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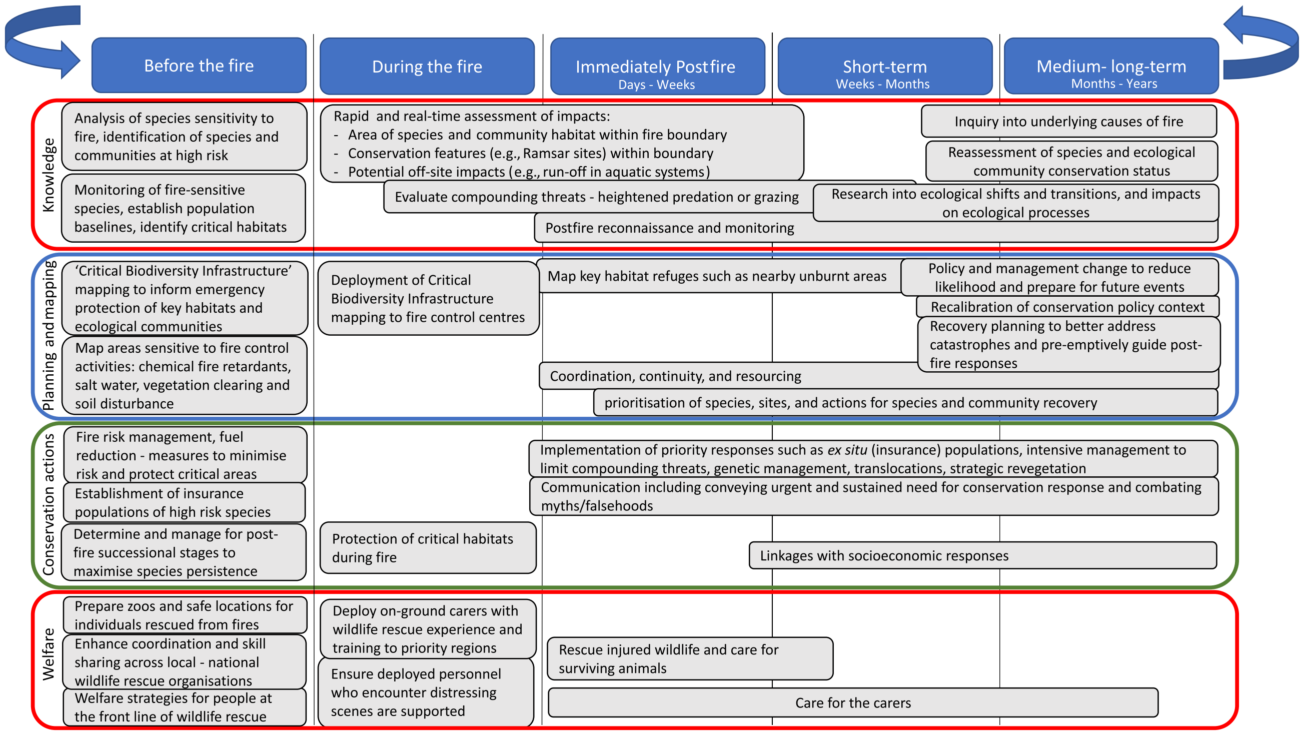

Figure 2. Key Activities in Bushfire Preparation and Response to Minimise the Loss of Biodiversity and to Help Ensure and Expedite its Recovery. Activities are organised according to the relevant timing (columns) and under broad families of activities (rows). Crucial elements in the preparatory phase 'before the fire' that were not adequately addressed before the 2019–2020 Australian megafires include analysis and synthesis of species sensitivity to fire, monitoring, surveying, and mapping to delineate critical habitats for protection and emergency postfire action. Undertaking adequate preparation will help ensure that, during and immediately post fire, actions will be efficiently deployed to protect sensitive and critical biodiversity assets and rapidly drive their recovery. Many of the medium–long-term postfire activities support preparation for the next fire event, such as policy and management changes, to reduce the likelihood and minimise the impacts of future events.

Acknowledgements

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Resources

[i]www.environment.gov.au/biodiversity/bushfire-recovery/research-and-resources

[ii]www.bom.gov.au/climate/current/annual/aus/#tabs=Overview

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Science & Society

Valuing Ecosystem Services Can Help to Save Seabirds

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Biodiversity provides crucial but overlooked contributions to human wellbeing. One way to call attention to these contributions is to monetise them. We have estimated that the value of seabird nutrient deposition could be up to US$473.83 million annually. This figure should increase

awareness of the importance of seabird conservation.

