Improving monitoring and conservation efforts with the development of a Flyway Digital Twin

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Summary

The application of Digital Twins (DTs), virtual representations of physical objects, in ecological studies holds great potential for advancing our monitoring and assisting our conservation efforts with the provision of important scientific findings. The East Atlantic Flyway (EAF), as one of the most important migratory paths for waterbirds, makes it an ideal candidate for Digital Twin application. We highlight possible input sources like bird counts, weather and climate data that can be implemented into a Digital Twin and furthermore what functionalities a Flyway Digital Twin can offer for people involved in the project like scientists, conservationists and policymakers. We emphasize the need for a robust infrastructure to join existing data sources, assimilation of knowledge for the start of development and a possible expansion of collected data in temporal and spatial resolution. The potential outputs of a Flyway Digital Twin are diverse, offering insights into population dynamics, bird distributions and how stressors like urbanization, pollution and other disturbing factors can affect the populations. By harmonizing various sources of data, the Digital Twin can become a powerful tool connecting researchers, conservationists and policymakers and ultimately leading to more evidence-based management practices. This report concludes by outlining the essential steps in the development of a Flyway Digital Twin, making it a tool that combines various sources of data from all parts of the project and further advances ecological research.

Introduction

A Digital Twin is a virtual representation of a real-life object, that combines historical data with constant updates of new incoming data to provide forecasts, and ultimately a better understanding of the physical object itself, as well as an assessment of the impacts of potential scenarios that might change its properties. Historically, ecological research was limited in spatial and temporal scale of its analysis due to methodological constraints. The introduction of Digital Twins may help us to solve these problems and deepen our knowledge on ecosystems as a whole and their global interaction.

The East Atlantic Flyway, emerging as a critical ecological corridor for waterbirds, stands out as a hotspot for biodiversity (van Roomen et al., 2022). The bird communities, their habitats and pressures on the East Atlantic Flyway have been well-studied subjects for many years. Due to its vast geographic extent, connecting both breeding grounds in the Arctic and wintering areas in Africa, research and monitoring efforts involve many different groups of scientists from a large range of countries. As a result of its international significance, ecological complexity and important role for conservation, the East Atlantic Flyway provides a compelling context for the application of a Digital Twin.

The first applications in urban planning and infrastructure management using DT's, were developed in 2018 (Bolton et al., 2018; Charitonidou, 2022; Schrotter & Hürzeler, 2020), and the concept of DT's have been used to simulate e.g. transportation networks and buildings and the technology expanded tackling biological systems including agriculture (Verdouw et al., 2021) and forest management (Buonocore et al., 2022; Jiang et al., 2022). Extending these applications to a Flyway Digital Twin could assist our understanding of the complexities of bird migration, habitat dynamics, and the influence of anthropogenic factors on one of the globally important migratory flyways.
In this report we aim to promote the development of a Flyway Digital Twin and highlight its transformative potential in advancing our understanding of this complex migratory system. We will highlight specific requirements and functionalities of a Digital Twin, discuss applications to enhance monitoring and guide conservation efforts, and introduce a possible starting point for the development of such a Digital Twin.

An East-Atlantic Flyway Digital Twin

To effectively design an East Atlantic Flyway Digital Twin, comprehensive information and data from many different sources are essential (Fig. 1). The East Atlantic Flyway program has been collecting data from various channels over the years, including bird counts, GPS tracking data, direct observations in the field, detection by drones or satellite-images. In addition, weather data (wind patterns, temperature, precipitation) can help us to identify mechanisms for migration behavior and smaller scale movements. To identify potential long-term changes in species specific migratory behavior and population trends due to our changing world, long-term climatic variables can be used (e.g., mean temperature, high/low in seasons, wind & precipitation). In addition, land cover data combines information on habitat changes and different types of landscapes along the Flyway area that can be assessed by remote-sensing technologies (Kersten et al. 2023). Stringent data checks must be implemented to ensure data quality and consistent temporal and spatial availability of observation data. Assimilating knowledge (Fig. 1) is integral to creating models within a Flyway Digital Twin. The effectiveness of the Digital Twin is contingent with the depth and breadth of information infused into its virtual representation, e.g. species-specific knowledge (physiology, behavior, migration routes, life cycle, interactions within their environment, interactions with other species, phenology, etc.), anthropogenic effects (land use, urbanization, agriculture,) and factors along the Flyway (habitats, barriers, conditions, stopover sites, connectivity).

