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ORIGINAL PAPER

Global Island Monitoring Scheme (GIMS): a proposal for the long-term coordinated survey and monitoring of native island forest biota

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Abstract Islands harbour evolutionary and ecologically unique biota, which are currently disproportionately threatened by a multitude of anthropogenic factors, including habitat loss,

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Data accessibility The species distribution data used in this study are available from the authors upon request, as they are still being analyzed within the projects NETBIOME-MOVECLIM (M2.1.2/F/04/2011/NET), NETBIOME-ISLANDBIODIV (NETBIOME/0003/2011) and MACDIV (FCT-PTDC/BIABIC/0054/2014).

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invasive species and climate change. Native forests on oceanic islands are important refugia for endemic species, many of which are rare and highly threatened. Long-term monitoring schemes for those biota and ecosystems are urgently needed: (i) to provide quantitative baselines for detecting changes within island ecosystems, (ii) to evaluate the effectiveness of conservation and management actions, and (iii) to identify general ecological patterns and

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processes using multiple island systems as repeated 'natural experiments'. In this contribution, we call for a Global Island Monitoring Scheme (GIMS) for monitoring the remaining native island forests, using bryophytes, vascular plants, selected groups of arthropods and vertebrates as model taxa. As a basis for the GIMS, we also present new, optimized monitoring protocols for bryophytes and arthropods that were developed based on former standardized inventory protocols. Effective inventorying and monitoring of native island forests will require: (i) permanent plots covering diverse ecological gradients (e.g. elevation, age of terrain, anthropogenic disturbance); (ii) a multiple-taxa approach that is based on standardized and replicable protocols; (iii) a common set of indicator taxa and community properties that are indicative of native island forests' welfare, building on, and harmonized with existing sampling and monitoring efforts; (iv) capacity building and training of local researchers, collaboration and continuous dialogue with local stakeholders; and (v) long-term commitment by funding agencies to maintain a global network of native island forest monitoring plots.

Keywords Beta-diversity · Ecological gradients · Forest monitoring protocols · Island conservation · Long-term monitoring · Sampling standardization

Introduction

Islands are well known for their unique biodiversity (Whittaker and Fernández-Palacios 2007). Amounting to just 5.3% of the global landmass (Weigelt et al. 2013), islands hold

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a disproportionate amount of the world's biodiversity (Whittaker and Fernández-Palacios 2007; Kier et al. 2009), and this is manifest at taxonomic, functional and phylogenetic levels of diversity (Jønsson and Holt 2015; Warren et al. 2015; Rominger et al. 2016). High levels of in situ speciation and endemism are an attribute of the most remote islands, where strong dispersal effects leads to the absence of some and the overrepresentation of other taxonomic groups (Carlquist 1974; Whittaker and Fernández-Palacios 2007; Weigelt et al. 2015).

The majority of recorded extinctions have occurred on islands (Whittaker and Fernández-Palacios 2007; Whittaker et al. 2017), including 75% of the better-documented terrestrial vertebrate extinctions (Tershy et al. 2015). Halting biodiversity loss is a key challenge for the twenty-first century (Cardinale et al. 2012; Liu et al. 2015), and this is particularly true for islands, which are currently highly impacted at all levels of biodiversity (from genes to ecosystems) (Ricketts et al. 2005; Caujapé-Castells et al. 2010), with dramatic consequences for community composition, ecosystem functioning and human well-being (Chapin et al. 2000; Weiss 2015). The recognised importance of islands for global biodiversity conservation is reflected by the inclusion of many island archipelagos within the biodiversity hotspots designated by *Conservation International* (see Mittermeier et al. 2005). Island ecosystems face multiple threats, including species invasions (Kueffer et al. 2010; van Kleunen et al. 2015), land-use change (Caujapé-Castells et al. 2010), resource depletion (including hunting of endangered species; Alcover et al. 2015), and global climate change (Bellard et al. 2014; Harter et al. 2015). Although these problems are recognized among scientists and conservation managers, there is a substantial lack of societal concern about biodiversity loss and there have been only limited policy responses to it (Balmford and Cowling 2006; Renn 2008), which adds to the risk of biodiversity loss and island ecosystem degradation.

One of the greatest challenges in modern ecology is to distinguish natural changes (e.g. spatial and temporal turnover) from those that arise from, or are mediated by, anthropogenic activities (e.g. native forest loss) (Magurran et al. 2010), specifically on islands (Nogué et al. 2017). Long-term studies are needed to address this problem (e.g. Essl et al. 2015), but island forests are currently poorly represented in the pertinent research networks such as the International Long-Term Ecological Research sites (ILTER—https://www.ilter.network/) (see more details below in Ongoing inventory and monitoring initiatives within oceanic archipelagos section). Although whole ecosystem manipulative experiments have been undertaken in certain tropical forest ecosystems (Fayle et al. 2015), this kind of approach bears obvious risks at the scale of island ecosystems, including threatening globally unique biota. However, the 'experiment-like', repeated availability of similar changes on different islands, such as the ongoing expansion of invasive plant species within montane island forests worldwide (e.g. Cronk and Fuller 1995; Alexander et al. 2011), creates opportunities for long-term monitoring of biodiversity, ecosystem functioning and global change effects. Coordinated studies can thus provide improved monitoring benchmarks and can shed new light on how island communities are structured, how biodiversity is maintained and how it changes due to anthropogenic influences. It is thus both a challenge and an opportunity to investigate patterns and processes of long-term change across different islands, spanning large climatic gradients and different degrees of isolation, for a variety of taxa, for different facets of diversity (taxonomic, functional and phylogenetic), and using comparable methods and metrics that quantify spatial and temporal changes in diversity (see e.g. Cardoso et al. 2014, 2016).

Montane forests are often the last remnants of the pristine forests that existed prior to human arrival and which once covered the majority of oceanic volcanic islands in the low- to mid-latitudes. These habitats are today of critical importance for the protection of island biodiversity, and for the provisioning of a variety of ecosystem services (e.g. water regulation, erosion control, pollination, pest-control, food supply, recreation and tourism). Native montane forests on islands thus contribute to the livelihoods and well-being of local people (MEA 2005). However, despite the major importance of native island forests, data are lacking for many of them, a concern further increased by the vulnerability of these systems to global change (Secretariat of the Convention on Biological Diversity 2014). Here, we review several inventory and monitoring programs focusing on native island forest biodiversity, with a particular emphasis on mountainous areas in oceanic islands (although the schemes may apply equally well to other biogeographical categories of island). We then propose and outline a Global Island Monitoring Scheme (GIMS) that is based on permanent forest plots, consistent methods, and selected indicator groups of organisms. Our proposal adds to recent calls for enhanced biodiversity monitoring (Schmeller et al. 2017; Stephenson et al. 2017; Walters and Scholes 2017) and implies cooperation between environmental agencies responsible for the management of protected areas, and scientists working on the long-term dynamics of biodiversity in native island forests. Our main aim is to propose scientific standards for a global monitoring scheme of spatial and temporal ecological changes in native island forests. Specifically, the GIMS will: (i) quantify biodiversity at the ecosystem scale, (ii) quantify changes in species diversity and community composition, (iii) evaluate current conservation practices, and (iv) more broadly, enhance our general understanding of human–biosphere interactions.

The proposed monitoring scheme builds on a growing interest in the use of insular (e.g. Kueffer et al. 2014b; Borges et al. 2016a; Patiño et al. 2017) and montane environments (Huber et al. 2006) to answer global questions about biodiversity, environmental change and sustainability (see Appendix S1 for a more detailed list of initiatives).

This contribution is structured into three main sections: (i) a description of ongoing initiatives for standardized studies on islands; (ii) a proposed Global Island Monitoring Scheme (GIMS) for biodiversity dynamics within native island forests; and (iii) implementation of the monitoring protocols and with a proposal for best practices.