Monetisation of Ecosystem Services

People rarely think about the contributions that biodiversity makes to human wellbeing because they are hard to perceive [1]; as such, it is challenging to inform the general public about the consequences of biodiversity loss. One way to do this is to monetise the **ecological functions** (see Glossary) performed and the **ecosystem services** provided by species [2]. Such an approach expresses the importance of biodiversity in similar terminology to that used in the economic and political sectors [2]. Additionally, the monetisation of ecosystem services is one way to prevent people from misinterpreting conservation efforts as a luxury [3].

Although monetising the role of species in ecosystem services can help to increase public awareness about the importance of biodiversity, it is not an easy task [2,4]. First, ecological functions and ecosystem services are hard to quantify at large scales. Second, these are often not traded in conventional markets. These factors complicate economic valuation [2,4]. Here, we present a first-cut analysis of the monetisation of the ecosystem services provided by **seabirds**. Seabirds – which are heavily threatened [5] – perform ecological functions that are key to the health of coastal and marine ecosystems and the organic fertiliser markets [6–8]. Here, using data from 302 seabird species, we attempt to estimate this value considering the **guano** production and the minimum cost to replace the nutrients deposited annually by seabirds in coastal ecosystems around the world.

Valuing Seabird Nutrient Deposition

Seabirds can be viewed as biological pumps between marine and terrestrial habitats. They release high concentrations of nitrogen (N) and phosphorus (P) through their faeces [6], causing important environmental changes in these ecosystems [8]. Therefore, they present a case where an ecosystem service (guano) and an ecological function (N and P deposition) can be quantified. Some seabirds produce guano (guano-producing species), which is used as an organic fertiliser in countries like Peru and Chile [7]. Because seabird guano is a commodity, we can calculate the value of this ecosystem service from its market price. The N and P released by the non-guano-producing seabirds also supports ecosystem services with direct benefits to human wellbeing (Box 1). However, calculating the value of these benefits is not currently feasible due to a lack of data. Thus, we used a replacement cost approach, which estimates the value of an ecological function as the cost of replacing it with human-made substitutes [2]. This approach is often used for conservation purposes [4]. We valued the N and P deposition of non-guano-producing seabirds by multiplying the amount of N and P they excrete annually [6] by the price of inorganic N and P (fertilisers) that are traded on the international market (Box 1). Our valuation is a minimum estimate of the value of N and P deposited by seabirds. Because other costs are context dependent, they should be considered in conservation projects evaluating the replacement cost of this ecological function in a given location.

We estimate the N and P deposition and guano production to have a value of at least US$454.4 million and US $19.4 million, respectively (Box 1); a total of US$473.8 million per year. This is 17 times the annual expenditure of BirdLife International[i] in 2017 and almost three times the 2018 International Union for Conservation of Nature (IUCN) budget[ii]. The largest guano producers, Peru[iii] and Chile[iv], extracted 27 000 tons of guano in 2018, which was sold for US$12.2 million. This amount of guano represents approximately one-sixth of the guano potentially produced annually by seabirds (Box 1).

Groups of seabirds vary in their contribution to guano production and N and P deposition due to the differences in population size and species-specific per capita excretion (Figure S1 in the supplemental information online). Three seabird species produce most of the guano traded today: the Guanay cormorant (*Leucocarbo bougainvilliorum*), the Peruvian pelican (*Pelecanus thagus*), and the Peruvian booby (*Sula variegata*); the Guanay cormorant is the most important in terms of total production [7]. Fifty-five percent of the N and P deposited annually comes from penguin species (Figure 1A). N and P deposition levels of some species is similar despite different per capita excretion rates due to the differences in population sizes (Figure S1 in the supplemental information online). For example, overall, emperor penguins (*Aptenodytes forsteri*) and common murres (*Uria aalge*) are responsible for similar amounts of N and P annually. However, the per capita contribution of the former is 39 times higher with a population 39 times smaller than the latter (Figure S1 in the supplemental information online). Some species have significant impacts at both local and global scales, for example, the macaroni penguin (*Eudyptes*

Glossary

Added value: the difference between the market price of a given product and the cost of its production.
Ecological function: the result of interactions between biotic or abiotic components of the environment that can change (over time) an ecosystem or an ecological system.
Ecosystem service: components of the ecosystem that can potentially be used by humans.
Guano: seabird accumulated excrement, rich in N and P, which has been used as fertiliser since ancient times.
Seabirds: bird species for which a large proportion of the population rely on a marine environment for at least part of the year.

