A typological framework of non-floodplain wetlands for global collaborative research and sustainable use

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Abstract
Non-floodplain wetlands (NFWs) are important but vulnerable inland freshwater systems that are receiving increased attention and protection worldwide. However, a lack of consistent terminology, incohesive research objectives, and inherent heterogeneity in existing knowledge hinder cross-regional information sharing and global collaboration. To address this challenge and facilitate future management decisions, we synthesized recent work to understand the state of NFW science and explore new opportunities for research and sustainable NFW use globally. Results from our synthesis show that although NFWs have been widely studied across all continents, regional biases exist in the literature. We hypothesize these biases in the literature stem from terminology rather than real geographical bias around existence and functionality. To confirm this observation, we explored a set of geographically representative NFW regions around the world and characteristics of research focal areas. We conclude that there is more that unites NFW research and management efforts than we might otherwise appreciate. Furthermore, opportunities for cross-regional information sharing and global collaboration exist, but a unified terminology will be needed, as will a focus on wetland functionality. Based on these findings, we discuss four pathways that aid in better collaboration, including improved cohesion in classification and terminology, and unified approaches to modeling and simulation. In turn, legislative objectives must be informed by science to drive conservation and management priorities. Finally, an educational pathway serves to integrate the measures and to promote new technologies that aid in our collective understanding of NFWs. Our resulting framework from NFW synthesis serves to encourage interdisciplinary collaboration and sustainable use and conservation of wetland systems globally.

1. Introduction
Wetlands provide multiple benefits and services that are essential in achieving the global Sustainable Development Goals. Non-floodplain wetlands (NFWs) are a common type of wetlands, surrounded by uplands outside of floodplains and riparian areas (Lane et al. 2018). These waters are numerous, widely distributed, and tightly linked to socio-economic development, but their typically small size...
(even down to 0.01 ha; Lane and D’Amico 2016) and shallow nature (water depth < 6 m; Ramsar Convention 1971) leave them frequently unmonitored and unmapped. Thus, due to their minimal physical stature, NFWs remain poorly protected and vulnerable to degradation and destruction caused by both hydro-climatic and anthropogenic drivers (e.g. agricultural intensification, urban expansion, eutrophication, salinization, and invasive species) (Van Meter and Basu 2015, Creed et al 2017, Golden et al 2019). Over the last decade, NFWs have however been increasingly recognized for their functional role in providing multiple ecosystem services, that were once primarily associated with larger, more widely studied systems such as riverine and coastal floodplain wetlands (Cohen et al 2016, Rains et al 2016, Golden et al 2017, Lane et al 2018). This recognition has led to a range of recent initiatives highlighting the importance of NFWs and emergence of collaborative efforts at national and transnational levels to achieve their sustainable use (Hill et al 2018, Sullivan et al 2019, Cheng et al 2020, Sayer and Greaves 2020, Swartz and Miller 2021, Lane et al 2022).

The 1971 Ramsar Convention is by far the most far-reaching international agreement on wetland conservation and sustainable use. A major objective of the Convention is to provide opportunities for the global community to learn and collaborate based on the geographical, functional, and biological representation of the Ramsar wetland sites (Bridgewater and Kim 2021). This is yet far from being achieved for the world’s NFWs, with lacking coordinated research and collaborative utilization at cross-regional to global scales. Starting with terminology, ‘NFW’ is derived from ‘isolated wetlands’ and ‘geographically isolated wetlands (GIWs);’ terms more widely published in North America (Leibowitz and Nadeau 2003, Leibowitz 2015). Although ‘NFW’ has gradually gained acceptance in academia for emphasizing the geographical location rather than falsely generalizing the hydrological isolation of these waters (Mushet et al 2015, Calhoun et al 2017a, Lane et al 2018), it is used inconsistently and often accompanied by ‘GIWs,’ even in the recent research literature and government documents (e.g. U.S. Environmental Protection Agency 2015). Other terms including but not limited to ‘small water bodies’ (Biggs et al 2017), ‘neglected freshwater habitats’ (Hunter et al 2017), ‘temporary wetlands’ (Calhoun et al 2017b), ‘vulnerable waters’ (Creed et al 2017), and ‘wetlandscapes’ (Thorslund et al 2017, Ghajarnia et al 2020) are used or partially used in studying similar small wetlands, but often with a specific focus on wetland attributes (e.g. size, perimeter-area-volume relationship, and hydroperiod), functions (e.g. flood attenuation, nutrient retention, and biodiversity support), and study scales (e.g. individual wetlands, wetlands across landscapes, and wetlands at watershed and regional scales), respectively. Such marked heterogeneity has been cross-validated by several reviews and calls for improved research and collaborative utilization of these wetland systems (Hunter et al 2017, Chen et al 2019, Golden et al 2019, Sayer and Greaves 2020), which indicate the prevailing perspectives at local and regional scales—NFWs are studied with different emphases under different motivations, depending upon where they are located and what we are interested in. The lack of further refinement and organization on the heterogeneity obscures the representativeness of these wetland systems and is an obstacle to collaborative research and sustainable use at larger scales.

Given these knowledge gaps, we raise three questions that are central for promoting the theory and practice of sustainable NFW use to global scale: (a) how extensively have NFWs been studied in different parts of the world? (b) what are the patterns of their research focal areas across different regions? and (c) how can current research efforts aid in improving collaborative research and management of NFWs? We address these questions through the use of meta-analyses of recent scientific literature, an in-depth investigation of representative regions, and interdisciplinary research recommendations, with detailed methods and intermediate results in appendix 1–3. Although any term has inherent limitations for phenomenon that actually spans a continuum (e.g. river vs. stream; Richardson et al 2022), ‘NFW’ is favored over the others here, following previous studies of terminology consolidation (Leibowitz 2015, Mushet et al 2015, Calhoun et al 2017a, Lane et al 2018). This is because of the essential characteristics that distinguish NFWs from floodplain wetlands and our willingness to remain neutral to those different research objectives and motivations. Our exploratory examination of research activity and resulting framework represents a synthesis of what to date has been a diverse but dispersed knowledge base. In turn, this emerging framework can now be used to concentrate dialogue and also aid management and protection for similar small vulnerable waters (e.g. ephemeral or intermittent headwater streams; Lane et al 2022) in the context of global freshwater challenges.

2. NFWs have been widely studied with strong North America influences

Using a dual-step search procedure, our meta-analysis on NFW research yielded 2213 peer-reviewed articles, published over a period of 20 years (2001–2020) and cataloged in the Web of Science™ Core Collection. This procedure contains a first step to retrieve three synthesis types of studies (i.e. review, commentary,
We first identified 36 specific NFW types, and organized them into 9 main types and 27 subtypes, according to the inland wetland classification scheme of the Ramsar Convention (Ramsar Convention Secretariat 2013) and the U.S. Environmental Protection Agency (www.epa.gov/wetlands/classification-and-types-wetlands) (figure 1(a)). Ponds, including its subtypes farm ponds, temporary ponds, multipond systems, karst ponds, chain-of-ponds, and Delmarva ponds, are most studied. Ponds account for 34% of the 2213 articles, despite a recent functional definition involving surface area, depth and coverage of emergent vegetation, that distinguishes them from lakes and wetlands (Richardson et al. 2022). Other NFW types, in descending order of research frequency (ranging from 27% to 5%), include pools, constructed wetlands, marshes, potholes, swamps, fens, and bogs (including their subtypes), while other less-studied wetland types aggregate third at 16%.

