LETTER

Conservation Letters
A journal of the Society for Conservation Biology — Open Access

WILEY

Using feathers to map continental-scale movements of waterbirds and wetland importance

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Abstract
Waterbirds are highly mobile, moving over large distances to access resources. Although consistent migration routes are observed in highly seasonal and predictable environments, movement patterns to utilize ephemeral resources in dryland environments are largely unknown. This makes conservation planning and water policy challenging as the relative importance of widely dispersed wetlands is difficult to rank. We addressed this challenge by combining a citizen science project with the novel application of X-ray fluorescence of feathers to detect continental scale movement of waterbirds using elemental signatures. By doing so, we gained important insight into the movements of 24 waterbird species, including the significance of the Murray–Darling basin as a key source of waterbirds across the continent. Our approach highlights the benefits of elemental signatures to identify key areas of habitat use and priorities for wetland management.

KEYWORDS
citizen science, elemental signatures, noninvasive, water policy, X-ray fluorescence

1 | INTRODUCTION

Birds are among the most mobile organisms on the planet. Although many are sedentary, some engage in mass seasonal migration along well-traveled routes, yet others engage in nomadic movements, following quasi-cyclic and ephemeral resources. The ability of waterbirds to efficiently and quickly move large distances allows them to exploit resource rich habitats, such as ephemeral wetlands (Kingsford et al., 2010). Forty-six percent of the worlds' wetlands are ephemeral (Davidson et al., 2018), providing critical habitats with high biodiversity values (Williams, 2000). However, they are often poorly conserved as it can be difficult to measure their importance and role in supporting nomadic species that occupy continental-scale environments. Given that 93% of wetlands occur in inland river basins, with a mix of ephemeral and permanent water bodies, management plans seeking to conserve waterbirds require sufficient knowledge of how basins and their wetlands are used by waterbirds (Haig et al., 1998). As this information is currently lacking, conservation planners are struggling to adequately respond to changing environmental conditions to ensure long-term persistence of these vital habitats.

Evidence for decline is stark as populations of waterbird species have declined globally since 1985 (Butchart et al., 2010), with estimates varying from 38% (Wetlands International, 2012) to 55% more recently (BirdLife International, 2017). Around 17% of all waterbird species are currently Red Listed as "Vulnerable" or worse (IUCN, 2019). Similarly, more than 50% of wetlands are estimated to have been lost globally (Finlayson et al., 1999), with ongoing declines driven primarily by habitat loss due to land use changes (Davidson, 2014), water resource development (Butchart et al., 2010), and other anthropogenic induced changes (Žydelis et al., 2009), including climate change (Erwin et al., 2011). Conservation policy aimed at protecting key wetlands has long demanded practical and effective methods for determining their importance for waterbirds (i.e., Ramsar Criterion 5 & 6). This information is frequently collected via a range of techniques including direct observation and invasive tracking (e.g., radio and satellite tracking) (Horns et al., 2016), which are time-consuming, expensive, and to date have not yielded sufficient data to inform basin-wide management decisions.

In contrast, advances in noninvasive tracking are increasingly providing sophisticated and accessible alternatives. Most of these noninvasive techniques center on interrogating dietary information stored in feathers, a technique that has been used to track large-scale movements of birds for a number of decades (Hobson, 1999). Once grown, keratin in feathers becomes inert and provides a historical record of diet. Matching the dietary signature of feathers to locations enables movement to be traced, typically utilizing stable isotope signatures such as oxygen and hydrogen (Bowen et al., 2005), sulfur (Hobson et al., 1997), strontium (Sellick et al., 2009), carbon and nitrogen (Hobson & Wassenaar, 2008), or a combination of multiple isotopes (García-Pérez & Hobson, 2014). However, other chemical elements are increasingly being explored as computational power and data analytic methods develop.