It is necessary to construct a solid infrastructure to real-time data upload from researchers and volunteers across the East Atlantic Flyway. This involves establishing servers with high storage capacity and accessibility for a wide range of contributors. Pipelines should be created to integrate data from citizen-science projects, ensuring a seamless flow of information. Outlining specific objectives and goals for the Flyway Digital Twin is necessary to identify key challenges and questions to address, such as understanding and predicting bird migration patterns, assessing habitat dynamics and links to birds, and evaluating the impact of climate change on the Flyway.

The East Atlantic Flyway has been subject to international waterbird counts since 2013, with a comprehensive effort covering the coasts of Europe and Africa every three years (van Roomen et al., 2022). The Wadden Sea Flyway initiative initiated an integrated monitoring scheme, including waterbird numbers, vital rates, and potential threats to waterbird populations along the Flyway. The monitoring scheme aims to provide reliable information about total population sizes, monitor changes, and guide conservation measures. The complexity of the monitoring scheme led to a review of scientific literature and consultations with experts to explore possibilities for improvement. The East Atlantic Flyway, encompassing breeding, staging, and wintering areas of waterbirds along the entire Atlantic coast from Europe to southern Africa, is vital for waterbirds breeding in many parts of the northern latitudes (van Roomen et al., 2022). Coastal waterbirds include shorebirds, gulls, terns, ducks, geese, herons, egrets, grebes, spoonbills, and cormorants. Monitoring the flyway is crucial due to the dynamic movements of waterbirds within the annual cycle, emphasizing the need for international collaboration and conservation efforts.

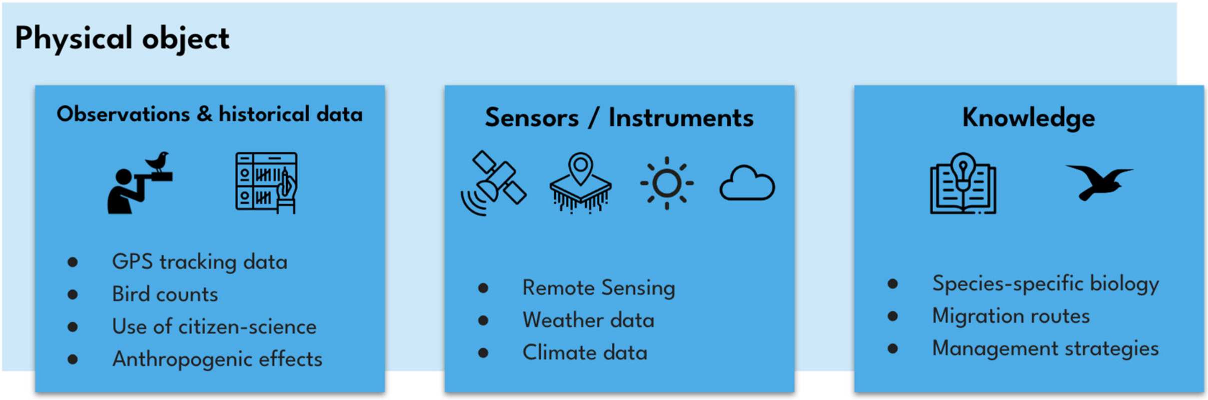

Figure 1: Input data for a Flyway Digital Twin. This kind of information poses as potential sources for data that a Digital Twin could be fed with.

The use of Digital Twins enables us to visualize the current state of the East Atlantic Flyway in terms of multiple categories: Population dynamics, Distribution & Connectivity/Networks (Fig. 2). A Digital Twin should incorporate multiple sources of observed information (count & tracking data, habitat conditions, weather) from the past and in real time to predict possible changes in mentioned categories and visualize complex ecological processes for conservationists and policymakers. **The creation of sophisticated models that can assist us in simulating interactions within the East Atlantic Flyway on a coarse resolution will make up the core element of a potential Flyway Digital Twin**. These models serve as the computational backbone, allowing researchers to gain insights into bird migration patterns, habitat changes, and the influence of various factors on the Flyway ecosystem (Fig. 3).