Based on the specific NFW types, relevant studies have been found across all seven continents, but the studies are predominantly located in North America (between 39% and 96%, for the nine main types; figure 1(b)). This result is presumably due to the origination of ‘NFW’ terminology, and the further development of legislative/regulatory and management/funding policies around NFWs in the U.S. (Sullivan et al. 2020, Wade et al. 2022). Apart from potholes, in which the dominant subtype of prairie potholes is endemic to North America, literature from Asia and Europe have a combined share of pond, marsh, and constructed wetland research, reaching 33%–53%, each close to or higher than that of North America. Subsequently, NFW research in Africa, South America, and Australia shows an average share of 3.3%, 4.6%, and respectively.
with the total share of swamps (17%) close to that of Asia, while no studies on fens or bogs being found in Africa. Moreover, Antarctica has a small but noteworthy share at 0.9%–1.1% for the categories of ponds, pools, and other wetland types (i.e. 4 out of the 11 polar wetlands in figure 1(a); see table A2 for further elaboration). The geographic distribution of widely studied NFWs were cross-validated by several global wetland databases, including HydroLAKES (www.hydrosheds.org/page/hydrolakes/) and MERIT Hydro (http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/). Note, these datasets also highlight the inherent lack of a generalized framework for NFW research as they are both missing geographic distribution data for Antarctica (Hu et al 2017, Zhang et al 2021).

3. Emerging research patterns across representative NFW regions

The above meta-analysis revealed strong North America influence in the NFW studies, which we hypothesize stem from terminology rather than real geographical bias around existence and functionality. To confirm any potential bias in publication frequency, we selected 30 representative regions for an in-depth investigation of research characteristics across NFWs around the world (figure 2). The selection criteria were based around trying to include as many identified NFW types as possible, to cover a wide geographical distribution (by continent) and hydro-climatic settings (by the updated Köppen-Geiger climate classification system; Peel et al 2007), and to cover active NFW study areas, based on recent literature and relevant projects on sustainable wetland use. Further narrations on the selection criteria, grouping experiments, and analytical procedures are in appendix 2. In particular, we analyzed the land-cover characteristics for grouped representative regions, and then linked these regions with a subset (229 site-related articles) of the above full set of articles to assess 12 research focal areas (including hydrogeomorphology, water resource, hydrological and biogeochemical processes, nutrient retention, greenhouse gas regulation, biodiversity, ecosystem services, sustainable agriculture, inventory mapping, and climate change) on NFWs. These research focal areas were summarized from the Millennium Ecosystem Assessment (WHO 2006) and retrieved literature, and to quantified to converge scientific and management concerns across the representative regions (appendix 3).

Using the updated Köppen-Geiger climate classification system as a grouping criterion, and based on grid-formatted Esri 2020 Global Land Cover map (https://livingatlas.arcgis.com/), our results identified similarities in land-cover types around NFWs in different regions of the world. Specifically, tropical and cold zones have common dominant land-cover types around NFWs, including trees, flood vegetation, and scrub-shrub (17%–28%), followed by a smaller proportion of water, grass, crops and build area (2%–15%), despite their huge difference in climatic conditions. Similarly, both arid and polar zones have a higher proportion of scrub-shrub and bare ground (17%–57%), although the second largest land-cover type in arid zones (20%), i.e. crops, does not exist in polar zones, while snow-ice in polar zones (26%) is statistically higher (p-value < 0.1) than that of all other zones combined and almost none in arid zones. Moreover, around NFWs, the proportion of crops, trees, and build area in temperate zones (38%, 24%, and 21%, respectively) and waters in cold zones (6%) are statistically higher than that of the same land-cover type in all other zones combined.

Commonalities and patterns were discovered with regard to the 12 NFW research focal areas. Biodiversity stands out from the others, with high prevalence across all climate zones (44% on average here and throughout). Hydrological and biogeochemical processes are also common across all zones (both 40%), whereas wetland protection is popular in tropical, arid, and temperate zones (52%), but with a lower focus in cold and polar zones (21%). Inventory mapping, nutrient retention (although a subset of biogeochemical processes), and sustainable agriculture have been least studied (13%–14%), although the first one in tropical zones and the latter two in temperate zones are more prominent. Additionally, evaluated publications appear to focus to a larger extent on climate change (44%) and greenhouse gas regulation (40%) in tropical, polar, and cold zones, and ecosystem services in tropical zones (38%) with moderate ecosystem service concerns in arid, temperate and cold zones (25%). Hydrogeomorphology in arid, cold and polar zones (26%) and water resources in arid and temperate zones (24%) are moderately studied.

These emerging patterns of research focal areas, discovered here at global scales, can be attributed to cross-regional differences in hydro-climatic settings and NFW land-cover characteristics. Specifically, greater motivations in studying hydrological and biogeochemical processes are presumably due to relatively limited precipitation but equally necessary freshwater resources in arid and cold zones (Lawford et al 2013, Pekel et al 2016). Higher sensitivities to climate change in tropical, polar, and cold zones at extreme latitudes (IPCC 2021) have led to more attention towards climate change related topics, including greenhouse gas regulation. Extensive cropland and human activities are associated with all land-cover types except snow-ice, confirming higher prevalence of nutrient retention in temperate zones and ecosystem services in all zones outside the polar zones, respectively.
4. New opportunities for global collaborative research and sustainable use

We have demonstrated that NFWs have been widely studied across all continents (including the often-overlooked Antarctica), but with a strong North America influence that may bias interpretation of typology, prevalence, and importance (although the reasons behind the North America influence were not quantified in this study). Moving beyond terminology to wetland functionality, we have further shown commonalities and patterns of research focal areas in representative regions of different NFW types and climate zones. This convergence of scientific evidence on NFW typology and prevalence implies that additional efforts to develop a common framework for collaboration and sustainable use of NFWs are needed. We present here a vision for global collaboration, and outline four pathways that will enhance our understanding and sustainable use of these wetland systems across regions—from classification and simulation as theoretical and technical bases, to improved legislative/regulative support via mutual learning of governments, and bidirectionally reinforced education and science (figure 3). These recommendations, particularly for countries with similar geo-climatic settings and socioeconomic development levels (due to better opportunities to learn from each other),
can complement existing frameworks of NFW utilization and protection for governments and agencies (Golden et al. 2017, Hunter et al. 2017, Calhoun et al. 2017b, Chen et al. 2019, Swartz and Miller 2021), and have potential to galvanize broader international collaborations on sustainable wetland use.

