of why those migratory birds were surprisingly, massively, and extremely exhausted throughout the western U.S. in the summer of 2020?

3. Migratory birds' starvation: an ecological cascade effect

Based on available publications and news, we argued below the chains of mechanisms by which the environmental impacts of concurrent wildfires and snowstorms killed such a massive number of migratory birds throughout the western U.S. during summer 2020 in two different phases (1–31 August and 1–23 September 2020) adopted by Yang et al. (2021).

- Phase 1 (1–31 August 2020) – Every year, a wide diversity of birds migrates from the tundra landscape in Alaska and Canada towards the wintering grounds in Central and South America (Wetson, 2020). During this migration, the birds frequently land – called stopovers – in the western U.S. to get some rest and refuel from the resource-rich coastal ridges (Wetson, 2020). That is why numerous deaths of migratory birds were mostly reported from Western U.S. coasts during 1–31 August 2020 (Fig. 1a) on the citizen science platform (Johnson, 2020a). In California, for example, bird corpses were observed more on the coastal shoreline (Fig. 1a) than in inland forest areas, which experienced extraordinary wildfires in the summer of 2020 (Fig. 1b) (Chinchar and Brink, 2020). The possible scientific reason is that the hot and humid weather in response to the wildfire radiation and the oceanic evaporation might have resulted in killing heat stress (Arjona et al., 1988) for migratory birds across some coastal parts of California. It should be noted that civil scientists highly tend to visit such shorelines more frequently than the forests amid smoke and flames, particularly during the summer seasons.
- Phase 2 (1–23 September 2020) – The record-setting wildfires swelled from the western coastal ridges and forest areas to the Mountain West in the U.S. (Pennisi, 2020) through this phase (Fig. 1d). The heat and smoke of such wildfires might force the migratory birds to (i) abandon feeding grounds before having a chance to be physiologically ready for their long-distance flyways, and (ii) re-route their common traveling pathway towards inland regions, where water and food are naturally scarce (Wetson, 2020). During 8–11 September, a weather whiplash surprisingly plummeted SAT (Fig. 2) and ushered in summertime snowstorms across the Rocky Mountain states in the western U.S. (Cappucci, 2020). Based on Schaefer et al. (2008), this cold snap could particularly urge those already weak migratory birds to fly southward before effectively recovering their physical and mental capabilities. Such durable extreme starvation, dehydration, and exhaustion finally brought the skinny migrants low in the southwestern U.S. (Fig. 1c), where recent mega-droughts had already declined the population of insects as the main nourishment source for different migratory bird species (Berardelli, 2020). Thus, numerous dead migratory birds with severely emaciated body conditions (Wetson, 2020) were reported from the southwestern parts of the U.S., particularly the Chihuahuan Desert (Fig. 1c).

4. Conserving migratory birds from compound climate events

Global warming has already increased the risk of compound climate extreme events (AghaKouchak et al., 2020), with considerable challenges to environmental conservation and biodiversity (Foden and Young, 2016; Harris et al., 2018). Today, swelling wildfires (AghaKouchak et al., 2018; Nolan et al., 2020), in response to significant increases in concurrent droughts and heatwaves (AghaKouchak et al., 2020), are crucially impacting ecosystem sustainability and wildlife population on Earth (Harper et al., 2019; Alexandra and Finlayson, 2020). In Australia, for example, the