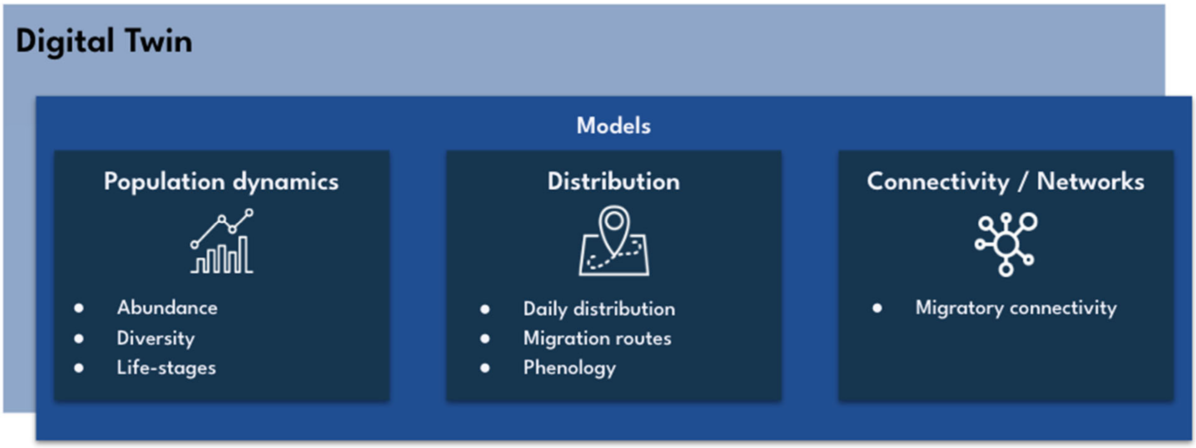

Figure 2: Examples for potential data that's processed into multiple models within a Digital Twin. The models can be used to generate output and receive more information about the studied subject.

Population dynamics models (Fig. 2) can help us to understand changes and trends in bird populations over time in order to assess their risk status with the use of e.g. bird counts, tracking data or ring recoveries. Distribution models (Fig. 2) offer a visual depiction of bird movements across landscapes, providing dynamic and spatially explicit insights into how bird populations utilize diverse areas throughout their annual cycles. This encompasses the identification of crucial habitats for breeding, foraging, and resting. Recognizing stopover locations where birds pause to rest and refuel is pivotal for effective conservation efforts, especially during extensive long-distance migrations. Additionally, these models play an essential role in mapping migration routes, facilitating an understanding of the connectivity of habitats along the entire migratory journey. This information proves valuable in assessing potential threats along migration pathways, such as obstacles or changes in land use.

Connectivity models (Fig. 2) can help us to advance our comprehension of avian ecology, providing insights into the interplay between breeding and wintering grounds. Derived from tracking, ring recovery, and resighting data, these models offer a comprehensive view of bird populations' migratory journeys, unraveling the complex connectivity patterns that link geographically distant locations. By identifying the essential connections between breeding and wintering grounds, these models highlight locations integral to a bird species' life cycle and further crucial areas for conservation. Understanding the routes taken by birds during migration allows for the establishment of protected corridors that mitigate potential threats like habitat fragmentation and obstacles, thereby enhancing the safety and success of the migratory journey.

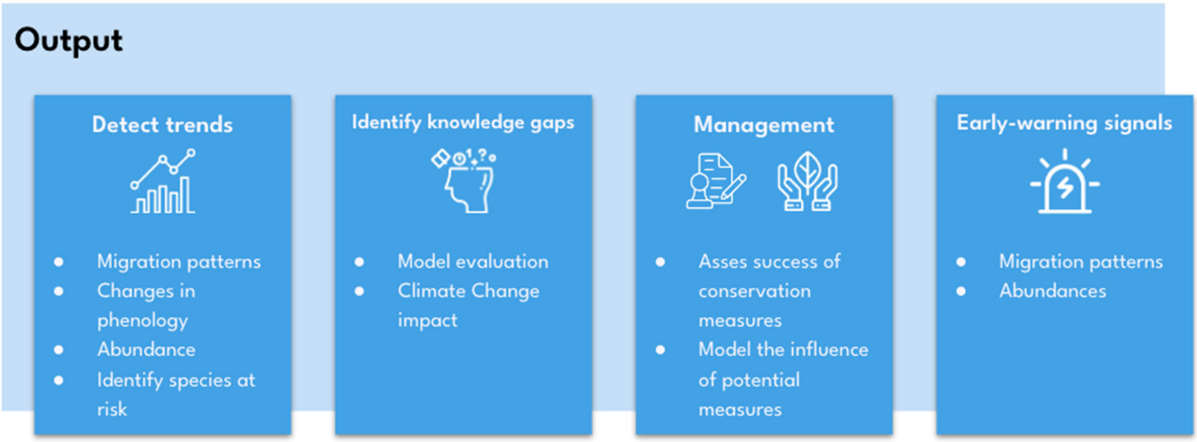

Figure 3: Examples for potential output data that's created by the Flyway Digital Twin in different application contexts.