4.1. Classification
NFWs have heterogeneous naming criteria in different geographical settings, e.g. relating to hydroperiod for temporary ponds (Calhoun et al. 2017b), landforms for karst ponds (Hill et al. 2018), structures for chain-of-ponds (Williams et al. 2020), and purpose for farm ponds (Takeuchi et al. 2016) (figure 1(a)). Previous studies have attempted semantic mediation among the terms used (Leibowitz 2015, Mushet et al. 2015, Calhoun et al. 2017a). This however continues to be a fundamental issue that requires urgent and systematic solutions for better understanding and inventorying across regions, as well as reducing regional influences. A systematized categorization can then be built upon main wetland types with subtypes identified, with particular focus on the ecosystem services that characterize NFWs (figure 2(b)) and hydrogeomorphic settings that shape NFWs (e.g. classification systems of Tiner 2003, Dvoretz et al. 2012), plus additional reference to historical classics that reveal how NFWs evolve (e.g. historical records in Gao et al. 2015, Poschlod and Braun-Reichert 2017). On this basis, mutual aid with local adaption considerations (i.e. taking local conditions into considerations), especially on the dominant hydro-climatic characteristics and landscape processes, e.g. the freeze-thaw processes for polar wetlands (Rains 2011) and irrigation practices for multipond systems (Chen et al. 2020b), is preferred, when developing novel technologies, such as hyperspectral remote sensing (Wu et al. 2019), in detecting NFWs’ presence and physical characteristics. Together, these could be more reliable than the distance criterion currently in use (Lane and D’Amico 2016), whether it is 10 meters or longer. At continental and global scales, reassembling exemplary and sophisticated datasets like the U.S. National Wetlands Inventory and Pan-European High-Resolution Layers, while integrating observations of various research focal areas (e.g. the six data categories of the integrated monitoring framework proposed by Chen et al. 2019), with regular automatic or semi-automatic updates (e.g. via google Earth Engine Data Catalog), is recommended to reflect the impact of human activities in disparate regions and boost watershed and climate change sciences (Berrang et al. 2015, Golden et al. 2021).

4.2. Simulation
Recent advances have demonstrated that incorporating NFWs into watershed modeling (from watershed areas ranging from ∼10 km² like Chen et al. 2020b to ∼1000 km² like Evenson et al. 2016, Yeo et al. 2019, Zeng and Chu 2021, and to ∼5 × 10⁵ km² like, Rajib et al. 2020) can improve the accuracy of runoff and nutrient yield simulations. However, challenges remain in understanding the cumulative and comprehensive effects of these landscape mosaics (i.e. small but nonnegligible aquatic patches that embedded in various land-cover types, according to Mushet et al. 2019 and validated by figure 2(b)) at continental or global scales, given our general lack of understanding of their underlying hydrological processes and sensitivity to climate alteration. In terms of land-cover characteristics and research focal areas that characterize NFWs (figure 2), the emerging,
cross-regional differences we demonstrated confirm the diversity of current model refinements, e.g. hydrological connectivity for prairie potholes (Lane et al. 2018), phosphorus retention for farm ponds (Chen et al. 2019), and biodiversity support for vernal pools (Sullivan et al. 2019) in the cold, temperate and arid climate zones, respectively; while the commonalities we presented highlight the need and potential of mutual learning of model assumptions and coupling of model refinements, especially when assessing the coevolution of natural and human systems around NFWs at larger scales. Additionally, separate modeling and parameter estimation for typical study sites, followed by integration and comparison of simulation results, can help eliminate the issues of inconsistent model objectives and structures due to the lack of unified knowledge (i.e. epistemic uncertainty), but requires further inventory, calibration and fidelity assessment to reflect cross-regional discrepancies. Open web-distributed collaborative modeling frameworks, from implementation standards like OpenMI to service-oriented platforms like CSDMS and OpenGMS (Salas et al. 2020, Chen et al. 2020a), are a viable solution, especially in the trend of sharing and reuse for monitoring data.

4.3. Legislation/regulation
In contrast to the universal research focal areas across the globe (figure 2), environmental legislation and regulation for NFWs is uneven, much like the uneven proportions of NFW systems studied across different continents (figure 1(b)). At a more general level, wetland conservation priorities and actions are well developed (Pittock et al. 2015) and are embedded within broader freshwater conservation planning best practices (Nel et al. 2009). At the implementation scale, however, only a few countries, such as England (Biggs et al. 2005), have extensive experience in NFW (mainly pond) monitoring and restoration (Sayer and Greaves 2020). Not surprisingly, other countries, such as U.S., have different and often conflicting policies between federal and state governments—The former has once enforced rules that put NFWs at risk but now more generally promote conservation, whereas the latter have often enacted additional, protective regulations (e.g. Florida in particular) (Creed et al. 2017, Sullivan et al. 2019, 2020, Wade et al. 2022). Additionally, laws and regulations that implement indirect protection have been emerging in a few countries over the past two decades. Examples include Japan’s Satoyama Initiative that promotes the sustainable use of rural natural resources (Takeuchi et al. 2016), China’s Lake/River Chief Mechanism that ensures the water governance and ecological integrity throughout river basins (Wang et al. 2019), and Kenya and Tanzania’s Wildlife Act that improves the biodiversity of national nature reserves with relevance to the safety of large mammals (Cockerill and Hagerman 2020). These cases confirm the value of NFWs in larger ecosystems (i.e. rural, water and wildlife ecosystems) and effectiveness of indirect protection by enhancing existing legal frameworks relating to greater social concerns, although the reality on the ground may not be as effective as the legal framework (Xu et al. 2019). Structured analysis and extension of all these ongoing efforts in conjunction with comprehensive valuation and compensation of ecosystem services is recommended to promote win-win management investment for NFW protection and restoration. This recommendation is particularly useful for countries with similar geo-climatic settings around NFWs (figure 2) and socio-economic development levels, since similar monitoring, evaluating and management strategies can be employed, according to (Flörke et al. 2013, Aguilar 2020).

4.4. Education
The sustainable use of NFWs can be an excellent testbed for two-way interactions between science and education. For popular education and science popularization, cross-regional comparisons based on either formal lectures or field trips can enhance understanding of the ecosystem services provided by NFWs. For research and professional education, establishing connections between historical legacies of NFW terminology (e.g. chain-of-ponds and multipond systems in figure 1), commonalities and patterns in the characterizing land-cover types and research focal areas (figure 2), and geographical, historical, political, and cultural driving factors behind (which together contributed to the prevalence of a term), can help understand our diverse world, including the major current issues such as climate change and resource scarcity. Future scientific discovery on the valuation of NFWs’ ecosystem services, as has been tried in the U.S. (Creed et al. 2017), could explore macroeconomic indicators and ecological compensation systems that contribute to wetland sustainable use, for example. Meanwhile, technological advances are constantly making interdisciplinary knowledge comprehensible and participatory. Virtual reality and gamification, as a basis of the metaverse (Lee et al. 2021), for example, can be used to develop immersive, targeted exhibitions on NFWs in conjunction with iconic wildlife species (e.g. salamanders for vernal pools in the northeastern U.S.; Brooks 2005) and surrounding land-cover types (e.g. woodlands, plantations, grasslands, farmlands, irrigated ponds, canals, etc for the Satoyama landscape in Japan; Takeuchi et al. 2016), as have been applied in the online version of some prominent museums (Lee et al. 2020). The popularization of high-definition cellphone cameras, fifth generation mobile network, and edge machine learning capabilities (i.e. techniques that achieve real-time processing on resource-constrained terminal
devices of the Internet of Things, reducing reliance on the cloud network) can enhance crowdsourced data collection and real-time sharing and analysis on the ecological conditions of these small, vulnerable waters, if properly used to keep the applications attractive to the public participants (including local planners, citizens, farmers, travelers, etc as summarized by Chen et al 2019).