Ongoing inventory and monitoring initiatives within oceanic archipelagos

There are several global biodiversity monitoring schemes already in place, with a broad geographic and taxonomic scope, such as ILTER—*International Long-Term Ecological Research* (Vanderbilt and Gaiser 2017), or with a focus on specific taxa (e.g. the Pan European Common Bird Monitoring Scheme, www.ebcc.info/pecbm.html) or specific regions (e.g. the Circumpolar Biodiversity Monitoring Programme, https://www.caff.is/monitoring). There are also several global biodiversity indicator frameworks, such as the Biodiversity Indicator Partnership's indicators used to monitor national and global delivery of the Convention on Biological Diversity (Secretariat for the Convention on Biological Diversity 2014) and the Essential Biodiversity Variables proposed by GEO BON—*Group of Earth Observation Biodiversity Observation Network* (http://geobon.org/) (Pereira et al. 2013).

Islands, however, are underrepresented in these initiatives, reflecting broader gaps in global biodiversity data sets (e.g. Stephenson et al. 2017). Exceptions include the Kasuya Research forest (LTER-EAP-JP-07) and a small number of island forest plots within the CTFS-ForestGEO initiative (http://www.ctfs.si.edu/plots/summary; Anderson-Teixeira et al. 2015). Only a few long-term projects quantify the impact of global change drivers of island ecosystems (but see Aggemyr and Cousins 2012; Vellend et al. 2013). The Global

Observation Research Initiative in Alpine Environments (GLORIA; Grabherr et al. 2000) studies vegetation dynamics in high mountain systems. GLORIA protocols have been adopted for monitoring a few island mountain systems (e.g. Crete, Corsica) (Swerhun et al. 2009) but currently coverage is low for subtropical and tropical islands. The Mountain Invasion Research Network (MIREN) focuses on mountainous ecosystems and includes core research sites in the Canaries and Hawaii (see Kueffer et al. 2014a; Otto et al. 2014), but is focused on invasive plants occurring in anthropogenically disturbed habitats.

Noteworthy national and regional monitoring initiatives are already in place for island plants: (i) the Caribbean network of permanent forest plots for the study of forest dynamics (Lugo 2016); (ii) the Pacific islands initiative PABITRA (the Pacific-Asia Biodiversity Transect Network) comprising ocean-to-mountain transects on islands across the Pacific (Mueller-Dombois and Daehler 2005); and (iii) the New Caledonian Plant Inventory and Permanent Plot Network (NC-PIPPN), set up in 2005 (Ibanez et al. 2014).

With regards to terrestrial invertebrates, the first large-scale long-term survey of arthropod biodiversity within an oceanic archipelago using standardized sampling was initiated on the Azores in 1999, under the auspices of the BALA project (Biodiversity of Arthropods from the Laurisilva of the Azores; Borges et al. 2005; Ribeiro et al. 2005; Gaspar et al. 2008). Other recent biodiversity inventory and/or long-term monitoring projects focusing on island terrestrial ecosystems are listed in Table S1.

Proposal for long-term monitoring of biodiversity change in native island forests across oceanic archipelagos

Objectives and criteria

Species inventories which aim to collect data to assess the taxonomic, phylogenetic and functional facets of biodiversity often involve time-consuming sampling protocols. Species monitoring, in contrast, ideally builds on comprehensive inventories and focuses on a minimum set of indicators that involve less time-consuming protocols but deliver the minimum data necessary to infer temporal trends of community change. For example, inventorying may involve assessing alpha diversity by maximizing the sampled diversity with optimized effort (alpha-sampling sensu Cardoso et al. 2016), whereas monitoring may require assessment of temporal changes in species composition and/or abundances (i.e. beta-diversity) with minimum sampling effort (beta-sampling sensu Cardoso et al. 2016).

We therefore propose an integrated Global Island Monitoring Scheme (GIMS) that: (i) is accurate and sustainable in the long-term, (ii) includes protocols that can be applied to both ‘short-term’ (as a minimum, two comparisons in time within maximum of a 10 year interval) and ‘long-term’, continuous, monitoring programs, (iii) assesses long-term effects of key global change drivers, and (iv) generates data to inform biodiversity conservation and ecosystem management. Efficiency should be attained by minimizing spatial and seasonal variability (sampling the same sites through time, during the same season), maximizing the environmental variability within the sampled locations, and minimizing sampling bias (through sampling standardization) to reveal true trends in diversity descriptors. In the case of seasonal organisms (e.g. arthropods), sampling each season in a year over several years may be possible if resources are available (see e.g. Borges et al. 2017), but it is costly and in most cases the pragmatic choice is to sample in the best season in terms of number of species available.

Experimental design

Proxies of ecosystem change should consider effects of climate, land-use and exotic species. Based on the aforementioned objectives, and on the specificities of each island/archipelago, we advocate the implementation of a general experimental design that is optimized to cover the entire range of ecosystem change (assessed as an index—e.g. LDI—Landscape Disturbance Index [Cardoso et al. 2013]). Sampling along an elevational transect allows an evaluation of the impact of climate change at a mesoclimatic scale by investigating e.g. shifts in species abundances and distributional ranges in relation to key environmental gradients such as temperature and precipitation (Alexander et al. 2011). To cover the entire range of ecosystem change, we suggest first placing plots in native forest habitats, and, second, depending on the available resources, placing additional plots in modified habitats (e.g. production forests, secondary forest, and/or invaded forests). One key challenge is to combine environmental gradients (e.g. elevation) with gradients of forest disturbance, disentangling their relative influences on biodiversity. This could be achieved by statistical approaches based on variation partitioning techniques (Legendre 2008) or direct measurements using indicators of habitat quality, as described in GEO BON (2015) (see e.g. "Biodiversity Habitat Index" or "Local Biodiversity Intactness Index"). For instance, paired elevation/disturbance gradients are increasingly popular study systems in mainland areas (e.g. Ensslin et al. 2015; Gomez-Diaz et al. 2017).

We suggest the use of permanent plots of 50 m × 50 m, based on our previous experience (see NETBIOME-ISLANDBIODIV, Emerson et al. 2017). Nevertheless, there are islands (e.g. Tahiti) where the rugged terrain does not allow for the use of plots of that size, and there are taxa for which a plot-based approach is not adequate (e.g. vertebrates) and other methods may be more appropriate (e.g. transects; whole island surveys) (see Appendix S2). Moreover, subsampling can also be made inside these plots, for instance, for small organism such as a bryophytes. The frequency of sampling will differ depending on the objectives, protocols, taxa and available resources (see Appendix S2). Plots can be placed every 200 m along the elevational gradient, as in the NETBIOME-MOVECLIM project (Gabriel et al. 2014; Henriques et al. 2016), which may be sufficient to reflect climatic changes affecting species distribution in all selected taxonomic groups (see e.g. Ferreira et al. 2016; Patiño et al. 2016).

Selected taxonomic groups

Within the GEO BON scheme, Pereira et al. (2010) advocate the use of plants and birds for global terrestrial species monitoring programs. However, a broader mix of taxa is needed for understanding ecosystem functions and the consequences of global changes. Based on our experience with native island forests, we suggest the monitoring of the following groups.

Bryophytes are a sensitive indicator group that respond rapidly to environmental change and also provide important ecosystem functions and services (e.g. water supply, nutrient cycles, erosion control). In the absence of roots and a protective cuticle, bryophytes are unable to regulate water exchange, and hence, depend more directly on precipitation and fog than higher plants, making them highly sensitive indicators of variation in precipitation regimes (Tuba et al. 2011) and human disturbance (e.g. Bates and Farmer 1992). Bryophytes are highly dispersive species, usually present in all elevation belts. As they are rarely consumed by herbivores, their distributions can be expected to be at equilibrium with climate (Mateo et al. 2013). Moreover, bryophytes are an important group of pioneer organisms and contribute to humus accumulation and regulation of microclimate (e.g. Van Tooren et al. 1985), which is particularly important for the maintenance of forest ecosystems. Together, this makes bryophytes an important group for the evaluation of the impacts of global changes on native island forests.