Many chemical elements are incorporated into keratin from dietary sources, providing new opportunities to trace the origins of wildlife (Brandis, Meagher, et al., 2018). Compared to isotopic ratios, elemental abundances have received little attention as geographic markers in animal movement studies to date. These elemental abundances stand out because they provide a readily available, noninvasive, nondestructive, and inexpensive method of tracing the movement and origins of wildlife. They are also of further interest because they provide wide-ranging information on diet, animal health, and the presence of toxins. The abundance of elements in a sample of keratin (or any material) can be readily obtained using X-ray fluorescence technology (XRF), a nondestructive method commonly used in manufacturing and mining. Elemental signatures (here defined as the unique combination of chemical elements and their abundances) contained in biological tissues are influenced both by the geochemical components within habitats (e.g., soil) and the bioavailability of trace elements within food items (Iyengar, 1989). Elemental signatures therefore vary with geographic location as function of geology, hydrology, atmospheric processes, and food availability. To date, elemental signatures within feathers have not been used to determine movement patterns in birds.

Here, we used elemental signatures within waterbird feathers, detected using XRF, to identify continental-scale movement patterns. We obtained feathers from citizen scientists who collected naturally shed waterbird feathers from wetlands around Australia over a 2-year period, as part of a citizen science project publicized as the "Feather Map of Australia." Our goal was to highlight the efficacy of using elemental signatures to trace movement patterns of wide-ranging waterbird species and to provide insight on multispecies use of wetland habitats to inform conservation and water policy development at a continental scale.

2 | METHODS

2.1 | Sample collection

Waterbird feather samples were collected from wetlands across Australia between March 2016 and June 2018. We developed a national citizen science project, the Feather Map of Australia, supported by a media campaign (radio, television, print, internet, social media), to encourage the collection of molted waterbird feathers from wetlands (www.ansto.gov.au/feathermap). Australian wetland scientists were also encouraged to collect juvenile feathers, as juvenile feathers were less targeted by the general public but crucial to the analytic method in detecting movement. All submitted feathers received a unique ID and associated metadata were recorded: location (latitude, longitude), wetland name, waterbird species (if known), bird age class (chick or adult, if known), collector name, and the date of collection. Where possible, feathers were classified to waterbird species by researchers after submission.

To generate geographical references for elemental signatures, we categorized feathers from known species as either "resident" (i.e., representative of the location they were found) or "nomadic" (i.e., of unknown origin) using a combination of published movement accounts (Garnett et al., 2015) and expert knowledge. Resident species included chicks at their natal site and those who are predominantly sedentary, like the Australian wood duck (*Chenonetta jubata*) (Garnett et al., 2015) at the basin scale. Nomadic species included those classified as nomadic or migratory, such as the straw-necked ibis (*Threskiornis*

spinicollis) (Table S1). We selected 210 feathers (109 resident, 101 nomadic) from 158 different wetlands, representing 29% of the wetlands sampled, from the Feather Map of Australia library to provide good continental coverage, dietary guild representation, species variation, and movement status (nomadic or resident) (Figure S1). A total of 24 waterbird species were represented, including one carnivore species (12 feathers), seven herbivore species (65 feathers), 10 invertivore species (67 feathers), four omnivore species (52 feathers), and one piscivore species (14 feathers).

2.2 | Elemental signatures

Feathers were cleaned of surface dirt using reverse osmosis water and air dried. We used an ITRAX micro X-ray fluorescence (μXRF) core scanner to determine elemental signatures of feathers, mounted lengthways along the scanning platform and scanned at a resolution of 200 μm. Small feathers <5 cm were scanned in their entirety, whereas large feathers were subsampled and only the first grown part of the feather was sampled (~top 3 cm) (following Bostwick, 2016). This process aimed to reduce variability within a sample, ensuring we were identifying a single location and to minimize ITRAX processing time. Counts of elemental abundances were collected for 26 elements for each feather (Table S2), subsampled every 200 μm, along the length. The number of scans per feather averaged 123 (range: 13–522 scans), producing 29,310 scans for analysis. Chromium was removed from the processed elemental data due to a high frequency of null values, leaving 25 elements for analysis.