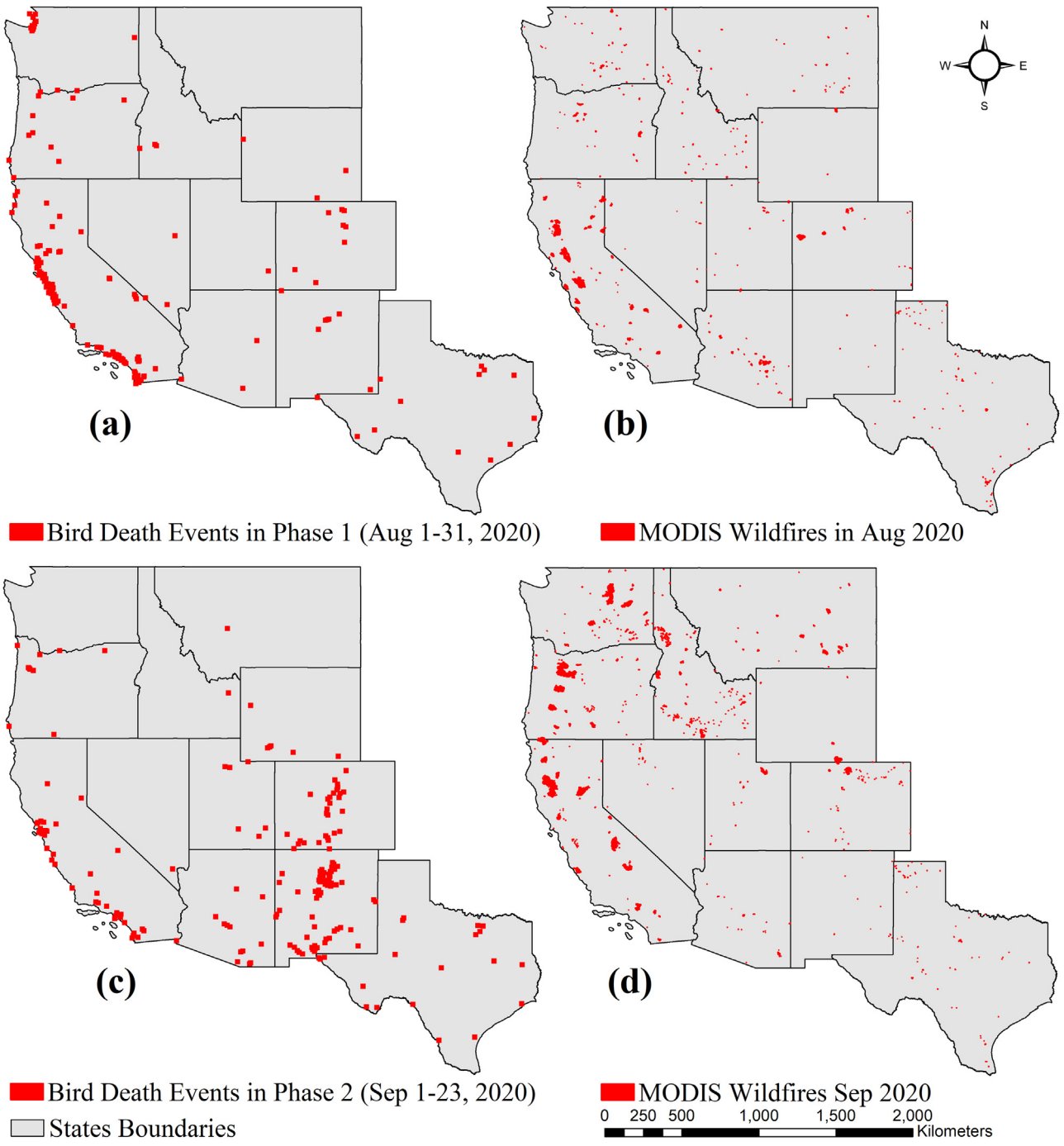


Fig. 1. The geographical distribution of bird death events and wildfires during August (a and b) and September (c and d) 2020 throughout the western states of the USA obtained from the citizen science database (provided by the Southwest Avian Mortality Project at iNaturalist platform: https://www.inaturalist.org/projects/southwest-avian-mortality-project) and the satellite-based sensor MODIS (Moderate Resolution Imaging Spectroradiometer), respectively. .