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Box 1. Monetising Seabird Guano Production and N and P Deposition

We calculated the potential amount of guano produced annually by guano-producing seabirds using literature data on their population sizes and guano production (Table S1 in the supplemental information online). We considered the mean international market price of Peruvian and Chilean guano (US$584 per ton in 2018) and used its added value (20% of the market value [13]) to monetise the global amount of guano produced by seabirds. For the remaining seabirds, we used the annual amount of nitrogen (N) and phosphorus (P) excreted by each species [6]. We monetised these using urea and triple superphosphate (TSP) prices[v] (the annual average from 2014 to 2018 in present dollars), considering that 46% of urea is N, and 20.1% of TSP is P [14,15]. We followed Cordier *et al.*'s [4] framework to illustrate the value of some ecosystem services provided by seabirds (Figure I).

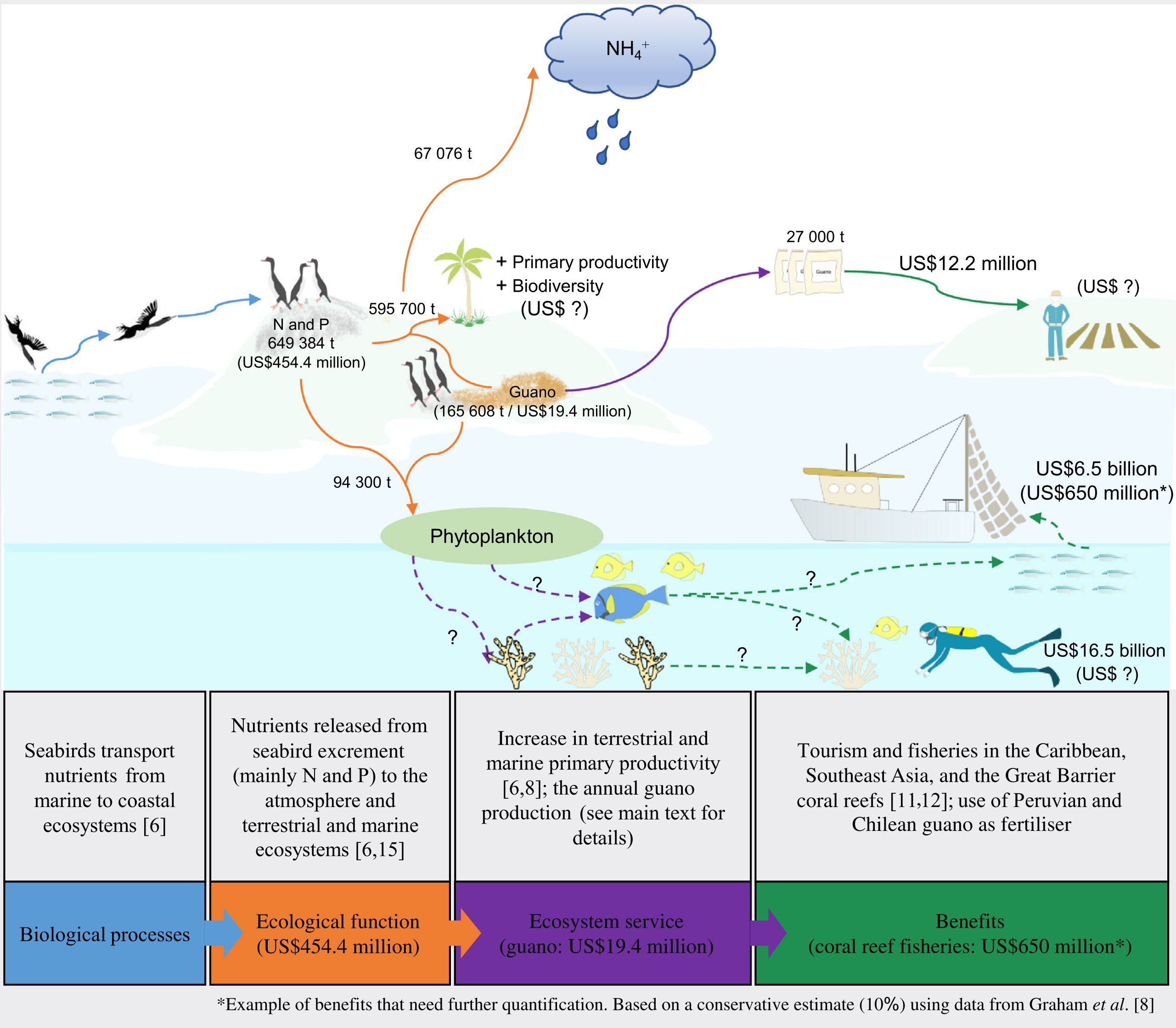

Figure I. Annual Seabird Nitrogen and Phosphorus (N and P) Deposition and Guano Production (in Tons and US Dollars) and Their Contribution to Some Ecosystem Goods and Services Used by Humans. Unbroken and broken lines represent, respectively, direct and indirect seabird contributions. Question marks indicate unknown values. See also [6,8,11,12,14,15].
For a Figure360 author presentation of Figure I, see the figure legend at https://doi.org/10.1016/j.tree.2020.06.008.

chrysolophus) contributes 18.3% of the total N and P deposition by seabirds globally but occurs only in Antarctica where it contributes 21.2% to Antarctic N and P deposition [6]. Meanwhile, other species make significant local contributions despite their lower global impacts. For example, terns contribute < 1% of global seabird N and P deposition but are vital sources of nutrients in the Chagos Archipelago [8]. Therefore, to use this ecological function in decision making for local seabird

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(See figure legend at the bottom of the next page.)

conservation, it will be necessary to consider the relative importance of species to both local and global biogeochemical cycles.

Ecosystem Services at Risk

Of the 302 species included here, nearly 31% are threatened. These species are responsible for 27% of the N and P deposition and 6% of the guano produced every year (Figure 1A). Because these amounts are related to the species population size (Figure S1 in the supplemental information online), paying attention to temporal population trends is necessary. Currently, >44% of the N and P deposition and guano production is from species with declining populations (Figure 1B). Therefore, conserving seabird populations is necessary to maintain their ecological functions in terrestrial and marine ecosystems.