We attributed each feather to one of 12 river basins described by Geoscience Australia, with boundaries defined by the Australian Hydrological Geospatial Fabric (Bureau of Meterology, 2019) (Figure S1). To determine the origins of nomadic waterbird feathers from their elemental signatures, we first classified the signatures of river basins from resident feathers using tree-boosting machine learning algorithms. Feathers from resident birds with known river basin provenance were randomly allocated into training (80%) and testing sets (20%). Elemental data from resident feathers were preprocessed to impute missing data using a k-nearest neighbor function, and then standardized by range (normalized between 0 and 1). To enhance the information available from elemental signatures, ratios of all pairwise combinations of elements were also included as features during model building. An eXtreme Gradient Boosting (XGBOOST) classification model for basin identification was built using the package "xgboost" v.1.0.2 in the program Python. Classification was based on the scalable end-to-end tree gradient boosting framework (Friedman, 2001), including a novel sparsity-aware algorithm and a weighted quantile sketch suitable for approximate tree classification algorithms. The model was then trained using five stratified cross-validations (Brownlee, 2020), repeated three times. The overall and balanced accuracy of each stratified fold was quantified to evaluate the model's performance. A recursive feature elimination approach was embedded in each model building process to select the top ranked predictors (elemental abundance and ratios of elements) and optimize accuracy. Test data were then preprocessed and the model independently validated.

Within each fold, the top 15 elements/ratios that best discriminated between river basins were selected (Figure S2a). The classification model had an overall and balanced accuracy of 0.96 and 0.90, respectively, from cross-validation across the three model replications (Table S3). The accuracy of basin classifications for each resident feather was calculated, along with the variation in accuracy for different sample sizes (Figure S2b). River basin classifications of nomadic feathers were then predicted using the model trained from resident species, providing the predicted basin of origin for each feather. Basin origin for a feather was determined from the consensus of elemental signatures sampled from each feather. Prediction rates of samples within feathers of nomadic species varied considerably between waterbird taxa, whereas the conformity of samples taken from each feather was influenced by dietary guild more so than by foraging environment (Figure S4).