5. Connecting the disconnected

Protection and sustainable use of wetlands is an important global challenge without a simple solution. Local and regional efforts on NFW conservation and sustainable use are often piecemeal and subject to parochial boundaries, while to date cross-regional collaborations have been limited due to lack of consistent terminology, differentiated research focal areas, and heterogeneity at different scales. The meta-analysis and synthesis of the global literature presented here, however, has shown that there are multiple commonalities that emerge for NFW systems. The emerging commonalities and patterns in NFW research focal areas resulted in a framework that spans global climate zones and captures biodiversity, hydrological and biogeochemical processes. This framework in turn serves as a means to identify top research topics and their geographic locations. These NFW research hotspots include climate change impacts and greenhouse gas regulation in tropical, polar, and cold zones. Conversely, inventory mapping, nutrient retention, and sustainable agriculture are the least studied NFW attributes, suggesting room for further collaborative research. These findings suggest that there is more that unites disparate wetland research and management efforts than we might otherwise appreciate. They can also help us move forward with practical work, connecting pathways for new opportunities for sustainable NFW use by the global community—from (a) classification to support inventory mapping, measurement with local adaptations, and data integration, to (b) simulation to promote cognition of different model assumptions, coupling of model refinements, and online collaborative modeling, (c) sharing and learning of legislation/regulation experience from countries with similar backgrounds, and (d) stimulated two-way interaction between science and education with the use of emerging technologies. These recommendations should be further explored to improve collaboration and global realization of sustainable wetland systems.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Appendix 1. Literature retrieval and wetland type analysis

We developed a dual-step search procedure to retrieve peer-reviewed articles on non-floodplain wetlands (NFWs; including main types and subtypes, as described below) from the Web of Science Core Collection (WoS, www.webofscience.com; the 30 September 2021 Release). To capture the latest knowledge and scientific advances in this field, we focused on published literature within the most recent two decades; 2001–2020. Table A1 shows the search strings, instructions, and results of the search procedure, as detailed below.

In the first step, both ‘NFW’, ‘isolated wetland’, ‘geographically isolated wetland’, and other keywords that reveal the characteristics and research focal areas of these wetlands, were used to retrieve review, commentary, and perspective studies in the field. Studies on aquaculture and water treatment facilities were excluded because the ecosystem processes, particularly the hydroperiod of these waters, are largely human-controlled. Specific NFW types were then manually screened from the result 57 articles based on the authors’ expertise as wetland scientists, and then organized into main wetland types and subtypes (table A2). To make subsequent search steps concise and effective, common modifiers (e.g. ‘blanket’ in ‘blanket bogs’ and ‘ephemeral’ in ‘ephemeral pools’) and equivalents (e.g. ‘constructed ponds or pools’ that are equal to ‘constructed wetlands’) were omitted here. Even so, the alphabetical collection of wetland types in table A2 should be interpreted with caution—it is not a strict classification scheme for
Table A1. Dual-step search procedure for published articles on NFWs.

| Search string and keyword                                                                 | Instruction                                      | Result                                                                 |
|--------------------------------------------------------------------------------------------|--------------------------------------------------|------------------------------------------------------------------------|
| **Step 1**                                                                                |                                                  |                                                                        |
| (non-floodplain wetland OR isolated wetland OR geographically isolated wetland OR small water bodies OR small vulnerable waters OR neglected freshwater habitat OR temporary wetland OR wetlandscape) \(\text{AND}\) (review OR commentary OR perspective) | (a) Each retrieved article was read through to ensure that it is a review, commentary, or perspective study of NFWs. | 57 articles and organized wetland types in table A2. |
|                                                                                            | (b) Studies on aquaculture and water treatment facilities were excluded. |                                                                        |
|                                                                                            | (c) Specific wetland types were manually screened and organized from the eligible articles. |                                                                        |
|                                                                                            | (a) Only one keyword in the left parentheses and one keyword in the right parentheses were joined for each search. |                                                                        |
|                                                                                            | (b) Results were ranked by relevance.            |                                                                        |
|                                                                                            | (c) Abstract, conclusions, and figures were perused for each retrieved article from top to bottom, to filter out articles that are not related to NFWs. |                                                                        |
|                                                                                            | (d) A maximum of 50 eligible articles were selected for each search. |                                                                        |
| **Step 2**                                                                                |                                                  |                                                                        |
| (each wetland type in Table A2) \(\text{AND}\) (wetland OR small water bodies OR small vulnerable waters OR neglected freshwater habitat OR wetlandscape) |                                                  | 2213 articles.                                                        |

Table A2. Main NFW types and subtypes, organized according to the inland wetland classification scheme of the Ramsar Convention and the U.S. Environmental Protection Agency.

| Main type          | Subtype                  | Main type          | Subtype                  |
|--------------------|--------------------------|--------------------|--------------------------|
| Bogs               | Kettle-holes             | Ponds (continued)  | Karst ponds              |
|                    | Pocosins                 |                    | Multipool systems        |
| Constructed wetlands (CWs) |                    | Temporary ponds   | Temporary pools          |
| Cypress domes\(^a\) |                    | Seasonal pools     | Vernal pools             |
| Delmarva and Carolina bays\(^a\) |                    |                    | Limesinks                |
| Desert springs\(^a\) |                    |                    | Prairie potholes         |
| Fens               | Alvar wetlands           | Wet meadows        | Sinkholes                |
| Marshes            | Playa\(^a\)              | Playa lakes        | Desert seeps            |
|                    | Sandhills wetlands\(^a\) |                    | Hillside seeps           |
| Polar wetlands\(^a,\) | Chain-of-ponds          |                    |                          |
|                    |                        |                    |                          |
|                    | Delmarva ponds           |                    |                          |
|                    | Farm ponds               |                    |                          |
|                    | Delmas \(^a\)            |                    |                          |
|                    | Seeps\(^a\)              |                    |                          |
|                    | Swales\(^a\)             |                    |                          |
|                    | Swamps                   |                    |                          |

\(^a\) These wetland types and their subtypes are organized into ‘other wetland types’ in figure 1 in the main manuscript, due to the relatively smaller number of articles that related to them (as described below).

\(^b\) ‘Polar wetlands’ is a generic term used in literature for wetlands in the Arctic, Antarctic, and Tibetan Plateau.

NFWs, as some terms of types are used as synonyms in the literature (e.g. ‘constructed wetlands’ and ‘ponds’, and ‘vernal pools’ and ‘temporary pools’).

In the second step, we expanded the search criteria by joining each wetland type in table A2 and characteristic keywords used above, to retrieve all published articles on NFWs, i.e. not limited to review, commentary, and perspective studies. Some terms like ‘constructed wetlands’, ‘marshes’ and ‘ponds’ had a large number of retrieved results (>10000), while the others like ‘Delmarva ponds’, ‘multipond systems’ and ‘limesinks’ had, comparatively, very few results (<30). To address this issue and evenly use the above wetland types, we ranked the retrieved articles by relevance according to the WoS built-in algorithm (30 September 2021 Release), and then reviewed the abstract, figures, and conclusions of each article manually, to ensure the remaining articles are related to NFWs, and filter out articles that are not related to NFWs. In other words, with particular attention paid to geographical features (i.e. non-floodplain), articles were retained only when the research object belongs to, contains, is within NFWs, or the research topic is explicitly related to NFWs.
Otherwise, a minimum distance of 10-meters far away from rivers, coasts, and floodplains was used as a criterion for the visual inspection of NFWs, according to Lane and D'Amico (2016). Based on this procedure and filtering out repetitive articles that have already been retrieved, the top 50 eligible articles (or all articles if less than 50) were selected for each search, resulting in a total dataset of 2213 articles for this step. The maximum number of 50 was used to balance the number and relevance of articles for each retrieval.