Vascular plants are the principal primary producers and structural elements of most island ecosystems, providing usually the largest share of biomass, as well as crucial ecosystem functions and services (e.g. water supply, nutrient cycles, erosion control). Vascular plants have been frequently used as model systems to study the impact of global change on ecosystem functioning (Naeem et al. 1999).

Arthropods: spiders and beetles Arthropods dominate most ecosystems in terms of diversity and abundance. Arthropods are also crucial to ecosystem functioning, and are involved in various ways in regulating invertebrate pests, pollination and decomposition. The choice of spiders and beetles is based both on a comparatively high abundance and diversity in island forest ecosystems and on the existence of an efficient, well-tested inventory and monitoring protocol (COBRA, see below).

Vertebrates: birds/mammals are the best-known vertebrates inhabiting island forests. Birds are particularly sensitive to forest loss, degradation and alteration (Pereira et al. 2010) and this is more acutely true of the sub-set of forest-specialist species (Matthews et al. 2014). Insular mammal assemblages often contain a large proportion of non-native species (e.g. rabbits, rats, pigs, sheep, goats, cats), which can have strong negative effects on island ecosystems, particularly by suppressing plant cover and regeneration, leading to increased erosion and habitat degradation (Courchamp et al. 2003). However, large and less isolated islands often have native (often endemic) mammals that may be impacted by non-native species, and in these cases monitoring and eradication efforts should be designed to benefit native species (Harris 2009; Rickart et al. 2011). The monitoring of these vertebrate taxa is thus extremely important for the conservation and management of native island forests.

We acknowledge that other taxonomic groups are also of tremendous importance for forest ecosystems, e.g. fungi (including lichens), molluscs, bees, butterflies, parasitic wasps, moths, amphibians, reptiles, and could potentially be included in a future expansion of the current GIMS proposal, which is already available at IslandLab (http://islandlab.uac.pt/software/ver.php?id=27).

Monitoring protocols and optimization

Several protocols have been proposed for the target taxonomic groups described above (Table 1 and Appendix S2). Often it is necessary to perform a detailed initial inventory for the selected permanent plots (or for the whole island in the case of vertebrates), particularly for less-studied groups (bryophytes, spiders, beetles). A combination of several methods is proposed to this end (Table 1). The BRYOLAT protocol (Ah-Peng et al. 2012; Gabriel et al. 2014) is proposed for bryophytes and ferns. Three protocols are proposed for vascular plants: one based on remote sensing, which can provide cost-efficient data; another for the vegetation as a whole, targeting both alpha and beta diversity; and a third one for monitoring rare species of vascular plants, which can also be applied to bryophytes. The COBRA protocol (Cardoso 2009) is proposed to monitor spiders and beetles. Protocols for birds and different groups of mammals are also suggested (see Appendix S2). The GIMS protocols should be conducted by trained field teams in order to generate reliable

Table 1 List of protocols and their characteristics

Protocol code	Protocol name	Type of protocol	Target taxon	Minimum sampling frequency
1A	BRYOLAT—complete	Inventory	Bryophytes	The first survey in a given island
1B	BRYOLAT—monitoring	Monitoring	Bryophytes	Five or ten years
2	Remote sensing	Monitoring	Vegetation patches at the community level	Yearly or seasonal
3	Whole plot plant species survey	Inventory/monitoring	All vascular plants	The first survey in a given island and then each five or ten years
4	Population monitoring of rare species	Monitoring	All vascular plants (rare species)	Yearly
5A	COBRA—complete	Inventory	Spiders; beetles	The first survey in a given island
5B	COBRA—monitoring	Monitoring	Spiders; beetles	Five or ten years
6	Point-counts	Inventory/monitoring	Birds	Yearly
7	Bat	Inventory/monitoring	Bats	Yearly
8	Non-flying small mammals	Inventory/monitoring	Non-flying small mammals	Five years
9	Mammal carnivores	Inventory/monitoring	Carnivore mammals	Five years
10	Mammal herbivores	Inventory/monitoring	Herbivore mammals	Five years

For a full description see Appendix S2

data and results, although non-scientists can be involved if properly familiar with the taxa and sampling techniques.

As mentioned previously, an optimal inventory strategy requires the maximization of sampled alpha diversity while minimizing sampling effort (alpha-sampling). In contrast, optimal monitoring requires minimizing the difference between sampled and true beta diversity (i.e. beta-sampling; Cardoso et al. 2016), while still minimizing sampling effort. The protocols listed in Table 1 for vascular plants, birds and mammals are comparatively less time consuming than those for bryophytes and arthropods (BRYOLAT and COBRA protocols), which were originally designed for the inventory of biodiversity, and thus need to be optimized for monitoring. To optimize the protocols for the purpose of monitoring, we took several steps building on previous work by Cardoso et al. (2016), and developed a version of BRYOLAT-Monitoring and COBRA-Monitoring protocols (see Appendix S2-Protocols) using the R package BAT (Cardoso et al. 2015).

Diversity metrics and indicators

Our proposed protocols allow the calculation of key diversity metrics, including alpha and beta diversity, the latter involving two processes, replacement of species and loss or gain of species between sites or dates (Carvalho et al. 2012, 2013). This framework allows the measurement of directional turnover in assemblage structure (e.g. through time or along environmental gradients) and the quantification of changes in community composition (or of a single species population of particular interest) in space and time (Table 1 and Appendix S2). The changes through time can be compared with an initial baseline inventory for each plot, and true beta replacement and species loss or gain can then be distinguished from random changes with minimal effort. To monitor ecological and anthropogenic drivers and pressures, several indicators can be used, such as the relative abundance or percentage coverage of non-native species and invasive species, detailed microclimatic variables (e.g. Giambelluca et al. 2013) or indicators such as the "Biodiversity Habitat Index" or "Local Biodiversity Intactness Index", which imply the use of remote-sensing with modelling of local species diversity metrics (GEO BON 2015).

The collection of standardized time-series data across regional and global site networks is also relevant from a basic science perspective and enables an evaluation of how different macroecological patterns vary in space and time. For example, as noted by Magurran (2007), temporal variation in the form of Species Abundance Distributions (SADs) has been largely overlooked. Analysis of changes in the shape of the SAD, and the position of individual species within it, should enable more rigorous tests of community assembly models (e.g. niche and neutral models), and facilitate a more comprehensive understanding of commonness and rarity in communities (Magurran 2007; Matthews and Whittaker 2015). The collection of standardized temporal abundance data also allows for a better understanding of sampling effects on different macroecological patterns (e.g. species–area relationships and SADs), and will be critical to advance ecological theory (Vellend 2016). For example, it has been shown that the SADs of samples collected over short durations approximate log-series distributions, whereas the SADs of samples collected over longer durations approximate log-normal distributions (Hubbell 2001; Magurran 2007). In addition, if ecological information regarding the sampled species is available (e.g. a species' functional role) it is possible to explore how different species (e.g. the core–satellite dichotomy) affect different patterns, for example the SAD, and how these effects change through time (Magurran and Henderson 2003; Matthews and Whittaker 2015). Depending on the time interval between surveys, the collection of long-term monitoring data enables researchers to address questions related to temporal turnover in ecological communities, for example, how rates of temporal turnover vary across archipelagos, and how anthropogenic factors affect turnover rates (see Magurran et al. 2010). Such data may be a value input for initiatives such as the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES).