Seabirds face various threats in both marine and terrestrial ecosystems, including climate change, bycatch, and overfishing [5]. The impacts of these are higher on the ecosystem services provided by seabirds than on the seabirds themselves (Figure 1C,D). For example, climate change threatens 80% of the amount of N and P deposition by seabirds but 'only' 44% of seabird species (Figure 1D). Because there are no solutions to directly mitigate impacts of climate change, eradication of invasive alien species and the reduction of fishery impacts are essential for seabird conservation [5]. Penguins require special attention because 61.4% of their N and P deposition is attributed to species with declining populations (Figure 1B). The N and P deposited by penguins has a crucial role in Antarctic ecosystems, increasing marine and terrestrial biodiversity and productivity [6,9].

Why Should We Care about Seabird Guano and N and P Deposition?

Seabirds support – directly and indirectly – several ecosystem services and products used by humans (Box 1). Valuing these services can help us to prevent the consequences of losing seabird species [4]. For example, the global stocks of phosphate rock are expected to be depleted by 2060 [10]. Consequently, because seabird guano is a rich source of P [6], demand for this could increase. Thus, protecting guano-producing seabird populations, as done in Peru [7], has future economic implications. As we show in Box 1, N and P deposition also generates several additional benefits that affect human wellbeing, which we were unable to monetise on a global scale. However, we can make a rough estimate of seabird importance for coral reef fisheries. Some evidence suggests that nutrients released by seabirds can increase reef fish biomass by 48% [8]; therefore, we might estimate that, in the absence of seabirds, reef fish stocks would be reduced by a third. Since this will vary across coral reefs, we can make a conservative estimate that 10% of coral reef fish stocks depend on seabird nutrients. If we consider the annual economic return of commercial fisheries on Caribbean, Southeast Asian, and the Great Barrier coral reefs to be US $6.5 billion [11,12], and estimated the 10% figure, the back-of-the-envelope calculation for the value of seabird nutrient deposition on these coral reef fisheries can be estimated to be US$650 million per year. Inclusion of these functions could easily raise the value of seabird N and P deposition to US$1.1 billion.