Based on the full set of literature, we analyzed the number of articles where each NFW type (main and subtypes) occurs and the proportion of studies (main types) on each continent (figure 1 in the main manuscript). The number of articles was counted by using the advance search tool of Zotero (www.zotero.org/). Results were shown in a grouped tag cloud (figure 1 in the main manuscript), rather than standard statistical charts (e.g. pie charts), because, as mentioned above, the wetland types we organized here were not a strict classification scheme for NFWs, while some articles were double-counted in the analysis. Specifically, when calculating the proportions of wetland types being studied, the number of continent-related articles increased by one, if a review study includes a specific NFW identifier (IDs) as in figure 2 in the main manuscript, and in tables A3, A4 and A7 below. Additionally, on-site photos of similar NFWs and surrounding landscapes can be found in Google Images (https://images.google.me/) by searching for the specific wetland types and locations in table A3. They can serve as a reference for the general readership. The grid-formatted Esri 2020 Global Land Cover map was used to analyze the proportion of land-cover types for each site. This dataset was built on the European Space Agency Sentinel-2 satellite imagery and has a recent release date (July 2021) and high spatial resolution (10 m) at global scales. The land-cover map was clipped by twice the extent of the imagery for each site in figure A1; showing NFWs and surrounding landscapes, climate group, wetland type, and location information (table A3) of the 30 representative regions are presented, with the same identifiers (IDs) as in figure 2 in the main manuscript and in tables A3, A4 and A7 below. Additionally, on-site photos of similar NFWs and surrounding landscapes can be found in Google Images (https://images.google.me/) by searching for the specific wetland types and locations in table A3. They can serve as a reference for the general readership. The grid-formatted Esri 2020 Global Land Cover map was used to analyze the proportion of land-cover types for each site. This dataset was built on the European Space Agency Sentinel-2 satellite imagery and has a recent release date (July 2021) and high spatial resolution (10 m) at global scales. The land-cover map was clipped by twice the extent of the imagery for each site in figure A1 to better grasp the land-cover characteristics around NFWs, and then reclassified and removed null values (i.e. invalid values in the source files) using ArcToolbox (http://desktop.arcgis.com/), yielding the proportional results in table A4. Due the relatively small sample size in each group, an independent-samples t-test was performed using SPSS, to determine whether the proportions of one climate zone were statistically higher (p-value < 0.1) than those of the other climate zones in the same land-use type.

Appendix 2. Representative region selection and land-cover analysis

In addition to the meta-analysis, 30 representative regions were selected and grouped to investigate research characteristics across NFWs around the world. Following the selection criteria narrated in the main manuscript, the active projects around NFW were gathered from information within the European Pond Conservation Network (www.europeanponds.org/), Global Wetland Ecohydrology Network (www.gwenetwork.se/), and National Association of Wetland Managers (www.nawm.org/). Both classification and clustering experiments were conducted to group the representative NFW regions when investigating their land-cover types and research characteristics. The classification was based on the assumption that NFWs play different roles across different continents, land-cover characteristics, or hydro-climatic settings (by the updated Köppen-Geiger climate classification system), while the clustering, as a type of unsupervised learning, was performed by the Hierarchical Cluster Analysis tools of SPSS Statistics 26 (www.ibm.com/). These regions were eventually grouped by the climate zones due to the most explanatory results and widely-recognized hydro-climatic drivers of wetland change at global scales (Bertassello et al 2019, Åhlén et al 2021).

Satellite imagery (figure A1; showing NFWs and surrounding landscapes), climate group, wetland type, and location information (table A3) of the 30 representative regions are presented, with the same identifiers (IDs) as in figure 2 in the main manuscript and in tables A3, A4 and A7 below. Additionally, on-site photos of similar NFWs and surrounding landscapes can be found in Google Images (https://images.google.me/) by searching for the specific wetland types and locations in table A3. They can serve as a reference for the general readership. The grid-formatted Esri 2020 Global Land Cover map was used to analyze the proportion of land-cover types for each site. This dataset was built on the European Space Agency Sentinel-2 satellite imagery and has a recent release date (July 2021) and high spatial resolution (10 m) at global scales. The land-cover map was clipped by twice the extent of the imagery for each site in figure A1 to better grasp the land-cover characteristics around NFWs, and then reclassified and removed null values (i.e. invalid values in the source files) using ArcToolbox (http://desktop.arcgis.com/), yielding the proportional results in table A4. Due the relatively small sample size in each group, an independent-samples t-test was performed using SPSS, to determine whether the proportions of one climate zone were statistically higher (p-value < 0.1) than those of the other climate zones in the same land-use type.
Figure A1. Recent (July 2021) satellite imagery of the 30 representative NFW regions (numbered according to Site ID). Data source: Google Earth and Maxar Technologies (www.maxar.com). Red arrows points to NFWs if they are not obvious on the image.
Table A3. Information about the 30 representative NFW regions, including their distribution across the climate zones used, region name with specific wetland type, and detailed location (including coordinates).

| Climate zone | Region ID | Region name          | Detailed location                                                                 | Central coordinates of the satellite imagery |
|--------------|-----------|----------------------|------------------------------------------------------------------------------------|-----------------------------------------------|
| Tropical     | 1         | Swamps-North Colombia| Near the Ciénaga Grande de Santa Marta, Colombia                                  | 74.58 W, 10.49 N                              |
|              | 2         | Swamps-East Brazil   | Rural area of Canindé, state of Ceará, Brazil                                     | 39.27 W, 4.35 S                              |
|              | 3         | Swamps-Congo         | Sangha River basin, Congo                                                          | 17.31 E, 0.45 N                               |
|              | 4         | Temporary pools-Tanzania | Kilombero River valley, Tanzania                        | 36.05 E, 8.87 S                              |
|              | 5         | Marshes-Sri Lanka    | Jaffna peninsula, Sri Lanka                                                        | 79.99 E, 9.74 N                               |
|              | 6         | Swamps-Indonesia     | Near the Sentarum Lake National Park, Indonesia                                   | 112.14 E, 0.99 N                              |
| Arid         | 7         | Vernal pools-West U.S.| Sierra Nevada mountain range of California, U.S.                                | 118.81 W, 36.21 N                              |
|              | 8         | Swamps-North Mexico  | Northeast Coahuila, Mexico                                                        | 100.90 W, 28.99 N                              |
|              | 9         | Playa lakes-Spain    | Northwest Malaga Province, Spain                                                   | 4.85 W, 37.09 N                               |
|              | 10        | Swamps-Libya         | Southeast of the Maradah oasis, Libya                                             | 19.74 E, 28.93 N                              |
|              | 11        | Temporary pools-Uzbekistan | Amu Darya River delta, Uzbekistan                       | 58.87 E, 42.94 N                              |
|              | 12        | Playas-Central Australia | Between the Lake White and Gregory, Australia                                | 128.42 E, 20.87 S                              |
| Temperate    | 13        | Marshes-Southeast U.S.| Upper Ocklawaha River Basin, central Florida, U.S.                              | 81.67 W, 28.44 N                              |
|              | 14        | Temporary ponds-England | Northeast Norfolk, England                                                      | 1.16 E, 52.91 N                               |
|              | 15        | Temporary ponds-South Africa | Southeast suburb of Cape Town, South Africa                                 | 18.56 E, 34.03 S                              |
|              | 16        | Marshes-North India  | Jaunpur rural district, Uttar Pradesh, India                                     | 82.90 E, 25.92 N                              |
|              | 17        | Farm ponds-South China | Xifu River Watershed, Guangdong Province, China                            | 114.76 E, 23.05 N                              |
|              | 18        | Multipond systems-Southeast China | Huashan Watershed, Anhui Province, China                                   | 118.20 E, 32.32 N                              |
|              | 19        | Farm ponds-Japan     | Northeast of Himeji City, Honshu Japan                                           | 134.99 E, 34.94 N                              |
|              | 20        | Chain-of-ponds-Southeast Australia | Southern Tablelands of New South Wales, Australia                        | 149.63 E, 34.87 S                              |
| Cold         | 21        | Ponds-Alaska         | West of Lake Iliamka, Alaska, U.S.                                               | 156.23 W, 59.32 N                              |
|              | 22        | Prairie potholes-Canada | Southern Saskatchewan, Canada                                                      | 106.55 W, 50.74 N                              |
|              | 23        | Peat bogs-Canada     | Hudson Bay Lowlands, Ontario, Canada                                             | 85.19 W, 53.29 N                              |
|              | 24        | Marshes-Sweden       | Norrström drainage basin, Sweden                                                   | 14.29 E, 60.23 N                              |
|              | 25        | Peat bogs-West Russia | Near the Volga River Delta, Russia                                                | 46.29 E, 44.44 N                              |
|              | 26        | Peat bogs-Siberia    | Lena river basin, Siberia (Russian Far East)                                     | 121.71 E, 66.59 N                              |
| Polar        | 27        | Polar wetlands-West Antarctica | King George Island, Antarctica                                                   | 58.48 W, 62.17 S                              |
|              | 28        | Polar wetlands-Greenland | Disko Island, west central Greenland                                             | 52.15 W, 69.54 N                              |
|              | 29        | Ponds-Tibetan Plateau | East of Lake Namuka Co, Tibetan Plateau (the Third Pole)                           | 90.16 E, 31.92 N                              |
|              | 30        | Polar wetlands-East Antarctica | The Pyramid Trough Region, Antarctica *                                         | 163.32 E, 78.28 S                              |