The indicators that can be derived from our monitoring native island forests proposal are aligned with the Essential Biodiversity Variables (EBV) proposed by Pereira et al. (2013). In fact, the EBV classes "abundances and distributions", "phenology", and "taxonomic diversity" can be generated in straightforward manner from the implementation of the protocols proposed here (Appendix S2). Such data will be also crucial for validating model predictions (Honrado et al. 2016) and demonstrating the impacts of climate change on species distributions on islands (e.g. Ferreira et al. 2016; Patiño et al. 2016) and to develop proper programs for controlling and eradicating invasive species. This type of data will also be relevant for many island nations to identify threatened species through IUCN Red List assessments and to monitor the delivery of the Convention on Biological Diversity (CBD) Aichi Targets and the United Nations Sustainable Development Goals (SDGs). Key SDG indicators supported by this work will include the Red List Index and the proportion of countries resourcing work on invasive species.

Steps for implementation of a Global Island Monitoring Scheme (GIMS): roadmap and best practices

The implementation of this multi-archipelago monitoring scheme of island forests implies a number of steps and tasks that we detail below.

Map native forest habitats on islands

First, it is advisable to acquire both the most recent and the oldest aerial photographs, satellite imagery, historical maps and palaeoecological data (see e.g. Nogué et al. 2017), for comparative analyses. However, some caution should be taken when using only the most recent and oldest aerial photos, since these may lead to misleading conclusions if land cover change did not follow a linear pattern over time. Information on biomass evolution, growth form and chemical composition can be obtained by remote sensing, which appears to be the only method for efficiently collecting data over large spatial extents at high spatial resolution (Strand et al. 2007). At a high/medium spatial and medium spectral resolution, remote sensing multispectral imagery has been successfully used to map target plant species and communities (e.g. Mitchell and Glenn 2009). Hyperspectral images are currently the most widely used imaging source for vegetation studies. The main advantages of using hyperspectral data is that detailed spectral profiles can be developed for native and alien plants, and that specific spectral regions can be analyzed and that those data are most sensitive to the abundance of the species of interest (Underwood et al. 2003). If spectral information is not available, Synthetic Aperture Radar (SAR) data can be useful for vegetation management decision-support when combined with good field knowledge (Huang and Asner 2009). Airborne Laser Scanning (ALS, also referred to as LIDAR—Light Detection And Ranging) may also constitute a suitable tool for mapping key ecosystem properties such as canopy height, biomass and stand structural complexity (Maltamo et al. 2014).

The connection between the differences in vegetation structure observed in the field and the corresponding ALS-derived parameters can be established in a straightforward way (Zlinszky et al. 2012). In fact, some of the most successful and detailed insular remote sensing-based vegetation mapping studies have been undertaken on the Hawaiian Islands using a combination of both airborne hyperspectral and LIDAR technologies (e.g. Asner et al. 2011). To date, due to climate constraints and the general lack of free-of-charge satellite multispectral remote sensing data (e.g. Landsat) covering most oceanic islands, few successful examples of vegetation mapping are available for islands. Promising case studies exist, focusing on alien invasive species, and have been based on high/medium-spatial resolution multispectral satellite remote sensing data (e.g. Gil et al. 2011; Massetti et al. 2016).

Site selection

We propose to sample every 200 m along the elevational gradients from sea level (when native forest habitats are available) to the maximum elevation. The main goal is to study native island forests, selecting at least one 50 m×50 m plot every 200-m of elevation (in the case of BRYOLAT two smaller 10 m×10 m plots are set up; Ah-Peng et al. 2012). However, another possibility it to select at each elevation a set of plots that cover the entire range of disturbance to forests, from pristine (e.g. NETBIOME-MOVECLIM project; Gabriel et al. 2014) to anthropogenic habitats (e.g. Florencio et al. 2016). After selecting a 50 m×50 m plot at each 200-m elevation, an index of disturbance/transformation based on the distance to the nearest anthropogenic habitats should be calculated for each plot (see e.g. Cardoso et al. 2013). This will allow the monitoring of the impact of the pool of alien species available in the surrounding landscape. Variation partitioning techniques can be used to disentangle interdependency between level of ecosystem change and the environmental gradients (Legendre 2008). Along most elevational gradients on islands, the lower elevations are usually dominated by modified habitats. This might make it difficult to find native habitats at all elevation for monitoring. We suggest starting the lower elevation plot at the minimum elevation with adequate native or near-native habitat. In addition, ecological processes and key ecosystem variables (e.g. microclimate variables, soil pH, C:N ratios, net primary productivity, etc.) should be measured in each site/plot using standardized protocols (see e.g. Herrick et al. 2006).

Target groups and biodiversity monitoring protocol selection

Based on Table 1 and Appendix S2, researchers may first need to perform an inventory of biodiversity using different protocols for bryophytes (1A), vascular plants, including ferns (3), spiders/beetles (5A), birds (6), and mammals (7–10). After the initial inventory, monitoring should proceed using the protocols 1B (bryophytes), 2–4 (vascular plants), 5B (spiders/beetles), 6 (birds), and 7–10 (mammals). Caution should be taken when sampling and manipulation rare and threatened species. Some island states have lists of threatened species and permits should be obtained to sample and monitor those species (see more details in Appendix S2).

The workload required for comprehensive taxonomic surveys remains high and is particularly challenging for under-surveyed islands and taxa. For taxa like vascular plants and vertebrates, species identification should be straightforward and based on vouchers for morphological identification and/or DNA barcoding (see e.g. Gonzalez et al. 2009). For groups such as spiders and beetles, and some critical bryophyte and vascular plants genera, the taxonomic impediment (Linnean shortfall) can be an issue in tropical islands (e.g. Cardoso et al. 2011; Hortal et al. 2015), and in addition to the need for taxonomic expertise for identifying the species or determining morphospecies, it is desirable to have access to DNA barcoding for the detection of cryptic species and help on assignment of species that may be affected by splitting and lumping processes in sorting morphospecies (see also Emerson et al. 2017). Furthermore, the recent advances in sequencing techniques now allow third-generation sequencing directly in the field (e.g. Parker et al. 2017), which opens very promising avenues for novel ways of DNA-based identification beyond the limits of predefined barcoding regions. In particular, given the importance of being able to assess identity and abundance of all individuals in an entire community, approaches are being developed that allow massive sequencing of entire communities at minimal cost (Krehenwinkel et al. 2018). While species richness can be routinely identified by sequencing bulk samples, new approaches also allows estimation of species abundance (Krehenwinkel et al. 2017). This in turn allows development of metrics of community stability and turnover in the context of food web structure and species abundance distributions. Additionally, by integrating data on identity and food webs with phylogenetic data, these approaches provide insights into changes in communities based on genetic data.

Data and specimens archiving, sharing and science communication

Data archiving and sharing strategies are critical for the successful implementation of long-term biodiversity studies (Michener 2015; Mills et al. 2015). First, specimen archiving should be guaranteed using public natural history collections (registered herbaria for vascular plants and bryophytes, zoological collections for arthropods and eventually some birds and mammals or their DNA). Collected specimens are the primary data arising from surveys and monitoring and have to be stored and made publicly available for cross-checking and future research (see Schilthuizen et al. 2015). We advise also that some ethical procedures should be follow avoiding sampling with removal of rare plants and vertebrates. Data papers should be promoted (e.g. Borges et al. 2016b) to foster synthesis and comparative studies and we propose the creation of a repository of raw data following common community standards such as the Darwin Core, which is available at Biodiversity Data Journal via the Data Paper format and connected to GBIF using the Pensoft IPT server or other IPT server available in other institutions. Alternatively, a more sophisticated option will be the Ecological Metadata Language (EML), which can also be used to document ecological data in modules (see https://knb.ecoinformatics.org/#external//emlparser/docs/index.html).

Obtained distribution data should be also made available in regional portals such as the Azores Bioportal, https://azoresbioportal.uac.pt/ (Borges et al. 2010) or BIOTA Canarias (http://www.biodiversidadcanarias.es/atlantis/common/index.jsf) as well as globally aggregated in GBIF and through the IUCN Red List of Threatened species, as appropriate. It is further necessary to ensure that the data can be noticed and used by decision makers, and allow national reporting to multilateral environment agreements such as the CBD. Intellectual property rights and authorship issues need to be considered when making the data available, but access restrictions often hinder scientific use and synthesis of data from many monitory programs and databases (e.g. GLORIA, MIREN, TRY, sPlot, etc.). Monitoring protocols should thus ensure that data become (at least in time) publicly available and easily accessible. All these actions should be complemented by activities that promote science communication for conservation managers and the general public, using participatory strategies and web technologies (e.g. Amorim et al. 2016; Arroz et al. 2016).