bizarre 2019 fire season caused extensive habitat loss of rare species (Pickrell, 2019), huge population declines in aquatic biota (Silva et al., 2020), and consequently the silent deaths of more than one billion wild animals (Lewis, 2020). In summer 2020, record-setting atmospheric aridity enabled extraordinary wildfires in the western U.S. (Higuera and Abatzoglou, 2020), with about 7.8 million acres of burned areas until October 5 (Insurance Information Institute, 2020). Similar to those created anxiety for many wildlife species in Australia during 2019, such western U.S. wildfires also inflicted lasting catastrophic environmental and biological consequences; particularly the loss of habitats threatening endangered species as well as the failure of burned landscapes to rebound under global warming and climate change (Pickrell and Pennisi, 2020). In contrast with previous wildfires, however, those in the west of the U.S. during 2020 were exceptionally associated with a freezing snowstorm, cascading to unprecedented migratory bird mortality.

In North America, two-thirds (~389) of bird species are already at risk of extinction due to climate change (Yarnold, 2019). Since 1970, North America has also lost more than three billion (1 in 4) birds

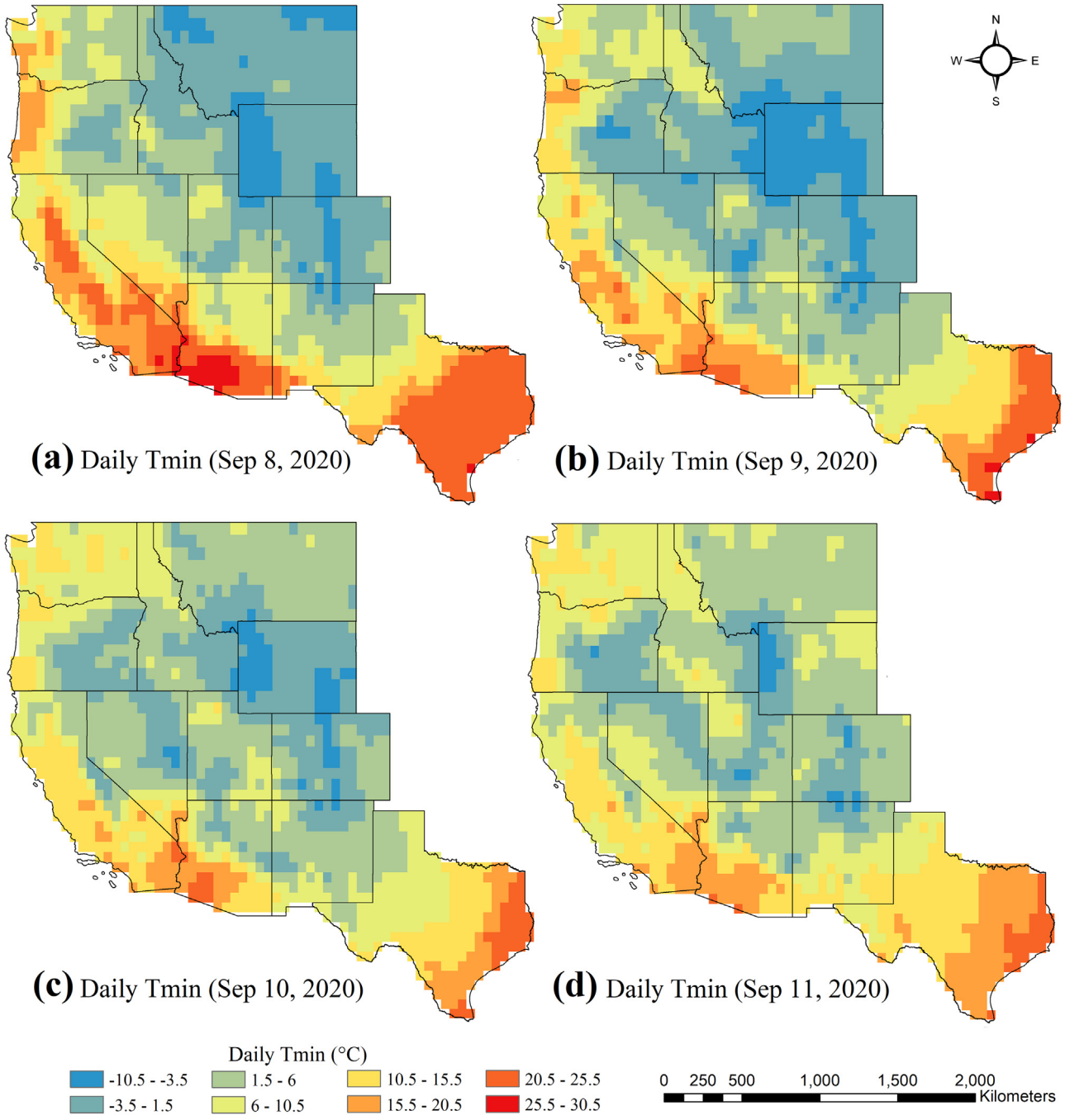


Fig. 2. The spatial distribution map of daily minimum surface air temperature (Tmin in °C) on the dates of 8 (a), 9 (b), 10 (c), and 11 (d) September 2020 throughout the western states of the USA obtained from the Climate Research Center (CRU) (Harris et al., 2020).

mainly because of multifold modifications in habitat and food sources (Rosenberg et al., 2019). The mass migratory bird die-off in the southwestern U.S. during the summer of 2020 revealed a new cascade effect of compound climate extreme events on migratory bird biodiversity. As a flourishing environmental challenge facing humanity today, such compound climate extreme events are seriously altering the ecology of migratory birds, particularly in both feeding and breeding aspects (e.g., Tobolka et al., 2015). In North America, such ecological cascade effects cannot only slow/hinder the recovery of lost birds, but also increase their extinction risk by inducing more challenging migrations and/or less breeding habitat for a large number of species (e.g., Loss et al., 2015). On Earth, hence, migratory species (e.g., birds) occupying habitats that are subjected to frequent natural and/or anthropogenic changes due to compound climate extreme events are today a serious challenge for conservation science.