3 | RESULTS

3.1 | River basin fidelity

We found strong evidence of mass continental-scale movement of nomadic waterbirds between river basins, with feathers often found thousands of kilometers from where they were predicted to be grown (Figure 1). Of the 101 nomadic feathers examined, 60% matched an elemental signature attributed to the Murray–Darling basin, even though only 22% were found in this basin (Table S4). Feathers from nomadic species attributed to the Murray–Darling basin were found in all river basins except the South Western Plateau and Tasmania. In terms of fidelity, feathers from nomadic species from the Murray–Darling basin had the highest percentage of retention, with 82% of feathers matching elemental signatures of resident feathers. In contrast, the next highest basin was the Carpentaria Coast with 36% retention, then Tanami-Timor Sea Coast with 19%, meaning that 64% and 81%, respectively, were arrivals from other basins. Only 10% of feathers from the Lake Eyre
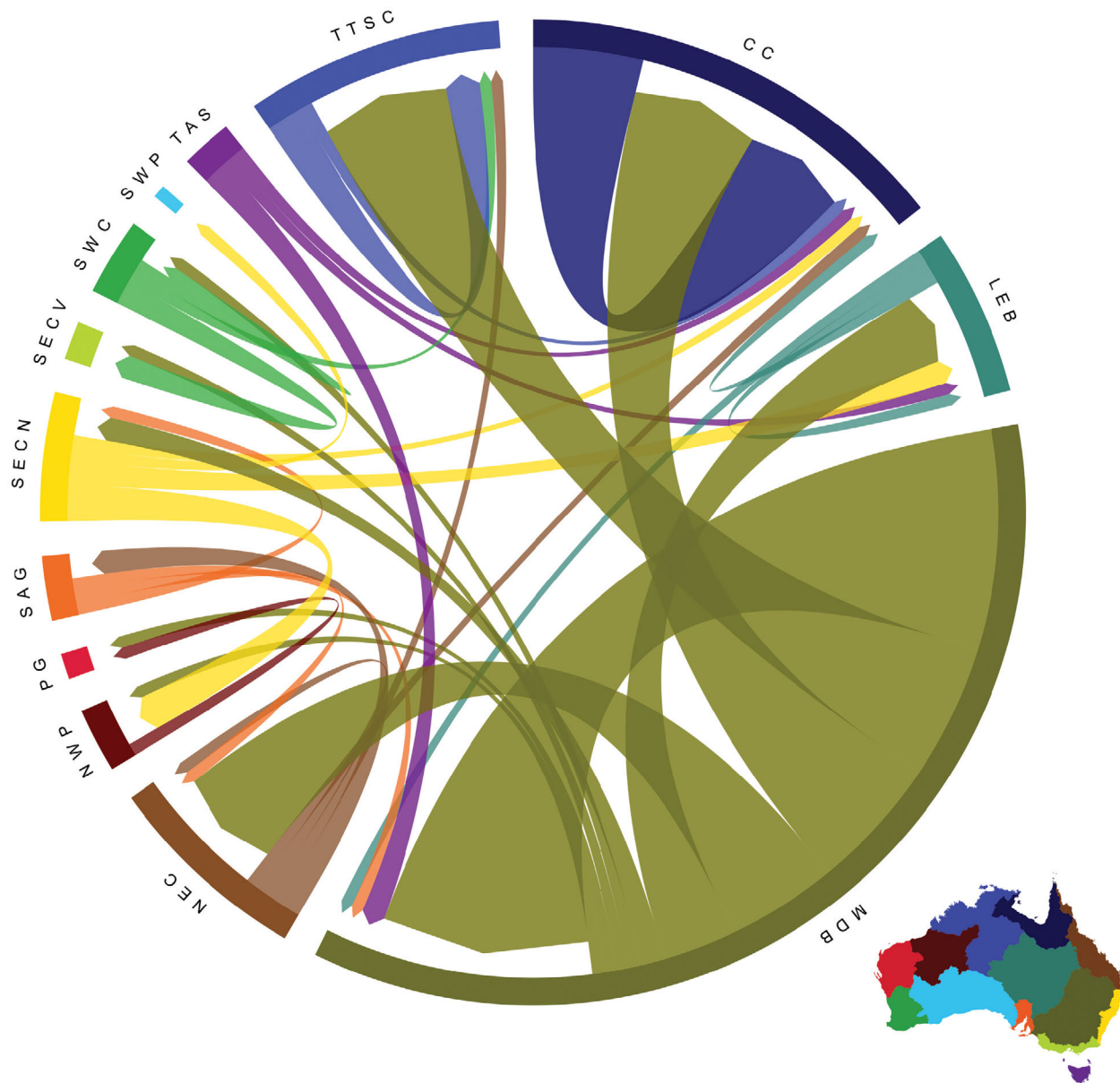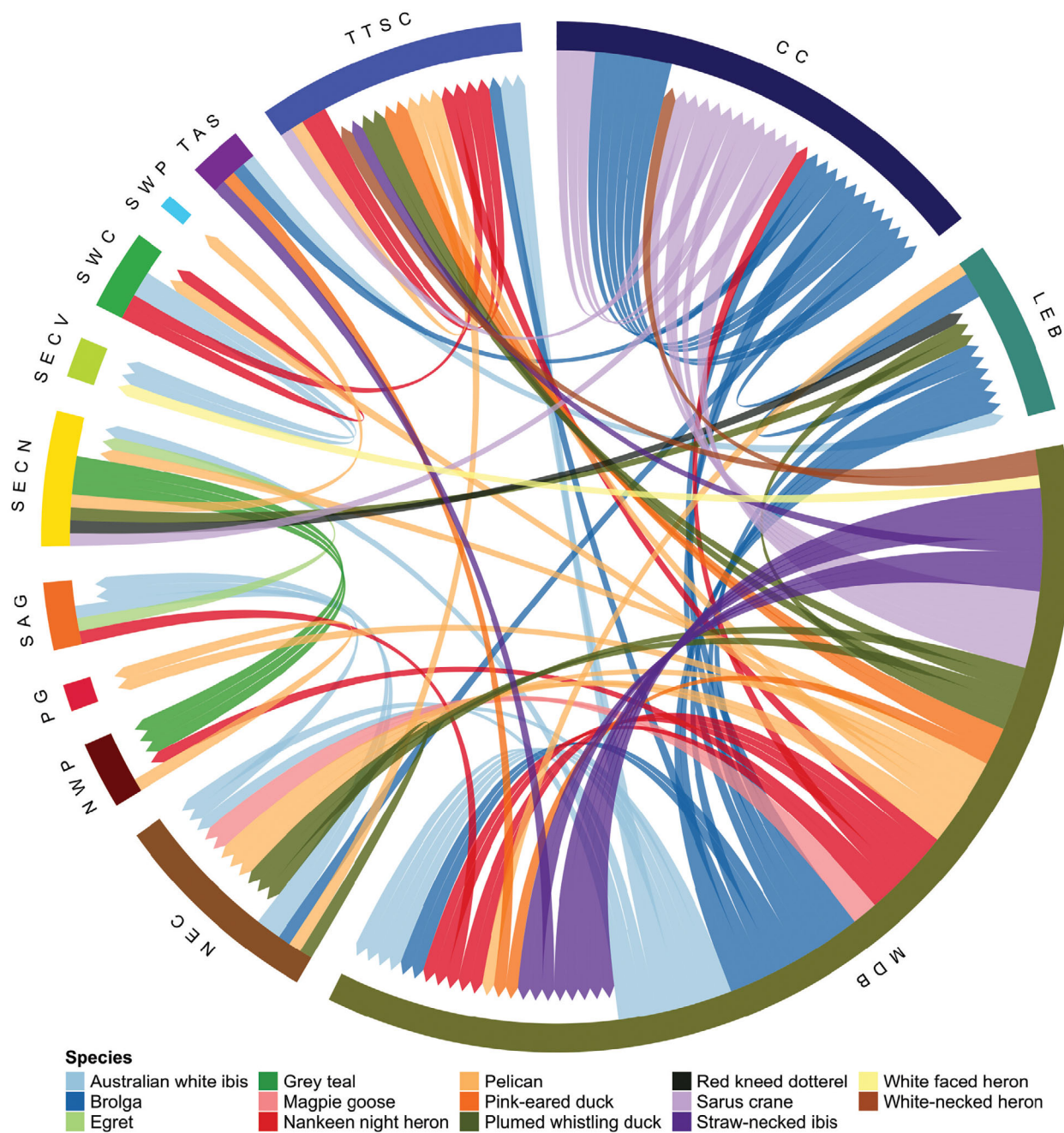
FIGURE 1 Chord diagram highlighting modeled movement of nomadic waterbirds among river basins in Australia. Modeled origins of feathers based on elemental signatures are displayed on the outer ring and location where feathers were found are represented by arrows. Arrow width represents the overall percentage of feathers. River basins are as follows: CC, Carpentaria Coast; LEB, Lake Eyre Basin; MDB, Murray-Darling Basin; NEC, North East Coast; NWP, North Western Plateau; PG, Pilbara-Gascoyne; SAG, South Australian Gulf; SECN, South East Coast – New South Wales; SECV, South East Coast – Victoria; SWC, South West Coast; SWP, South Western Plateau; TAS, Tasmania; TTSC, Tanami-Timor Sea Coast