Conclusions

If we wish to understand the consequences of ongoing global environmental change on island forest ecosystems, and make informed decisions on the conservation of biodiversity and ecosystem functions, long-term monitoring is a central prerequisite. The urgent need to quantify and compare rates of changes in species diversity and ecosystem properties and to establish such a monitoring scheme is widely recognized in e.g. the "Declarations for Islands" (Réunion 2008; Guadeloupe 2014) and initiatives such as the Council of Europe BERN Convention on Islands, CBD-GLISPA and the Samoa Pathway. The methods should build upon, and be consistent with existing measures, and be linked as far as possible to indicators for other biomes. To address these points, we propose a Global Island Monitoring Scheme (GIMS), inclusive of specific protocols for bryophytes, vascular plants, selected groups of arthropods and vertebrates (native and exotic). These protocols should be standardized, thus allowing the comparison of samples in space and time, and optimized, as resources are invariably scarce and efficiency is fundamental to obtaining as much information as possible with minimum sampling effort. Most of the protocols we propose have been previously tested and proved suitable, efficient, feasible, flexible, transparent and accountable. Importantly, we must ensure data are made available to local environmental stakeholders and decision-makers in forms that meet their needs (see e.g. Montambault et al. 2015; Stephenson et al. 2017). Our proposal focuses on native island forests, but some of the proposed experimental design and protocols can be extended to other habitats as well. In fact, this step has already been taken in the Azores (see e.g. Cardoso et al. 2009; Florencio et al. 2016).

A key challenge will be to apply the proposed protocols to many islands and archipelagos, attracting collaborative work towards achieving conservation goals (Kueffer 2012). Biodiversity surveying and monitoring does not have to be an expensive endeavour (Gardner et al. 2008; Pereira et al. 2010) and, considering the pressing current and future environmental change, effective management will not be possible without proper long-term monitoring of island ecosystems. Platforms like LIFE, BIODIVERSA, HORIZON2020 and BEST can be used to apply for funding. In addition, the inventorying and monitoring of biodiversity in the long-term, needs reinforcement of local teams, including technical assistants for field work and specimen sorting. Such monitoring cannot rely solely on project funding to be sustainable, but should involve also funding of permanent positions by regional governments and local conservation organizations as well as national parks and botanical gardens to ensure continuity.

Finally, we hope that our GIMS proposal will encourage colleagues from different archipelagos, leading them to implement long-term biodiversity monitoring protocols and to share their findings with the scientific community, decision-makers, and the general public. We believe that all the proposed steps are essential for improving knowledge on island biodiversity, and thus for valuing and safeguarding the unique natural legacy of the world's oceanic islands.

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References

Aggemyr E, Cousins SAO (2012) Landscape structure and land use history influence changes in island plant composition after 100 years. J Biogeogr 39:1645–1656. https://doi.org/10.1111/j.1365-2699.2012.02733.x

Ah-Peng C, Wilding N, Kluge J, Descamps-Julien B, Bardat J, Chuah-Petiot M, Strasberg D et al (2012) Bryophyte diversity and range size distribution along two altitudinal gradients: Continent vs. Island. Acta Oecol-Int J Ecol 42:58–65. https://doi.org/10.1016/j.actao.2012.04.010

Alcover JA, Pieper H, Pereira F, Rando JC (2015) Five new extinct species of rails (Aves: Gruiformes: Rallidae) from the Macaronesian Islands (North Atlantic Ocean). Zootaxa 4057(2):151–190. https://doi.org/10.11646/zootaxa.4057.2.1

Alexander JM, Kueffer C, Daehler CC, Edwards PJ, Pauchard A, Seipel T, MIREM consortium, (2011) Assembly of nonnative floras along elevational gradients explained by directional ecological filtering. Proc Natl Acad Sci USA 108:656–661. https://doi.org/10.1073/pnas.1013136108

Amorim IR, Arroz AM, São Marcos R, Borges PAV, Gabriel R (2016) Bugs and society II: testing two communication strategies for public engagement in the Azores. In: Castro P, Azeiteiro UM, Bacelar Nicolau P, Leal Filho W, Azul AM (eds) Biodiversity and education for sustainable development. Springer World Sustainability Series, Dordrecht, pp 125–153

Anderson-Teixeira KJ, Davies SJ, Bennett AC, Gonzalez-Akre EB, Muller-Landau HC, Joseph Wright S et al (2015) CTFS-ForestGEO: a worldwide network monitoring forests in an era of global change. Glob Chang Biol 21:528–549. https://doi.org/10.1111/gcb.12712

Arroz AM, Gabriel R, Amorim IR, São Marcos R, Borges PAV (2016) Bugs and society I: raising awareness about endemic biodiversity. In: Castro P, Azeiteiro UM, Bacelar Nicolau P, Leal Filho W, Azul AM (eds) Biodiversity and education for sustainable development. Springer World Sustainability Series, Dordrecht, pp 69–89

