Science of the Total Environment 574 (2017) 148–154

Contents lists available at ScienceDirect

Science of the Total Environment

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

Minimal ecosystem uptake of selenium from Westland petrels, a forest-breeding seabird

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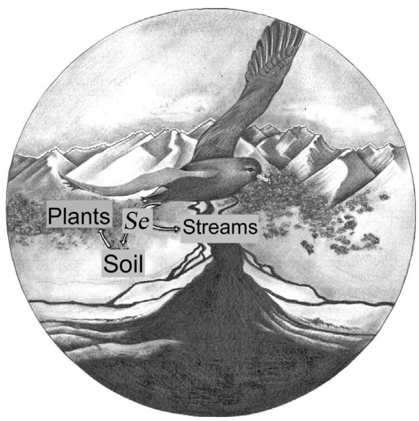
HIGHLIGHTS

- Seabirds boost Se in breeding colony soil, but subsequent uptake is unknown.
- Plant foliage from seabird and non-seabird sites had equally low Se contents.
- Seabird and non-seabird stream biota had indistinguishable Se status.
- Incorporation of trace elements brought ashore by seabirds cannot be assumed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 30 August 2016
Accepted 30 August 2016
Available online xxxx

Editor: D. Barcelo

Keywords:
Guano
Procellariidae
Seabird soil
Stream ecosystem
Trace element

ABSTRACT

Endemic Westland petrels (*Procellaria westlandica*) are a remnant of extensive seabird populations that occupied the forested hill country of prehuman New Zealand. Because seabird guano is rich in Se, an often-deficient essential element, we proposed that Westland petrels enhance Se concentrations in ecosystems associated with their breeding grounds. We sampled terrestrial (soil, plants, riparian spiders) and freshwater (benthic invertebrates, fish) components from Westland petrel-enriched and non-seabird forests on the western coast of New Zealand's South Island, an area characterised by highly leached, nutrient-poor soils. Median seabird soil Se was an order of magnitude higher than soil from non-seabird sites (2.2 mg kg^{-1} compared to 0.2 mg kg^{-1}), but corresponding plant foliage concentrations (0.06 mg kg^{-1}; 0.05 mg kg^{-1}) showed no difference between seabird and non-seabird sites. In streams, Se ranged from 0.05 mg kg^{-1} (riparian foliage) to 3.1 mg kg^{-1} (riparian spiders and freshwater mussels). However, there was no difference between seabird and non-seabird streams. Stoichiometric ratios (N:Se, P:Se) showed Se loss across all ecosystem components relative to seabird guano, except in seabird colony soil where N was lost preferentially. Seabirds therefore did not enrich the terrestrial plants and associated stream ecosystems in Se. We conclude that incorporation of trace elements brought ashore by seabirds cannot be assumed, even though seabirds are a significant source of marine-derived nutrients and trace elements to coastal ecosystems world-wide.

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http://dx.doi.org/10.1016/j.scitotenv.2016.08.203

1. Introduction

Selenium (Se) is an essential trace element found in antioxidant and regulatory proteins (Brown and Arthur, 2001), the best known being the glutathione peroxidases. Although comparatively little is known of the importance of Se deficiencies to individual species in natural habitats unaffected by human activities (Araie and Shairaiwa, 2009), Se deficiency in humans is associated with remarkably diverse health effects. These range from diabetes mellitus to mental illness (Rayman, 2012; Conner et al., 2015), and individuals prioritise biosynthesis of the various selenoproteins in response to their Se status (Howard et al., 2013; Lin et al., 2015). Industrial activities and enriched soil parent material enhance Se in some aquatic systems and terrestrial soils and biota to toxic levels, but low concentrations bordering on deficiency are more common (Fordyce, 2013). In such places, Se from outside sources can be particularly important.

The comparatively high Se concentrations found in marine vertebrates probably assist mercury and cadmium detoxification (Ikemoto et al., 2004; Lovvorn et al., 2013; Siscar et al., 2014). Before global human expansion the marine-terrestrial interface was more porous, with many rivers seasonally occupied by anadromous fish and seabirds breeding considerable distances inland (Doughty et al., 2015). Numerous studies in the systems that still host these marine visitors have shown uptake by terrestrial and stream systems of marine-derived nutrient elements, particularly nitrogen (N). As well as nutrients, seabirds enrich the soils of their breeding and roosting sites with a suite of trace elements, including Se (Xu et al., 2011; Mallory et al., 2015).

Although organic selenides (Se(II)) are particularly important in marine systems, soil solution and freshwater Se is mostly divided between Se(IV) and Se(VI) (Cutter and Cutter, 1995; Baines et al., 2001; Miller et al., 2013). Of the inorganic forms of the higher oxidation states, selenite (Se(IV)) is the more useful to terrestrial plants, but its affinity for soil colloids is stronger than selenate (Se(VI)) thereby decreasing its availability. In turn, the affinity for soil colloids is affected by competing ions sulphate (affecting selenate) and phosphate (affecting selenite) (Hopper and Parker, 1999). Plant uptake of soil Se is controlled by a combination of soil concentration, mineralogy, redox potential, pH and microbial activity, and plant physiology (Fordyce, 2013; Durán et al., 2013). Furthermore, redox speciation and adsorption by soil colloids is highly dynamic under typical soil conditions, so predicting plant response to changes in total Se concentration is problematic.