To improve our chances of saving birds' biodiversity, we need immediate actions with regard to conscious policies and sustained efforts based on scientific evidence and knowledge. To unravel the role and mitigate the consequences of compound climate events in the migratory birds' ecology, scientists should particularly: (i) assess the direct and cascade impacts of such environmental stressors on birds' communities and health (e.g., Gangoso et al., 2020), like migratory species' starvation to death; (ii) develop sustainable land use management strategies, e.g. introducing alternative forest tree species and

splitting forests into smaller compartments (Schelhaas et al., 2015) ; (iii) prepare sanctuaries and/or shelters for birds, which are facing extinction (Associated Press, 2020), like the "European Stork Villages" initiative (https://www.storkvillages.net/) through the EuroNatur project (https://www.euronatur.org/en) to counterbalance the habitat loss for storks in Europe; and (iv) implement ex-situ cultivations as well as reintroductions of endangered local species (Lee et al., 2020). These actions can significantly contribute to achieving one of the 2030 United Nations' sustainable development goals (SDGs) (United Nations, 2015): "Life On Land" (SDG 15).

Although substantial anthropogenic-induced warming is leading to more frequent and intensive compound climate extreme events around the world (AghaKouchak et al., 2020), their ecological cascading effects have rarely been acknowledged as a serious threat to migratory birds' conservation in both scientific literature and ecosystems' management practice. One possible reason behind this is the lack of interactions among different scientific disciplines as well as between the scientific and practitioners' communities. We also need to enhance our capacity in monitoring, early warning, and predictive modeling. Finally, scientific understanding and knowledge must be the basis for conscious policy-making. Paying attention to such facts today can also lead us to act towards achieving SDG 13 ("Climate Action") around the world. Accordingly, this paper urges all financial communities, research institutions, stakeholders, policy-makers, and politicians interested in conservation science to participate in a careful interdisciplinary and transdisciplinary assessment of cascading ecological risks induced by compound climate extreme events to migratory birds, particularly those North American species flying through the Pacific and Central migration pathways across the western U.S.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

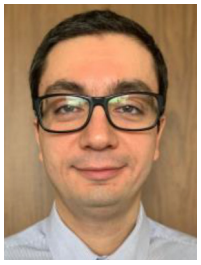
CRediT authorship contribution statement

Masoud Irannezhad: Conceptualization, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Mohadeseh S. Tahami:** Conceptualization, Formal analysis, Writing – original draft, Writing – review & editing. **Behzad Ahmadi:** Data curation, Formal analysis, Writing – review & editing. **Junguo Liu:** Supervision, Funding acquisition, Writing – review & editing. **Deliang Chen:** Writing – review & editing.