Asner GP, Hughes RF, Mascaro J, Uowolo AL, Knapp DE, Jacobson J, Kennedy-Bowdoin T, Clark JK (2011) High-resolution carbon mapping on the million-hectare Island of Hawaii. Front Ecol Environ 9:434–439. https://doi.org/10.1890/100179
Balmford A, Cowling RM (2006) Fusion or failure? The future of conservation biology. Conserv Biol 20:692–695. https://doi.org/10.1111/j.1523-1739.2006.00434.x
Bates JW, Farmer AM (1992) Bryophytes and lichens in a changing environment. Clarendon Press, Oxford
Bellard C, Leclerc C, Courchamp F (2014) Impact of sea level rise on the 10 insular biodiversity hotspots. Global Ecol Biogeogr 23:203–212. https://doi.org/10.1111/geb.12093
Borges PAV, Aguiar C, Amaral J, Amorim IR, André G, Arraiol A et al (2005) Ranking protected areas in the Azores using standardized sampling of soil epigean arthropods. Biodivers Conserv 14:2029–2060. https://doi.org/10.1007/s10531-004-4283-y
Borges PAV, Gabriel R, Arroz A, Costa A, Cunha R, Silva L, Mendonça E, Martins AF, Reis F, Cardoso P (2010) The Azorean Biodiversity Portal: an internet database for regional biodiversity outreach. Syst Biodivers 8:423–434. https://doi.org/10.1080/14772000.2010.514306
Borges PAV, Cardoso P, Gabriel R, Ah-Peng C, Emerson B (2016a) Challenges, advances and perspectives in Island Biogeography. Front Biogeogr 8:e29136
Borges PAV, Gaspar C, Crespo L, Rigal F, Cardoso P, Pereira F et al (2016b) New records and detailed distribution and abundance of selected arthropod species collected between 1999 and 2011 in Azorean native forests. Biodivers Data J 4:e10948. https://doi.org/10.3897/BDJ.4.e.10948
Borges PAV, Pimentel R, Carvalho R, Nunes R, Wallon S, Ros Prieto A (2017) Seasonal dynamics of arthropods in the humid native forests of Terceira Island (Azores). Arquipél Life Marine Sci 34:105–122
Cardinale BJ, Duffy JE, González A, Hooper DU, Perrings C, Venail P et al (2012) Biodiversity loss and its impact on humanity. Nature 486:59–67. https://doi.org/10.1038/nature11148
Cardoso P (2009) Standardization and optimization of arthropod inventories—the case of Iberian spiders. Biodivers Conserv 18:3949–3962. https://doi.org/10.1007/s10531-009-9690-7
Cardoso P, Lobo JM, Aranda SC, Dinis F, Gaspar C, Borges PAV (2009) A spatial scale assessment of habitat effects on arthropod communities of an oceanic island. Acta Oecol-Int J Ecol 35:590–597. https://doi.org/10.1016/j.actao.2009.05.005
Cardoso P, Borges PAV, Triantis KA, Ferrández MA, Martín JL (2011) Adapting the IUCN red listing criteria for invertebrates. Biol Conserv 144:2432–2440. https://doi.org/10.1016/j.biocon.2011.06.020
Cardoso P, Rigal F, Fattorini S, Terzopoulou S, Borges PAV (2013) Integrating landscape disturbance and indicator species in conservation studies. PLoS ONE 8:e63294. https://doi.org/10.1371/journal.pone.0063294
Cardoso P, Rigal F, Carvalho JC, Fortelius M, Borges PAV, Podani J, Schmera D (2014) Partitioning taxon, phylogenetic and functional beta diversity into replacement and richness difference components. J Biogeogr 41:749–761. https://doi.org/10.1111/jbi.12239
Cardoso P, Rigal F, Carvalho JC (2015) BAT—biodiversity assessment tools, an R package for the measurement and estimation of alpha and beta taxon, phylogenetic and functional diversity. Methods Ecol Evol 6:232–236. https://doi.org/10.1111/2041-210X.12310
Cardoso P, Carvalho JC, Crespo LC, Arnedo MA (2016) Optimal inventorying and monitoring of taxon, phylogenetic and functional diversity. Biorxiv. http://biorxiv.org/content/early/2016/06/23/060400
Carlquist S (1974) Island biology. Columbia University Press, New York
Carvalho JC, Cardoso P, Gomes P (2012) Determining the relative roles of species replacement and species richness differences in generating beta-diversity patterns. Glob Ecol Biogeogr 21:760–771. https://doi.org/10.1111/j.1466-8238.2011.00694.x
Carvalho JC, Cardoso P, Borges PAV, Schmera D, Podani J (2013) Measuring fractions of beta diversity and their relationships to nestedness: a theoretical and empirical comparison of novel approaches. Oikos 122:825–834. https://doi.org/10.1111/j.1600-0706.2012.20980.x
Caujapé-Castells J, Tye A, Crawford DJ, Santos-Guerra A, Sakai A, Beaver K et al (2010) Conservation of oceanic island floras: present and future global challenges. Perspect Plant Ecol Evol Syst 12:107–130. https://doi.org/10.1016/j.ppees.2009.10.001
Chapin FS III, Zaveleta ES, Eviner VT, Naylor RL, Vitousek PM, Lavorel S et al (2000) Consequences of changing biotic diversity. Nature 405:234–242. https://doi.org/10.1038/35012241
Courchamp F, Chapuis JL, Pascal M (2003) Mammal invaders on islands: impact, control and control impact. Biol Rev 78:347–383. https://doi.org/10.1017/S1464793102006061
Cronk QCB, Fuller JL (1995) Plant invaders. Chapman & Hall, London
Emerson BC, Casquet J, López H, Cardoso P, Borges PAV, Mollare N et al (2017) A combined field survey and molecular identification protocol for comparing forest arthropod biodiversity across spatial scales. Mol Ecol Resour 17:649–707. https://doi.org/10.1111/1755-0998.12617

Ensslin A, Rutten G, Pommer U, Zimmermann R, Hemp A, Fischer M (2015) Effects of elevation and land use on the biomass of trees, shrubs and herbs at Mount Kilimanjaro. Ecosphere 6:45. https://doi.org/10.1890/Es14-00492.1
Essl F, Dullinger S, Rabitsch W, Hulme PE, Pyšek P, Wilson JRU, Richardson DM (2015) Delayed biodiversity change: no time to waste. Trends Ecol Evol 30:375–378. https://doi.org/10.1016/j.tree.2015.05.002
Fayle TM, Turner EC, Bassett Y, Ewers RM, Reynolds G, Novotny V (2015) Whole-ecosystem experimental manipulations of tropical forests. Trends Ecol Evol 30:334–346. https://doi.org/10.1016/j.tree.2015.03.010
Ferreira MT, Cardoso P, Borges PAV, Gabriel R, Azevedo EB, Reis F, Araújo MB, Elias RB (2016) Effects of climate change on the distribution of indigenous species in oceanic islands (Azores). Clim Chang 138:603–615. https://doi.org/10.1007/s10584-016-1754-6
Florencio M, Rigal F, Borges PAV, Cardoso P, Santos AMC, Lobo JM (2016) The role of plant fidelity and land-use changes on island exotic and indigenous canopy spiders at local and regional scales. Biol Invasions 18:2309–2324. https://doi.org/10.1007/s10530-016-1162-x
Gabriel R, Coelho MMC, Henriques DSG, Borges PAV, Elias RB, Kluge J, Ah-Peng C (2014) Long-term monitoring across elevational gradients to assess ecological hypothesis: a description of standardized sampling methods in oceanic islands and first results. Arquipélago 31:45–67
Gardner TA, Barlow J, Araujo IS, Ávila-Pires TC, Bonaldo AB, Costa JE et al (2008) The cost-effectiveness of biodiversity surveys in tropical forests. Ecol Lett 11:139–150. https://doi.org/10.1111/j.1461-0248.2007.01133.x
Gaspar C, Borges PAV, Gaston KJ (2008) Diversity and distribution of arthropods in native forests of the Azores archipelago. Arquipélago 25:1–30
GEO BON (2015) Global Biodiversity Change Indicators. Version 1.2. Group on Earth Observations Biodiversity Observation Network Secretariat. Leipzig
Giambelluca TW, Chen Q, Frazier AG, Price JP, Chen Y-L, Chu P-S, Eischeid JK, Delparte DM (2013) Online rainfall atlas of Hawai'i. Bull. Am. Meteor. Soc. 94:313–316. https://doi.org/10.1175/BAMS-D-11-00228.1
Gil A, Yu Q, Lobo A, Lourenço P, Silva L, Calado H (2011) Assessing the effectiveness of high resolution satellite imagery for vegetation mapping in small islands protected areas. J. Coast. Res. SI 64:1663–1667
Gomez-Diaz JA, Kromer T, Kreft H, Gerold G, Carvajal-Hernandez CI, Heitkamp F (2017) Diversity and composition of herbaceous angiosperms along gradients of elevation and forest-use intensity. PLoS ONE 12:e0182893. https://doi.org/10.1371/journal.pone.0182893
Gonzalez MA, Baraloto C, Engel J, Mori SA, Pétronelli P et al (2009) Identification of Amazonian trees with DNA barcodes. PLoS ONE 4:e7483. https://doi.org/10.1371/journal.pone.0007483
Grabherr G, Gottfried M, Pauli H (2000) GLORIA: a global observation research initiative in alpine environments. Mt. Res. Dev. 20:190–191. https://doi.org/10.1659/0276-4741(2000)020[0190:GAGORI]2.0.CO;2
Guadeloupe (2014) Message from Guadeloupe. International conference on biodiversity and climate change held in Guadeloupe from 22-25 October 2014. http://ec.europa.eu/environment/nature/biodiversity/best/pdf/message__from_guadeloupe_en__2_.pdf
Harris DB (2009) Review of negative effects of introduced rodents on small mammals on islands. Biol Invasions 11:1611–1630. https://doi.org/10.1007/s10530-008-9393-0
Harter DEV, Irl SDH, Seo B, Steinbauer MJ, Gillespie R, Triantis KA, Fernández-Palacios JM, Beierkuhnlein C (2015) Impacts of global climate change on the floras of oceanic islands—Projections, implications and current knowledge. Perspect Plant Ecol Evol Syst 17:160–183. https://doi.org/10.1016/j.ppees.2015.01.003
Henriques D, Borges PAV, Ah-Peng C, Gabriel R (2016) Mosses and liverworts show contrasting elevational distribution patterns in an oceanic island (Terceira, Azores): the influence of climate and space. J Bryol 38:183–194. https://doi.org/10.1080/03736687.2016.1156360
Herrick JE, Schuman GE, Rango A (2006) Monitoring ecological processes for restoration projects. J Nat Conserv 14:161–171. https://doi.org/10.1016/j.jnc.2006.05.001
Honrado JP, Pereira HM, Guisan A (2016) Fostering integration between biodiversity monitoring and modelling. J Appl Ecol 53:1299–1304. https://doi.org/10.1111/1365-2664.12777
Hortal J, de Bello F, Diniz-Filho JAF, Lewinsohn TM, Lobo JM, Ladle RJ (2015) Seven shortfalls that beset large-scale knowledge of biodiversity. Ann Rev Ecol Evol Syst 46:523–549. https://doi.org/10.1146/annurev-ecolsys-112414-054400
Huang C, Asner GP (2009) Applications of remote sensing to alien invasive plant studies. Sensors 9:4869–4889. https://doi.org/10.3390/s90604869