The outputs of a Flyway Digital Twin (Fig. 3) can be diverse and comprehensive but need to be accessible for multiple groups of people involved in the project. In general, the Digital Twin should assist us in connecting research with greater evidence-based management and conservation measures. **The potential outputs serve as valuable information for researchers, conservationists, and policymakers, offering insights into various aspects of bird migration, habitat changes, and the overall status of the ecosystem.** By continuously comparing incoming data with historical trends, the digital twin can detect anomalies. For instance, deviations in bird populations from typical migration patterns can trigger alerts, signaling potential risks to specific species. This early detection mechanism enables conservationists to intervene promptly, implementing measures to mitigate threats and support at-risk populations. The digital twin's outputs extend beyond real-time alerts, encompassing the identification of knowledge gaps. Regular assessments of the model's performance, coupled with validations against real-world observations, enable the recognition of areas where additional data or research is needed. This iterative feedback loop ensures the ongoing refinement and relevance of the Digital Twin, enhancing its capacity to provide accurate and up-to-date information. Furthermore, the Flyway Digital Twin empowers adaptive management strategies by simulating various future scenarios. Conservation interventions can be programmed and evaluated within the digital framework, allowing stakeholders to assess the potential success of different strategies. This proactive approach facilitates informed decision-making, assisting policymakers in developing and implementing conservation measures that are responsive to the evolving dynamics of the East Atlantic Flyway.

First steps for development of a Digital Twin

The development of a Flyway Digital Twin requires a systematic approach, integrating diverse data sources, advanced modeling techniques, and a collaborative framework. The initial steps are set in precisely defining the Digital Twin's goals and outlining the focus of its first version, possibly centering around specific species or targeted ecological facets for in-depth analysis. The engagement of stakeholders right from the very beginning is paramount for a thorough and inclusive development process. Setting the groundwork for the infrastructure involves the gathering and aggregation of existing data, encompassing bird observations, GPS tracking data, weather records, and habitat information. Rigorous checks and standardization of all data are imperative to seamlessly integrate it into the Digital Twin. The initial modeling phase prioritizes lower temporal and spatial resolutions, laying the foundation for subsequent enhancements with higher resolutions as the models evolve. To take real advantage of the technology of Digital Twins, we have to find ways to automate data upload, checks and standardization in real time. In addition, automated feedback loops for continuous model updates have to be established on the basis of the real-time updates, ensuring that the Digital Twin adapts to changing conditions and help researchers evaluate the meaningfulness of created models. We further have to ensure that the infrastructure allows researchers, conservationists and policy makers from diverse backgrounds to access and contribute data seamlessly. Using this connection, a Digital Twin could help as a tool for management, evaluating conservation measures based on the most recent information. As the Digital Twin evolves, additional functions should be implemented gradually, expanding its capabilities to assist us in conservation and monitoring, for example by adding more species to distribution models, increasing the spatial and temporal resolution of implemented data or including more sources of bird observations (e.g. drone counts and habitat monitoring).

To increase the ability for a Digital Twin as a new opportunity to correctly predict changes or outcome of conservation measures, we must spend efforts in increasing the coverage and quality of bird observations and habitat monitoring. Currently, historical data of observations vary greatly temporally and spatially (e.g. Europe, West & South Africa; Fig. 5), and highlights the need to invest into the monitoring of more remote, yet not well covered areas to improve our datasets and thus a robust Flyway Digital Twin. With greater temporal and spatial coverage and a greater monitoring quality, the data that's implemented into a Digital Twin will have fewer biases and can ultimately assist us even better in predicting changes along the Flyway and preparing evidence-based conservation measures.