* Upland ponds fed by intermittent, meltwater streams exist in the Pyramid Trough Region, according to Jungblut et al (2012) and Vincent et al (1994).
Table A4. Classified land-cover proportions (%) around the 30 representative NFW regions, quantified by using the grid-formatted Esri 2020 Global Land Cover map (https://livingatlas.arcgis.com/).

| Climate zone | Site ID | Water | Trees | Grass | Flooded vegetation | Crops | Scrub/Shrub | Built area | Bare ground | Snow/Ice |
|--------------|--------|-------|-------|-------|-------------------|-------|-------------|------------|-------------|----------|
| Tropical     | 1      | 2.19  | 5.22  | 14.16 | 36.22             | 1.48  | 40.37       | 0.36       | 0.00        | 0.00     |
| 2            | 0.73   | 0.56  | 0.02  | 0.00  | 0.00              | 0.02  | 95.26       | 3.41       | 0.00        | 0.00     |
| 3            | 1.10   | 61.82 | 25.96 | 7.76  | 0.00              | 0.00  | 3.28        | 0.08       | 0.00        | 0.00     |
| 4            | 1.81   | 0.29  | 1.80  | 15.43 | 46.57             | 46.57 | 28.88       | 5.23       | 0.00        | 0.00     |
| 5            | 1.34   | 0.26  | 0.31  | 0.26  | 29.13             | 29.13 | 0.33        | 68.36      | 0.00        | 0.00     |
| 6            | 7.02   | 47.29 | 0.00  | 43.60 | 0.00              | 0.00  | 2.09        | 0.00       | 0.00        | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |
| 7            | 0.09   | 5.75  | 0.19  | 0.00  | 0.00              | 0.00  | 90.97       | 2.89       | 0.10        | 0.10     |
| 8            | 1.00   | 2.28  | 0.00  | 0.00  | 9.87              | 9.87  | 83.44       | 2.99       | 0.41        | 0.10     |
| 9            | 1.12   | 3.22  | 0.07  | 0.00  | 37.58             | 37.58 | 52.26       | 3.32       | 2.43        | 0.00     |
| Arid         | 10     | 0.22  | 0.00  | 0.00  | 0.00              | 0.00  | 1.02        | 0.02       | 98.75       | 0.00     |
| 11           | 0.42   | 0.00  | 0.00  | 0.00  | 74.01             | 74.01 | 17.77       | 7.54       | 0.26        | 0.00     |
| 12           | 0.00   | 3.02  | 0.00  | 0.00  | 0.00              | 0.00  | 96.93       | 0.00       | 0.04        | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |
| Temperate    | 13     | 12.64 | 30.13 | 7.59  | 17.11             | 1.95  | 14.11       | 31.02      | 0.85        | 0.00     |
| 14           | 0.07   | 20.67 | 0.15  | 0.00  | 74.94             | 74.94 | 0.58        | 3.59       | 0.00        | 0.00     |
| 15           | 0.21   | 4.54  | 2.44  | 0.12  | 31.24             | 31.24 | 4.72        | 56.33      | 0.39        | 0.00     |
| 16           | 0.84   | 0.25  | 0.04  | 0.16  | 80.32             | 80.32 | 0.58        | 17.81      | 0.00        | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |
| Cold         | 17     | 15.00 | 59.52 | 0.19  | 0.00              | 18.69 | 14.11       | 31.02      | 0.85        | 0.00     |
| 18           | 4.63   | 28.10 | 0.00  | 0.00  | 55.74             | 55.74 | 0.11        | 11.42      | 0.00        | 0.00     |
| 19           | 3.24   | 45.16 | 2.16  | 0.00  | 11.03             | 11.03 | 0.85        | 37.56      | 0.00        | 0.00     |
| 20           | 0.06   | 2.79  | 60.46 | 0.00  | 27.18             | 27.18 | 8.27        | 1.24       | 0.00        | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |
| Polar        | 21     | 5.64  | 7.38  | 13.83 | 49.58             | 20.24 | 57.06       | 2.79       | 17.00       | 0.02     |
| 22           | 15.00 | 59.52 | 0.19  | 0.00  | 18.69             | 18.69 | 0.54        | 6.05       | 0.00        | 0.00     |
| 23           | 4.63   | 28.10 | 0.00  | 0.00  | 55.74             | 55.74 | 0.11        | 11.42      | 0.00        | 0.00     |
| 24           | 3.24   | 45.16 | 2.16  | 0.00  | 11.03             | 11.03 | 0.85        | 37.56      | 0.00        | 0.00     |
| 25           | 0.06   | 2.79  | 60.46 | 0.00  | 27.18             | 27.18 | 8.27        | 1.24       | 0.00        | 0.00     |
| 26           | 0.84   | 0.25  | 0.04  | 0.16  | 80.32             | 80.32 | 0.58        | 17.81      | 0.00        | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |
| 27           | 5.64   | 7.38  | 13.83 | 49.58 | 0.00              | 23.57 | 0.00        | 0.00       | 0.00        | 0.00     |
| 28           | 0.31   | 0.02  | 0.00  | 5.81  | 89.81             | 89.81 | 3.65        | 0.39       | 0.00        | 0.00     |
| 29           | 8.86   | 1.40  | 1.31  | 84.21 | 0.00              | 4.19  | 0.00        | 0.04       | 0.00        | 0.00     |
| 30           | 0.00   | 0.00  | 0.00  | 0.00  | 0.00              | 0.00  | 0.00        | 38.78      | 61.22       | 0.00     |
| Average      |        |       |       |       |                   |       |             |            |             |          |

*The one and two asterisks indicate statistical significance with confidence intervals of 90 and 95%, respectively.