Hubbell SP (2001) The unified neutral theory of biodiversity and biogeography. Princeton University Press, Princeton

Huber UM, Bugmann HK, Reasoner MA (eds) (2006) Global change and mountain regions: an overview of current knowledge, vol 23. Springer, Berlin

Ibanez T, Munzinger J, Dagostini G, Hequet V, Rigault F, Jaffré T, Birnbaum P (2014) Structural and floristic diversity of mixed tropical rain forest in New Caledonia: New data from the New Caledonian plant inventory and permanent plot network (NC-PIPPN). Appl Veg Sci 17:386–397. https://doi.org/10.1111/avsc.12070

Jønsson KA, Holt BG (2015) Islands contribute disproportionately high amounts of evolutionary diversity in passerine birds. Nat Commun 6:8538. https://doi.org/10.1038/ncomms9538

Kier G, Kreft H, Lee TM, Jetz W, Ibisch PL, Nowicki C, Mutke J, Barthlott W (2009) A global assessment of endemism and species richness across island and mainland regions. Proc National Acad Sci 106:9322–9327

Krehenwinkel H, Wolf M, Lim JY, Rominger AJ, Simison WB, Gillespie RG (2017) Estimating and mitigating amplification bias in qualitative and quantitative arthropod metabarcoding. Sci Rep 7:17668. https://doi.org/10.1038/s41598-017-17333-x

Krehenwinkel H, Fong M, Kennedy S, Huang EG, Noriyuki S, Cayetano L, Gillespie R (2018) The effect of DNA degradation bias in passive sampling devices on metabarcoding studies of arthropod communities and their associated microbiota. PLoS ONE 13:e0189188. https://doi.org/10.1371/journal.pone.0189188

Kueffer C (2012) The importance of collaborative learning and research among conservationists from different oceanic islands. Rev d'Ecol Suppl 11:125–135

Kueffer C, Daehler CC, Torres-Santana CW, Lavergne C, Meyer J-Y, Otto R, Silva L (2010) A global comparison of plant invasions on oceanic islands. Perspect Plant Ecol Evol Syst 12:145–161. https://doi.org/10.1016/j.ppees.2009.06.002

Kueffer C, Daehler C, Dietz H, McDougall K, Parks C, Pauchard A, Rew L (2014a) The mountain invasion research network (MIREN). Linking local and global scales for addressing an ecological consequence of global change. GAIA 23:263–265. https://doi.org/10.14512/gaia.23.3.11

Kueffer C, Drake DR, Fernández-Palacios JM (2014b) Island biology: looking towards the future. Biol Lett 10:20140719. https://doi.org/10.1098/rsbl.2014.0719

Legendre P (2008) Studying beta diversity: ecological variation partitioning by multiple regression and canonical analysis. J Plant Ecol 1:3–8. https://doi.org/10.1093/jpe/rtm001

Liu J, Mooney H, Hull V, Davis SJ, Gaskell J, Hertel T, Lubchenco J, Seto KC, Gleick P, Kremen C, Li S (2015) Systems integration for global sustainability. Science 347:6925. https://doi.org/10.1126/science.1258832

Lugo AE (2016) Caribbean foresters take steps towards a network of permanent forest plots in the Caribbean: a meeting report. Caribb Nat Spec Issue 1:13–17

Magurran AE (2007) Species abundance distributions over time. Ecol Lett 10:347–354. https://doi.org/10.1111/j.1461-0248.2007.01024.x

Magurran AE, Henderson PA (2003) Explaining the excess of rare species in natural species abundance distributions. Nature 422:714–716. https://doi.org/10.1038/nature01547

Magurran AE, Baillie SR, Buckland ST, Dick JM, Elston DA, Scott EM, Smith RI, Somerfield PJ, Watt AD (2010) Long-term datasets in biodiversity research and monitoring: assessing change in ecological communities through time. Trends Ecol Evol 25:574–582. https://doi.org/10.1016/j.tree.2010.06.016

Maltamo M, Næsset E, Vauhkonen J (2014) Forestry applications of airborne laser scanning: concepts and case studies. Springer, Berlin

Massetti A, Sequeira MM, Pupo A, Figueiredo A, Guiomar N, Gil A (2016) Assessing the effectiveness of RapidEye multispectral imagery for vegetation mapping in Madeira Island (Portugal). Eur J Remote Sens 49:643–672. https://doi.org/10.5721/EuJRS20164934

Mateo RG, Vanderpoorten A, Munoz J, Laenen B, Désamoré A (2013) Modeling species distributions from heterogeneous data for the biogeographic regionalization of the European bryophyte flora. PLoS ONE 8:e55648. https://doi.org/10.1371/journal.pone.0055648

Matthews TJ, Whittaker RJ (2015) On the species abundance distribution in applied ecology and biodiversity management. J Appl Ecol 52:443–454. https://doi.org/10.1111/1365-2664.12380

Matthews TJ, Cottee-Jones HE, Whittaker RJ (2014) Habitat fragmentation and the species–area relationship: a focus on total species richness obscures the impact of habitat loss on habitat specialists. Div Distrib 20:1136–1146. https://doi.org/10.1111/ddi.12227