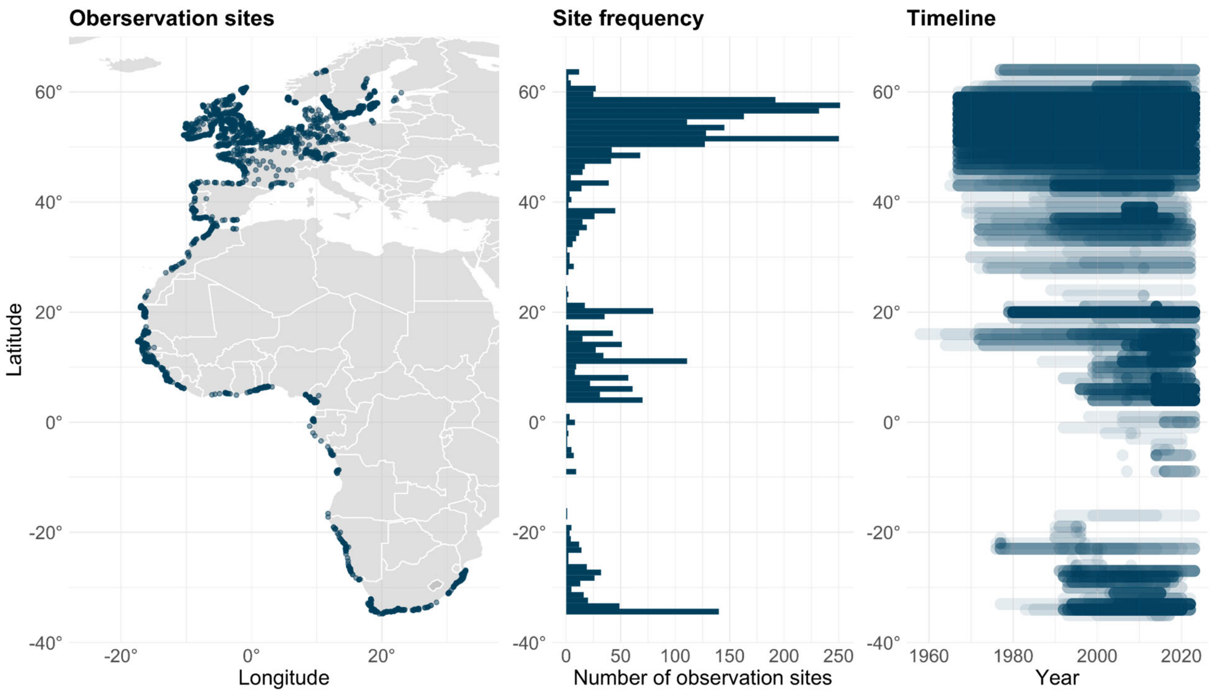

Figure 4: Overview of all count-sites of the Flyway-project. All sites are displayed in their spatial distribution (left plot), the frequency per latitude (one degree; middle plot) and the temporal scale of the count in project sites (per latitude, one degree; right plot).

Conclusion

Even though only few Digital Twins have been developed for ecological studies yet (e.g. Visser, 2023), their potential for improving research seems inevitable (Bauer et al., 2021;

De Koning et al., 2023). The East Atlantic Flyway as an internationally important hotspot for waterbird biodiversity represents a great subject for applying a Digital Twin.

In this report we displayed specific requirements and functionalities that are crucial for the development of a Flyway Digital Twin. The Flyway project includes various monitoring methods and contains an immense database of observations, dating back until 1960 (Fig. 4). Gathering even more sources of data, like additional bird observations, tracking and ring-recovery data, weather patterns and land-cover data, to just mention a few, turns the Digital Twin into a dynamic reflection of the ecosystem it represents. The knowledge about all facets of the Flyway, e.g. including species-specific biology, habitats and anthropogenic influences, forms the base of meaningful models within a Digital Twin. The diverse outputs like population trends, early-warning signals and adaptive management strategies makes the Digital Twin a powerful tool that is able to harmonize various sources of data and connect researchers, conservationists and policymakers.
As we have indicated ways for the future, this report aims to serve as a starting point, an inspiration for researchers, conservationists, and policymakers to utilize resources for a tool that is able harmonize various sources of Flyway data, to better understand waterbird population dynamics as well as local and global movements. **Ultimately, we consider a Flyway Digital Twin as an excellent tool to broadcast the complexity of the system, engage the general public and most importantly support conservation and management across the entire flyway**.

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