Appendix 3. Further investigation of research focal areas

Twelve investigated research focal areas were summarized according to the full set of literature retrieved above, the Millennium Ecosystem Assessment (WHO 2006), and the authors’ expertise in wetland sciences (table A5). These research focal areas were used to reflect the main scientific and practical concerns on sustainable NFW use, despite a few overlaps, e.g. among the hydrological and biogeochemical patterns and processes. Meanwhile, for each of the 30 investigated regions, we considered additional site-related articles to quantify the prevalence of the 12 classes of research focal areas (table A6). These articles were selected from the full set of literature, based on the criteria covering the representative regions in figure A1 and surrounding areas with the same type of wetland. Each article has been exhaustively reviewed (without references) for expert judgment and categorization. Table A7 shows the aggregated proportions of research focal areas for the 30 regions, categorized according to the five climate zones. The proportional values were organized into three groups using the Jenks Natural Breaks Classification method implemented in ArcGIS (https://pro.arcgis.com/), to conduct the analysis of research focal areas in the main manuscript.
Table A5. Research focal areas of NFWs and surrounding landscapes.

| Research focal areas             | Description                                                                                                                                 |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Hydrogeomorphology (HM)          | Hydrological regime and geomorphic settings that shape and develop the various wetland types and further influence their functions.            |
| Water resource (WR)              | Natural resources of water in wetlands (e.g. storage capacity) that are useful or potentially useful to agricultural, industrial, domestic and other human activities. |
| Hydrological processes (HP)      | Components that influence the water budget, including precipitation, evaporation, surface and subsurface inflows, spillage and seepage outflows, groundwater recharge and discharge, etc. |
| Biogeochemical processes (BP)    | Complex interactions between HP, mineralogical transformations, bacterial and vegetation communities, soil stores of carbon and nutrients, including the regulation/cycling of carbon, nitrogen, phosphorus, sulfur, mercury, and other elements. |
| Nutrient retention (NR)          | Role of wetlands as a sink that reduce nutrient loads for downstream waters. This item is valid only when the term 'retention', 'reduction', or 'removal' is mentioned, as relevant mechanisms including sedimentation, plant uptake, and microbial decomposition were classified to belong to BP. |
| Greenhouse gas regulation (GG)   | Fluxes of greenhouses gases (e.g. carbon dioxide, methane, and nitrous oxide), emitted into and absorbed from the atmosphere, and the driving mechanisms like photosynthesis, respiration, decomposition, nitrification, and denitrification. |
| Biodiversity (BD)                | The large number and variety of plants, animals, and microorganisms that wetlands support, as well as the food, habitats, and breeding grounds for these creatures that wetlands provide. |
| Ecosystem services (ES)          | The four categories of provisioning, regulating, cultural and supporting services, defined by the Millennium Ecosystem Assessment (WHO 2006). This item is valid only when the term 'ecosystem services' is mentioned, i.e. these services are recognized as a whole. |
| Sustainable agriculture (SA)     | Wetland-related agriculture that holds a multi-pronged goal: a healthy environment, sufficient food production, economic profitability, and good quality of life for the practitioners. This item is valid when any of the goals are mentioned. |
| Inventory mapping (IM)           | Dataset and digitized map that provides information on the actual or potential location, size, and type of wetlands.                          |
| Climate change (CC)              | Global warming caused by human activity, particularly the burning of fossil fuels and removal of forests, and its impacts on Earth's weather patterns. This item is valid only when CC is associated with NFWs in the literature. |
| Wetland protection (WP)          | Protecting and conserving the areas where wetland exist. This item is valid only when the term 'protection', 'conservation', or 'preservation' is mentioned. |
### Table A6. Site-related literature, including their research focal areas of the 30 NFW representative regions.

| Site ID | Site-related literature                                                                 | Research focal areas |
|--------|----------------------------------------------------------------------------------------|----------------------|
|        |                                                                                       | HM WR HP BP NR GG BD ES SA IM CC WC |
| 1      | Craven J et al 2017 Development and testing of a river basin management simulation game for integrated management of the Magdalena-Cauca river basin Environ. Modell. Softw. 90 78–88 | √ a √ √ √ |
| 2      | Garcés O O et al 2019 Marine litter and microplastic pollution on mangrove soils of the Ciénaga Grande de Santa Marta Colombian Caribbean. Mar. Pollut. Bull. 145 455–462 | √ √ |
| 3      | Jaramillo F et al 2018 Effects of hydroclimatic change and rehabilitation activities on salinity and mangroves in the Ciénaga Grande de Santa Marta Colombias. Wetlands 38 755–767 | √ √ √ √ √ |
| 4      | Konnerup D et al 2014 Nitrous oxide and methane emissions from the restored mangrove ecosystem of the Ciénaga Grande de Santa Marta Colombias. Estuar. Coast. Shelf S. 140 43–51 | √ √ |
| 5      | Polanía J et al 2015 Recent advances in understanding Colombian mangroves Acta. Oecol. 63 82–90 | √ √ √ √ |
| 6      | Rivera M et al 2011 Salinity and chlorophyll a as performance measures to rehabilitate a mangrove-dominated deltic coastal region: The Ciénaga Grande de Santa Marta-Pajarales Lagoon Complex Colombias. Estuar. Coast. 34 1–19 | √ √ √ |
| 7      | Wemple B C et al 2018 Ecohydrological disturbances associated with roads: Current knowledge, research needs, and management concerns with reference to the tropics Ecohydrology 11 e1881 | √ √ √ √ |
| 8      | Zamora S et al 2020 Carbon fluxes and stocks by Mexican tropical forested wetland soils: A critical review of its role for climate change Mitigation Int. J. Env. Res. Pub. He. 17 7372 | √ √ √ √ |
| 9      | Zipper S C et al 2020 Integrating the water planetary boundary with water management from local to global scales Earth Future 8 e2019EF001377 | √ √ √ √ √ |