Although the enrichment of seabird roosting and breeding soils with nutrients and trace elements (including Se) is well known, effects on the wider environment have been largely ignored. The holding capacity of soil for any added element is limited by the availability of binding sites. Once this capacity is exceeded in contexts with unusually high input fluxes, inputs must inevitably be balanced by outputs (Hawke, 2005). Neither Se(IV) nor Se(VI) has a significant gas phase under natural conditions. Consequently, Se inputs from seabirds should ultimately be released into any nearby streams leading to potential Se enhancement of stream biota.

The western coast of New Zealand's South Island (the "West Coast") has localised seabird breeding in forests with strongly leached, infertile soils. Our previous work found unexceptional Se concentrations in seabird colony plant foliage from the West Coast (Hawke and Wu, 2012). In our current study, we hypothesised that even lower concentrations would be found in West Coast soils and plants away from the influence of seabirds, and that stream biota downstream of seabird colonies would be enriched in Se. We also applied a stoichiometric approach (N:Se; phosphorus: Se, P:Se) to determine accumulation patterns within seabird-affected streams.

2. Materials and methods

2.1. Experimental design

Westland petrels are one of the few substantive remnants of the formerly extensive seabird populations in New Zealand. The species is restricted to the West Coast, with 4000 breeding pairs spread across four forested catchments 1–2 km from the coast (Wood and Otley, 2013). The conservation status of the species is "Vulnerable" (IUCN, 2013), and access to breeding sites and the associated landscape is restricted by conservation authorities to a single colony of 200–400 breeding pairs (Waugh et al., 2015). The seaward boundary of the area set aside for Westland petrel protection lies just inland of a coastal highway. Access to streams between the protected area and the highway is unrestricted.

In our first comparison we added soil and terrestrial plant sampling from a control location to data from the only accessible West Coast seabird colony site (Hawke and Wu, 2012). Because different plant taxa grow at the control and seabird sites, we included some archival samples from another control site which has a plant taxon (tree ferns *Cyathea* spp.) in common with the seabird site. In our second comparison we sampled streams (including riparian plants and soil) draining all four seabird catchments alongside five control streams.

The other constraint we addressed in our study design was the minimum sample size for Se analysis of 200–500 mg. Given the small sample mass of individual stream invertebrates and the small size of available streams, we needed to allow for the possibility that no stream would yield sufficient material across all functional feeding groups even with pooled samples. We therefore set up sampling to provide paired comparisons between seabird and non-seabird streams across as many functional feeding groups as possible, and sampled all available streams. The small size of the streams, with their highly mobile pebble and cobble substrates, combined with frequent intense rain events to make periphyton sampling impractical.

2.2. Study sites

Samples came from two native forests 175 km apart, Punakaiki (seabird and non-seabird soil, plant and stream samples) and Okarito (non-seabird soil and plant samples) (Fig. 1; Table 1). Both have a mild, humid climate typical of the West Coast, with a mean annual temperature of approximately 11 °C and 2500–3000 mm annual rainfall. Away from areas affected by seabirds, West Coast soils are typically P limited (Parfitt et al., 2005). There were no significant human land uses (e.g. urbanisation or farming) at the localities we sampled.

Okarito Forest is a multi-tiered podocarp rainforest as close to its pre-human state as any in New Zealand, and was included in the study for this reason and to provide a well-characterised locality with highly leached, nutrient-poor soils. The area we sampled (Johnston, 2014) has acidic (pH 4) silt loam soils developed on locally steep glacial outwash moraines. The landscape at Punakaiki comprises deeply dissected hill-country bounded by a narrow coastal plain. The hill-country seabird site we sampled has been occupied by seabirds since at least 1750 (Holdaway et al., 2007) and has acidic (pH 3.5–4.0) silt loam soils developed on Late Miocene – early Pliocene blue-grey muddy sandstone. Soils on the coastal plain adjoining the stream sampling sites are developed on Tertiary gravels (Nathan et al., 2002).

The seabird and non-seabird streams near Punakaiki (Fig. 1; Table 1) are 1st or 2nd order streams in regenerating forest following logging many decades ago. One of the four non-seabird streams, Canoe Creek, is a larger 4th order stream. The streams are slightly acidic (pH 6.4–6.7); with the exception of calcium, major component composition is dominated by sea salt inputs (RG-G and DL, unpub. data). Calcium in seabird streams is enhanced relative to non-seabird streams, potentially either co-leached with nitrate (Likens et al., 1998) or directly from seabird guano. The seabird status of McMillans Creek is unclear, with the valley being used as a petrel flyway to a breeding site just over the catchment boundary. The $^{15}N/^{14}N$ (expressed as $\delta^{15}N$) of stream biota is a useful indicator of seabird inputs (Harding et al., 2004), and $\delta^{15}N$ of benthic algae from McMillans Creek was lower than three of the four seabird creeks (Scotchmans, Hibernia and Liddys creeks) but higher than Waiwhero Creek (RG-G, unpub. data).