Basin and North East Coast matched resident signatures. Feathers from nomadic species from all of the remaining basins were identified as originating from other basins.

3.2 | Waterbird species

There was variation among species and predicted movement of waterbirds between where the feather was grown and where it was collected, highlighting varying degrees

of movement (Figures 2 and S5). Straw-necked ibis were surprisingly strong candidates for remaining in the basin of origin, despite having a wide continental distribution. Rufous night herons often remained in the basin of origin or else in a neighboring basin. Feathers from these two species were all primarily found in the basins where they were grown, with median prediction rates per feather above 80%. In contrast, Australian pelican, gray teal, sarus crane, pink eared ducks, and Australian white ibis were predicted to travel frequently and over greater

FIGURE 2 Chord diagram highlighting modeled movement of nomadic waterbird species among river basins in Australia. Origins of feathers predicted from elemental signatures are displayed on the outer ring and location where feathers were found are represented by arrows. Each arrow represents a unique feather (see Table S4). River basins are as follows: CC, Carpentaria Coast; LEB, Lake Eyre Basin; MDB, Murray-Darling Basin; NEC, North East Coast; NWP, North Western Plateau; PG, Pilbara-Gascoyne; SAG, South Australian Gulf; SECN, South East Coast – New South Wales; SECV, South East Coast – Victoria; SWC, South West Coast; SWP, South Western Plateau; TAS, Tasmania; TTSC, Tanami-Timor Sea Coast

distances. Brolgas, white-necked herons, magpie geese, and plumed whistling-ducks had median prediction rates between 60% and 70% per feather, suggesting that conformity within feathers to a single basin was lower for these species (Figure S4a). Within-feather conformity to a single basin was also relatively low (median prediction rates below 70%) for herbivores and omnivores, compared to carnivores (median prediction rates above 95%) and invertivores (median prediction rates above 85%) (Figure S4b). No difference in within-feather variation was apparent between species foraging in either aquatic or terrestrial environments (Figure S4c). Although conformity among within-feather samples for some feathers suggested that

basin origins should be subjected to further scrutiny, most feathers were assigned with high conformity (Table S4).

4 | DISCUSSION

Wetland conservation and management is needed to protect biodiversity, intrinsic values, and the ecosystem services these critical environments provide (Albert et al., 2020). As a vital measure of importance, the movement of waterbirds between wetlands is routinely used to inform the conservation and management of wetlands and water policy development, particularly at continental and basin scales. Therefore, the provision of information at a scale that is commensurate with the geographic distributions of species and ecosystems is vital (Albert et al., 2020). As shown in this study, elemental signatures of continental-scale movement data between river basins can help identify seemingly disparate regions of key importance for groups of waterbird species (Allen & Singh, 2016), many of which travelled large distances across the continent. Critically, we were also able to identify key areas for waterbirds by highlighting the relative importance of different basins across Australia, thereby improving our understanding of inter-basin connectivity (Bino et al., 2020) and enabling wetland/water managers and policy writers to make informed decisions and improve ecological outcomes.

Like wetlands globally, wetlands across Australia are under considerable pressure due to river flow regulation and climate change (Pittock & Finlayson, 2011). As a consequence, many wetlands are providing reduced opportunities for waterbird breeding (Brandis, Bino, et al., 2018). We identified the Murray–Darling basin as a key location for which many waterbirds spend time and then disperse across Australia. Ten of the 13 basins were found to have feathers from waterbirds that had spent time (and grown feathers) in the Murray–Darling basin (Figure 1). The Murray–Darling basin contains approximately 17% of Australia's wetlands, (Bino et al., 2016), the second largest extent after the Lake Eyre Basin (~25%). These wetlands are predominantly ephemeral palustrine (>5.5 million ha) and lacustrine (>1 million ha) (Bino et al., 2016), providing diverse habitat types for a wide range of species. The Murray–Darling basin is also Australia's most developed river basin: covering just 14% of Australia's land area it has the largest water storage capacity at 30,192 GL (Bino et al., 2016) and accounts for 52% of Australia's total water consumption. Without critical attention to the role that the Murray–Darling basin plays in providing breeding opportunities and habitat throughout the year, the persistence of waterbird populations across the continent will be increasingly difficult to protect. Observed declines in waterbird populations in eastern Australia over the past 35 years (Kingsford et al., 2020) are potentially reflective of continental patterns in waterbird populations.