(Continued.)
| Reference | Title                                                                 | Journal/Year | Page(s) | Notes |
|-----------|----------------------------------------------------------------------|--------------|---------|-------|
| 2         | Keddy P A et al. 2009 Wet and wonderful: The world's largest wetlands are conservation priorities | *Bioscience* 59 | 39–51   | ✓     |
| 3         | Mitchel E T 2018 The tropical forest carbon cycle and climate change | *Nature* 559 | 527–534 | ✓     |
| 4         | 2 Lyon S W et al. 2015 Interpreting the varied drainage-time scale variability across Kilombero Valley | *Hydrol. Process.* 29 | 1912–1924 | ✓     |
| 5         | 1 Gopalakrishnan T et al. 2019 Sustainability of coastal agriculture under climate change | *Sustainability* 11 | 7200    | ✓     |
| 6         | 2 Couwenberg J et al. 2010 Greenhouse gas fluxes from tropical peatlands in south-east Asia | *Global. Change Biol.* 16 | 1715–1722 | ✓     |
| 7         | 3 Graham L L et al. 2017 A common-sense approach to tropical peat swamp forest restoration in Southeast Asian | *Restor. Ecol.* 25 | 312–321 | ✓     |
| 8         | 1 Chen C C et al. 2014 Rich soil carbon and nitrogen but low atmospheric greenhouse gas fluxes from North Sulawesi | *Sci. Total. Environ.* 487 | 91–96   | ✓     |
| 9         | 2 Couwenberg J et al. 2010 Greenhouse gas fluxes from tropical peatlands in south-east Asia | *Global. Change Biol.* 16 | 1715–1722 | ✓     |
| 10        | 3 Graham L L et al. 2017 A common-sense approach to tropical peat swamp forest restoration in Southeast Asian | *Restor. Ecol.* 25 | 312–321 | ✓     |
|           | 4 Dohong A et al. 2017 A review of the drivers of tropical peatland degradation in south-east Asia | *Land Use Policy* 69 | 349–360 | ✓     |
|           | 5 Hergoualc'h K & Verchot L V 2011 Stocks and fluxes of carbon associated with land use change in south-east | *Global. Biogeochem. Cy.* 25 | 101881 | ✓     |
|           | 6 Kumar P et al. 2020 Towards an improved understanding of greenhouse gas emissions and fluxes in tropical | *Sustain. Cities. Soc.* 53 | 101881 | ✓     |
|           | 7 Margono B A et al. 2014 Mapping wetlands in Indonesia using Landsat and PALSAR data-sets and derived | *Geo-spat. Inf. Sci.* 17 | 60–71   | ✓     |
|           | 8 Murdiyarso D et al. 2010 Opportunities for reducing greenhouse gas emissions in tropical peatlands | *P. Natl. Acad. Sci.* 107 | 19655–19660 | ✓     |
|           | 9 Page S E et al. 2011 Global and regional importance of the tropical peatland carbon pool | *Carbon. Bal. Manage.* 12 | 1–12 | ✓     |
|           | 10 Warren M et al. 2017 An appraisal of Indonesia’s immense peat carbon stock using national peatland | *Carbon. Bal. Manage.* 12 | 1–12 | ✓     |
### Table A6. (Continued.)

|   | Reference                                                                 | Year | Categories                                                                 | Marka | Markb | Markc | Markd | Marke |
|---|---------------------------------------------------------------------------|------|----------------------------------------------------------------------------|-------|-------|-------|-------|-------|
| 7 | Black C H et al 2016 Using wildfires as a natural experiment to evaluate the effect of fire on southern California vernal pool plant communities | 2016 | | | | | | |
| 8 | Gosejohan M C et al 2017 Hydrologic influences on plant community structure in vernal pools of northeastern California | 2017 | | | | | | |
| 9 | Huntsinger J L & Oviedo J L 2014 Ecosystem services are social-ecological services in a traditional pastoral system: The case of California’s Mediterranean rangelands | 2014 | | | | | | |
| 10 | Kneitel J M et al 2017 California vernal pool endemic responses to hydroperiod, plant thatch, and nutrients | 2017 | | | | | | |
| 11 | Merriam K E et al 2016 Livestock use has mixed effects on slender orcutt grass in Northeastern California Vernal Pools Rangeland Ecol. Manag. | 2016 | | | | | | |
| 12 | Pyke C R 2005 Assessing climate change impacts on vernal pool ecosystems and endemic branchiopods | 2005 | | | | | | |
| 13 | Raimondo S et al 2019 A unified approach for protecting listed species and ecosystem services in isolated wetlands using community-level protection goals | 2019 | | | | | | |
| 14 | Rains M C et al 2008 Geological control of physical and chemical hydrology in California vernal pools | 2008 | | | | | | |
| 15 | Rice K J & Emery N C 2003 Managing microevolution: Restoration in the face of global change | 2003 | | | | | | |
| 16 | Sinnathamby S et al 2020 A sensitivity analysis of pesticide concentrations in California Central Valley vernal pools | 2020 | | | | | | |
| 17 | Sloop C M et al 2011 Conservation genetics of butte county meadowfoam (Limnanthes floccose ssp. California Arroyo), an endangered vernal pool endemic | 2011 | | | | | | |
| 18 | Varin M et al 2021 Mapping vernal pools using lidar data and multitemporal satellite imagery | 2021 | | | | | | |
| 19 | Wacker M & Kelly N M 2004 Changes in vernal pool edaphic settings through mitigation at the project and landscape scale | 2004 | | | | | | |
| 20 | Beach T et al 2009 A review of human and natural changes in Masa lowland wetlands over the Holocene | 2009 | | | | | | |
| 21 | Howeth J G et al 2008 Contrasting demographic and genetic estimates of dispersal in the endangered Coahuilan box turtle: a contemporary approach to conservation | 2008 | | | | | | |
| 22 | Krause S et al 2019 Ancient Maya wetland management in two watersheds in Belize: Soils, water, and paleoenvironmental change | 2019 | | | | | | |
| 23 | Minckley T A et al 2013 The relevance of wetland conservation in arid regions: A re-examination of vanishing communities in the American Southwest | 2013 | | | | | | |

(Continued.)
Table A6. (Continued.)

|   | First Name | Last Name | Title | Journal | Year | Pages | Status | Notes |
|---|------------|-----------|-------|---------|------|-------|--------|-------|
| 1 | Höbig N   | et al     | 2016 Palaeohydrological evolution and implications for palaeoclimate since the Late Glacial at Laguna de Fuente de Piedra, southern Spain | Quatern. Int. | 407  | 29–46 | √      |       |
| 2 | Kohfeld H | et al     | 2008 Characterising flow regime and interrelation between surface-water and ground-water in the Fuente de Piedra salt lake basin by means of stable isotopes, hydrogeochemical and hydraulic data | J. Hydrol. | 351  | 170–187 | √      |       |
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* A tick mark indicates this research focus is included in the literature.
Table A7. Aggregated proportions (%) of research activity for the 30 representative NFW regions, categorized according to the five climate zones and research focal areas.

| Climate zone | HM | WR | HP | BP | NR | GG | BD | ES | SA | IM | CC | WC |
|--------------|----|----|----|----|----|----|----|----|----|----|----|----|
| Tropical     | 17.95 | 38.46 | 30.77 | 7.69 | 51.28 | 46.15 | 38.46 | 12.82 | 20.51 | 51.28 | 48.72 | + |
| Arid         | 21.62 | 56.76 | 43.24 | 5.41 | 2.70 | 48.65 | 27.03 | 18.92 | 8.11 | 18.92 | 48.65 | + |
| Temperate    | 26.09 | 26.09 | 31.88 | 30.43 | 10.14 | 44.93 | 23.19 | 26.09 | 13.04 | 14.49 | 57.97 | + |
| Cold         | 17.74 | 53.23 | 45.16 | 22.58 | 32.26 | 35.48 | 24.19 | 4.84 | 9.68 | 38.71 | 19.35 | + |
| Polar        | 13.64 | 27.27 | 50.00 | 0.00 | 36.36 | 45.45 | 13.64 | 0.00 | 18.18 | 40.91 | 22.73 | + |

*The plus, minus and no marks indicate the three groups of all proportional data here, classified by the Jenks classification method implemented in ArcGIS.*

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