MEA-Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Michener WK (2015) Ecological data sharing. Ecol Inform 29:33–44. https://doi.org/10.1016/j.ecoinf.2015.06.010
Mills JA, Teplitsky C, Arroyo B, Charmantier A, Becker PH, Birkhead TR et al (2015) Archiving primary data: solutions for long-term studies. Trends Ecol Evol 30:581–589. https://doi.org/10.1016/j.tree.2015.07.006
Mitchell J, Glenn NF (2009) Leafy Spurge (*Euphorbia esula* L.) classification performance using hyperspectral and multispectral sensors. Rangel Ecol Manag 62:16–27. https://doi.org/10.2111/08-100
Mittermeier RA, Robles G, Hoffman M, Pilgrim J, Brooks T, Mittermeier CG, Lamoreux J, Fonseca GAB (2005) Hotspots revisited: earth's biologically richest and most endangered terrestrial ecoregions. University of Chicago Press, Boston
Montambault JR, Wongbusarakum S, Leberer T, Joseph E, Andrew W, Castro F et al (2015) Use of monitoring data to support conservation management and policy decisions in Micronesia. Cons Biol 29:1279–1289. https://doi.org/10.1111/cobi.12542
Mueller-Dombois D, Daehler CC (2005) The PABITRA project: island landscapes under global change. Pac Sci 59:133–139. https://doi.org/10.1353/psc.2005.0019
Naeem S, Chapin FS III, Costanza R, Ehrlich PR, Golley FB, Hooper DU et al (1999) Biodiversity and ecosystem functioning: maintaining natural life support processes. Issues Ecol 4:1–14
Nogué S, de Nascimento L, Froyd CA, Wilmshurst JM, de Boer EJ, Coffey ED, Whittaker RJ, Fernández-Palacios JM, Willis KJ (2017) Island biodiversity conservation needs palaeoecology. Nat Ecol Evolut 1:0181. https://doi.org/10.1038/s41559-017-0181
Otto R, Arteage MA, Delgado JD, Arevalo JR, Blandino C, Fernández-Palacios JM (2014) Road edge effect and elevation patterns of native and alien plants on an oceanic island (Tenerife, Canary Islands). Folia Geobot 49:65–83. https://doi.org/10.1007/s12224-013-9159-z
Parker J, Helmstetter AJ, Devey D, Wilkinson T, Papadopulos AS (2017) Field-based species identification of closely-related plants using real-time nanopore sequencing. Sci Rep 7:8345. https://doi.org/10.1038/s41598-017-08461-5
Patiño J, Mateo RG, Zanatta F, Marquet A, Aranda SC, Borges PAV et al (2016) Climate threat on the Macaronesian endemic bryophyte flora. Sci Rep 6:29156. https://doi.org/10.1038/srep29156
Patiño J, Whittaker RJ, Borges PAV, Fernández-Palacios JM, Ah-Peng C, Araújo M et al (2017) A roadmap for island biology: 50 fundamental questions after 50 years of The Theory of Island Biogeography. J Biogeogr 44:963–983. https://doi.org/10.1111/jbi.12986
Pereira HM, Belnap J, Brummitt N, Collen B, Ding H, González-Espinosa M et al (2010) Global biodiversity monitoring. Front Ecol Environ 8:459–460. https://doi.org/10.1890/10.WB.23
Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RHG, Scholes RJ, Bruford MW et al (2013) Essential biodiversity variables. Science 339:277–278. https://doi.org/10.1126/science.1229931
Renn O (2008) Risk governance. Coping with uncertainty in a complex world. Earthscan, London
Réunion (2008) Message from Reunion Island: message from the conference "the european union and its overseas entities: strategies to counter climate change and biodiversity loss", Reunion Island, 7–11 July 2008. http://cmsdata.iucn.org/downloads/080711_reunion_msg_en_1.pdf
Ribeiro SP, Borges PAV, Gaspar C, Melo C, Serrano ARM, Amaral J et al (2005) Canopy insect herbivores in the Azorean Laurisilva forests: key host plant species in a highly generalist insect community. Ecography 28:315–330. https://doi.org/10.1111/j.0906-7590.2005.04104.x
Rickart EA, Balete DS, Rowe RJ, Heaney LR (2011) Mammals of the northern Philippines: tolerance for habitat disturbance and resistance to invasive species in an endemic insular fauna. Div Distrib 17:530–541. https://doi.org/10.1111/j.1472-4642.2011.00758.x
Ricketts TH, Dinerstein E, Boucher T, Brooks TM, Butchart SHM, Hoffmann M et al (2005) Pinpointing and preventing imminent extinctions. Proc Natl Acad Sci USA 102:18497–18501. https://doi.org/10.1073/pnas.0509060102
Rominger AJ, Goodman KR, Lim JY, Armstrong EE, Becking LE, Bennett GM et al (2016) Community assembly on isolated islands: macroecology meets evolution. Glob Ecol Biogeogr 25:769–780. https://doi.org/10.1111/geb.12341
Schilthuizen M, Vairappan CS, Slade EM, Mann DJ, Miller JA (2015) Specimens as primary data: museums and 'open science'. Trends Ecol Evol 30:237–238. https://doi.org/10.1016/j.tree.2015.03.002
Schmeller DS, Böhm M, Arvanitidis C, Barber-Meyer S, Brummitt N, Chandler M et al (2017) Building capacity in biodiversity monitoring at the global scale. Biodivers Conserv. https://doi.org/10.1007/s10531-017-1388-7
Secretariat of the Convention on Biological Diversity (2014) Global biodiversity outlook 4. Secretariat of the Convention on Biological Diversity, Montréal
Stephenson PJ, Brooks TM, Butchart SHM, Fegraus E, Geller GN, Hoft R et al (2017) Priorities for big biodiversity data. Front Ecol Environ 15:124–125. https://doi.org/10.1002/fee.1473

Strand H, Höft R, Strittholt J, Miles L, Horning N, Fosnight E, Turner W (eds) (2007) Sourcebook on remote sensing and biodiversity indicators. Technical series # 32. Secretariat of the Convention on Biological Diversity, Montreal

Swerhun K, Jamieson G, Smith DJ, Turner NJ (2009) Establishing GLORIA long-term alpine monitoring in southwestern British Columbia, Canada. Northwest Sci 93:101–116. https://doi.org/10.3955/046.083.0202

Tershy BR, Shen KW, Newton KM, Holmes ND, Croll DA (2015) The importance of islands for the protection of biological and linguistic diversity. Bioscience 65:592–597. https://doi.org/10.1093/biosci/biv031

Tuba Z, Slack NG, Stark LR (2011) Bryophyte ecology and climate change. Cambridge University Press, Cambridge

Underwood E, Ustin S, DiPietro D (2003) Mapping nonnative plants using hyperspectral imagery. Remote Sens Environ 86:150–161. https://doi.org/10.1016/S0034-4257(03)00096-8

van Kleunen M, Dawson W, Essl F, Pergl J, Winter M, Weber E et al (2015) Global exchange and accumulation of non-native plants. Nature 525:100–103. https://doi.org/10.1038/nature14910

Van Tooren BF, During HJ, Lensink MJ (1985) The influence of the bryophyte layer on the microclimate in chalk grasslands. Abstr Bot 9:219–230

Vanderbilt K, Gaiser E (2017) The international long term ecological research network: a platform for collaboration. Ecosphere 8(2):e01697. https://doi.org/10.1002/ecs2.1697

Vellend M (2016) The theory of ecological communities. Monographs in population biology 57. Princeton University Press, Princeton

Vellend M, Brown CD, Kharouba HM, Mccune JL, Myers-Smith IH (2013) Historical ecology: using unconventional data sources to test for impacts of global environmental change. Am J Bot 100:1294–1305. https://doi.org/10.3732/ajb.1200503

Walters M, Scholes RJ (eds) (2017) The GEO handbook on biodiversity observation networks. Springer, Berlin. https://doi.org/10.1007/978-3-319-27288-7

Warren BH, Simberloff D, Ricklefs RE, Aquilee R, Condamine FL, Gravel D et al (2015) Islands as model systems in ecology and evolution: prospects fifty years after MacArthur–Wilson. Ecol Lett 18:200–217. https://doi.org/10.1111/ele.12398

Weigelt P, Jetz W, Kreft H (2013) Bioclimatic and physical characterization of the world's islands. Proc Natl Acad Sci USA 110:15307–15312. https://doi.org/10.1073/pnas.1306309110

Weigelt PD, Kissling W, Kisel Y, Fritz SA, Karger DN, Kessler M, Lehtonen S, Svenning JC, Kreft H (2015) Global patterns and drivers of phylogenetic structure in island floras. Sci Rep 5:12213. https://doi.org/10.1038/srep12213

Weiss KR (2015) Before we drown we may die of thirst. Nature 526:624–627. https://doi.org/10.1038/526624a

Whittaker RJ, Fernández-Palacios JM (2007) Island biogeography: ecology, evolution, and conservation, 2nd edn. Oxford University Press, Oxford

Whittaker RJ, Fernández-Palacios JM, Matthews TJ, Borregaard MK, Triantis KA (2017) Island Biogeography: taking the long view of nature's laboratories. Science 357:eaam8326. https://doi.org/10.1126/science.aam8326

Zlinszky A, Mücke W, Lehner H, Briese C, Pfeifer N (2012) Categorizing wetland vegetation by airborne laser scanning on Lake Balaton and Kis-Balaton, Hungary. Remote Sens 4:1617–1650. https://doi.org/10.3390/rs4061617