Valuating biodiversity is always challenging, and there is no consensus approach [4]. Concerning the guano valuation, we used the **added value** of the Peruvian and Chilean guano and did not consider the market price in other regions (e.g., Namibia, Australia). However, because Peru and Chile are the leading guano producers, it is likely that we captured the present market price fairly accurately. Nevertheless, future studies should also include a market prospection to evaluate the interest of the market for more guano and the impact of large-scale guano extraction on seabird populations. For N and P deposition, we considered the cost of replacing these nutrients with inorganic fertilisers. However, because our estimates are based on more than 3000 seabird colonies around the world [6], we did not include fertiliser transportation and distribution costs. Therefore, our valuation is certainly underestimated, and future studies that include the additional variables mentioned will potentially reach much higher figures.

Here, we have shown that the ecosystem services of seabirds could be valued at US $473.83 million annually (and potentially up to US$1.1 billion). However, seabird contributions go beyond their roles in nutrient cycles (e.g., birdwatching). Further quantification will potentially increase the value of seabird contributions. Nevertheless, the data we present here can be used as a starting point for seabird conservation initiatives involving consumers, fisheries, governments, and nongovernmental organisations.

Figure 1. Threats to the Annual Seabird Nitrogen and Phosphorus (N and P) Deposition and Guano Production. We present the N and P deposited and guano produced annually by seabirds by their International Union for Conservation of Nature (IUCN) red list status (A) and their population trends (B). For clarity, we show only seabird groups that contribute the most to N and P deposition (non-guano producing species indicated by the red broken line) and pooled all guano-producing species (Table S1 in the supplemental information online). We also show the main threats to guano production and guano-producing species (C) and the main threats to N and P and the non-guano producing species (D). Values in brackets are in million US dollars. Because a given species can be affected by more than one threat, we considered these species in each one of their threats. Abbreviations: CR, critically endangered; EN, endangered; LC, least concern; NT, near threatened; VU, vulnerable.

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[i]www.birdlife.org

[ii]www.iucn.org

[iii]www.agrorural.gob.pe

[iv]www.sernageomin.cl/mineria

[v]https://data.worldbank.org

Supplemental Information

Supplemental information associated with this article can be found online at https://doi.org/10.1016/j.tree.2020.06.008.

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Book Review

Sociality Influences Population Dynamics under Perturbation Regimes

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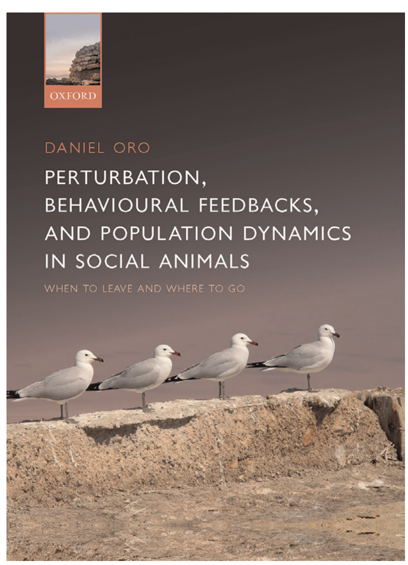

It is academically inspiring to see how a research program initially focused on the population dynamics of a social seabird species [1,2] grows over time, widening its scope in search of global ecological patterns in social animal species. This is even more interesting considering that our own species is one of the species analyzed. This book permeates the idea that animal populations are in permanent change (following transient dynamics in patch quality [3] and perturbations) and that this change usually follows a nonlinear pattern. Although disturbance may follow a gradual and linear pattern, ecological thresholds and tipping points are eventually reached and population density moves abruptly away from one local dynamic equilibrium to a new state, often without notice (i.e., without early-warning signals). These punctuated changes are reported to happen after multidecadal periods of stasis, often as short as two to three decades. Abrupt drops in the population dynamics of social species can take place via catastrophic mortality or through massive dispersal. This is a book about dispersal and decision-making in times of crisis. Populations of highly vagile social species (often structured in space) must decide when to leave and where to settle when a major perturbation impacts its breeding grounds. The book spins around a behavioral idea: social species can use both private (individually owned) and public (shared) information [4] when facing disturbance, whereas solitary species can make use of only the former. Collective dispersal can provide some advantages for better management of uncertainty in unstable environments. Additionally, dispersal in a solitary species has consequences for the dispersing individual only, whereas dispersal in populations of social species also may affect the recipient communities and biotopes; that is, the ecosystems of destination. The nature of runaway dispersal (i.e., dispersal forced by perturbation, a term coined by the author) is nonlinear because individuals of social