The management and policy implications of our findings include a greater imperative to successfully manage water resources for waterbird outcomes and wetland health at a continental scale. Many managed river and wetland systems have identified waterbirds as targets of environmental flow management, with aims to support breeding events, maintain nesting vegetation, and provision of foraging areas (Murray-Darling Basin Authority, 2012). However, the ability to achieve these outcomes at a magnitude large enough to reverse population declines with currently available environmental water allocations is contested (Wentworth Group of Concerned Scientists, 2020).

Knowledge of available wetland resources within basins and their use by waterbirds is central to the ability to adequately plan conservation actions and monitor change (Allen & Singh, 2016). In many regions of the world, this baseline knowledge is deficient, for example, in Africa (Seeteram et al., 2019), China (Xia et al., 2017), and the Middle East (Maleki et al., 2016). Similarly, knowledge of waterbird movements provides new context to current understanding of wetland habitats, such as the use of wetlands as refuge sites (Overdijk & Navedo, 2012), migratory stop-over points (Higuchi et al., 1998), or habitat connections at continental scales (Amezaga et al., 2002). Our findings suggest that utilizing elemental signatures to trace waterbird movements in these regions may greatly benefit global water policy by providing an efficient and accurate continental-scale view of the way nomadic waterbirds use wetlands. We were able to achieve this by using the elemental signatures captured in growing tissues to represent the wetland, or nearby wetland, it was grown at. By doing so, we could confidently identify the basins (containing the wetlands) where waterbirds grew their feathers: feather growth frequently occurs during breeding periods as chicks grow feathers for the first time, or as adults grow new feathers in pre- or postbreeding molts. At these key stages in the life histories of waterbirds, the availability and importance of wetlands for nomadic species can be used to construct effective conservation practice and policy by prioritizing the declaration of protected areas, nominations of national or global importance (e.g., Ramsar), appropriate management of water resources, and the declaration of intergovernmental treaties (e.g., China Australia Migratory Bird Agreement, Japanese Australian Migratory Bird Agreement, Republic of Korea Migratory Bird Agreement).

The contribution of citizen science was crucial to the success of the study across such a large geographic range. However, despite relatively high model accuracy, sample feathers were underrepresented in some river basins,

suggesting that targeted recovery of resident species feathers in those basins would likely improve basin signatures and model accuracy. In addition, further feather collection to allow for finer scale resolution of movement patterns between catchments and individual wetlands would likely assist policy implementation at local levels, approaching the fine spatial scales and high model accuracy currently achieved by satellite tracking. Irrespective of these caveats, elemental signatures show great promise as a complementary animal tracking technique that is noninvasive, relatively inexpensive, can target multiple species simultaneously, and cover large spatial and temporal scales. Furthermore, the elemental signatures obtained can provide additional information on diet, animal health, and the presence of toxins (Underwood, 1977). Because it is nondestructive, the sample can be used for other analysis techniques like stable isotopes and genetic studies. Signatures obtained using this technique provide critical information on the use of wetlands by waterbirds, particularly in areas dominated by ephemeral wetlands, allowing for the recognition of key habitat areas and development of targeted water management policy. The methods of this study are widely applicable and may be used on different taxa with keratinous tissues and different ecosystem types, providing additional avenues of tracking wildlife to established methods.

AUTHOR CONTRIBUTIONS

KJB was research leader. DM contributed to research concept and design. PG undertook XRF sample analysis. BJ contributed to model coding. RTK contributed to research concept and manuscript writing. DR contributed to research design, data analysis, and manuscript writing. All authors provided input into the final manuscript.

ETHICS STATEMENT

All sample collections were conducted under the following licenses and approvals: NSW SL101642; ACT LT2016870; NT 58383; QLD WISP16967616; SA A26504-2; VIC 10007719; WA SF010464, TAS—letter of approval. UNSW ACEC 15/76B.

DATA ACCESSIBILITY STATEMENT

Data available upon request from corresponding author.

CONFLICT OF INTEREST
The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Brandis KJ, Mazumder D, Gadd P, Ji B, Kingsford RT, Ramp D. Using feathers to map continental-scale movements of waterbirds and wetland importance. *Conservation Letters*. 2021;e12798. https://doi.org/10.1111/conl.12798