Author biographies

Masoud Irannezhad is a Senior Research Fellow in the Water, Energy and Environmental Engineering Research Unit at the University of Oulu in Finland. He was a Research Associate at the Portland State University (USA) in 2016–2017 and a Research Assistant Professor at the Southern University of Science and Technology (China) in 2018–2020. Masoud is also a contributing author to the AR6, IPCC 2022, WG II, Chapter 4, Water as well as a Young Career Researcher Editorial Board Member of the Hydrology Research journal. His research focuses on atmosphere-climate- & water interactions around the world. Masoud has published 36 peer-reviewed journal papers and 2 book chapters, which have totally been cited 612 times. Based on his publication in Science, Masoud is currently doing research on different climate drivers, hydrological implications, and environmental sustainability risks of future snow droughts in Fenno-Scandinavia.

Mohadeseh S. Tahami is a postdoctoral researcher at University of Jyväskylä, Finland. She has a specific expertise in animal biosystematics. She has conducted a wide array of research from reproduction, feeding behavior and conservation of freshwater fish, to taxonomy, biodiversity and phylogeny of invertebrates. She integrates her background knowledge into multidisciplinary studies by combining different genomics technique, bioinformatics, and phenotypic traits to decipher evolutionary mechanisms such as speciation and adaptation to extreme environments.



Behzad Ahmadi is a water resources engineer with WSP USA. He does design for surface water, stormwater and sanitary sewer projects, including hydraulic and hydrologic modeling. Prior to joining WSP, Behzad was research engineer at center for water-energy efficiency at UC Davis. He worked on designing and developing of a decision support system for urban water utility operators. In his doctoral dissertation, Behzad performed a comprehensive drought recovery analysis in both riverine and terrestrial ecosystems over the CONUS. He developed an empirical framework to detect hydrological droughts considering water quantity and quality, then he analyzed drought recovery duration in 400 streamflow stations.

Junguo Liu is a vice president of the North China University of Water Resources and Electric Power, and a Chair Professor at the Southern University of Science and Technology in China. His research involves hydrology and water resources, water-related disasters, global environmental change, and ecological restoration. Recognized as a highly cited researcher and elected member of Academia Europaea (The Academy of Europe), he serves as the President of the Society for Ecological Rehabilitation of Beijing, the Vice President of the Chinese National Commission for the International Association of Hydrological Sciences (IAHS), and the Chair of the Union of Societies for Ecological Restoration and Environmental Protection. Junguo is an author of over 260 scholarly publications and 7 books. He is also a Lead Author of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, and an expert consultant for UN-Water, UNEP, FAO, Alliance for Global Water Adaptation, and the Water Footprint Network.

Deliang Chen is a professor at the University of Gothenburg. His research includes Earth system science, global change, and impacts of climate change on the water cycle, ecosystem, and environment. He is an elected member of six academies including the World Academy of Sciences, the Royal Swedish Academy of Sciences, and the Chinese Academy of Sciences. He has served on numerous international and national committees and boards. Recent examples include Chair of the Nomination Committee of the Stockholm Water Prize; Chair of the Earth Science Division of the Royal Swedish Academy of Sciences; and member of the International Scientific Advisory Board of Stockholm Resilience centre. He also acted as a Coordinating Lead Author in Working Group I of the IPCC's sixth assessment report and serves as an editor for several international scientific journals. Recently, he was awarded the H. M. The King's Medal for his outstanding contributions to climate research.

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