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The biodiversity survey of the Cape (BioSCape), integrating remote sensing with biodiversity science

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There are repeated calls for remote sensing observations to produce accessible data products that improve our understanding and conservation of biodiversity. The Biodiversity Survey of the Cape (BioSCape) addresses this need by integrating field, airborne, satellite, and modeling datasets to advance the limits of global remote sensing of biodiversity. Over six weeks, an international team of ~150 scientists collected data across terrestrial, marine, and freshwater ecosystems in South Africa. In situ biodiversity observations of plant and animal communities, estuaries, kelp, and plankton were made using traditional field methods as well as novel approaches like environmental DNA and acoustic surveys. Biodiversity observations were accompanied by an unprecedented combination of airborne imaging spectroscopy and lidar measurements acquired across 45,000 km^2. Here, we review how the approaches applied in BioSCape will help us measure and monitor biodiversity at scale and the role of remote sensing in accomplishing this.

With over one million species' existence threatened, it is widely recognized that we are in the midst of a sixth mass extinction[1]. Safeguarding biodiversity demands that the "best available data, information and knowledge, are accessible to decision makers, practitioners and the public"[2]. Creating global biodiversity data products is complex; biogeographic zonation and independent evolutionary histories combined with climatic and environmental variation make biodiversity intrinsically site-specific and one-size-fits-all solutions inappropriate. High-fidelity biodiversity data products require local knowledge and field data, which can be labour intensive and expensive to collect. Recently, technological advancements in survey techniques have increased field data coverage, but spatio-temporal gaps in these measurements persist[3]. Next-generation remote sensing technology and models can help fill gaps in field data and produce integrated multi-scalar data sets that accelerate biodiversity product generation and improve tracking of progress towards conservation targets[4–7]. Due to the novelty of such approaches, there is an urgent need to better understand the potential and limitations of integrated field, remote sensing, and modeling datasets for measuring and monitoring biodiversity globally[8].

Integrated multi-scalar datasets are useful for uncovering the ecological processes responsible for observed patterns in species abundance and distribution and their change in time and space[9]. For example, integrated airborne imaging and field spectroscopy datasets allow the analysis of biodiversity and its relationship to ecosystem function continuously across communities and environmental gradients[10–13]. The addition of three-dimensional structural information to these datasets further enhances their ecological applications[14]. Looking forward, integrated datasets will increasingly include measurements from novel field survey approaches, such as autonomous sound recordings and environmental DNA (eDNA), often combined with citizen science observations[15,16]. Integrated datasets will also more prominently feature next-generation satellite products like light detection and ranging (LiDAR, herein lidar) and other structural data as well as ultraviolet (UV), visible to shortwave infrared (VSWIR), and thermal infrared (TIR) data from imaging spectrometers, as these expand in area covered, spatial resolution, and temporal latency[17–19].

Quantifying the opportunities and shortcomings of Open Access integrated datasets to conserve biodiversity has never been more important.

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Addressing this need motivated the US's National Aeronautics and Space Administration's (NASA) first field campaign focused on biodiversity - the Biodiversity Survey of the Cape (BioSCape)—which took place in South Africa in late 2023. Here, we introduce BioSCape, discuss the motivations for choosing South Africa, and review how the campaign advances remote sensing of biodiversity.

The Biodiversity Survey of the Cape

BioSCape pairs diverse field measurements made on land and in water with remotely sensed airborne and satellite observations to better understand the structure, function, and composition of ecosystems and how and why they are changing in time and space. BioSCape is organized around three research themes (Fig. 1):

1. Shifting community composition;
2. Ecosystem disturbance, resilience, and recovery; and
3. Ecosystem function and nature's contributions to people.

Field data were collected by 19 individually funded research projects, each with separate but coordinated objectives (see Expected Contributions). BioSCape's field data set is unique in its diversity and scope—containing novel and traditional field survey measurements in many types of aquatic and terrestrial ecosystems and across multiple environmental gradients. Terrestrial field observations included surveys of more than 600 vegetation plots in protected areas across environmental gradients and additional surveys done in estuarine ecosystems and in landscapes heavily invaded by invasive alien plants. Terrestrial observations also included multi-season sampling of water, soil, and sediment environmental DNA (eDNA) at 36 sites across two watersheds and audio recordings of birds and frogs at more than 500 sites across the region. In the aquatic realm, observations included kelp forest composition and physiological condition at 15 sites as well as biomass, abundance, and taxonomic identification of phyto- and zooplankton functional types in four marine bays and four freshwater bodies.

Contemporaneous airborne data were acquired using six sensors aboard two NASA and one South African Environmental Observation Network (SAEON) aircraft in October and November 2023. UV and VSWIR measurements were collected by the Airborne Visible/Infrared Imaging Spectrometer-Next Generation (AVIRIS-NG)[20] and the Portable Remote Imaging Spectrometer (PRISM)[21] integrated onto a NASA Gulfstream III aircraft, while the Hyperspectral Thermal Emission Spectrometer (HyTES)[22] and the Land, Vegetation, and Ice Sensor (LVIS)[23] were integrated onto a NASA Gulfstream V to collect TIR and full-waveform lidar measurements respectively. At select coastal sites, additional discrete return lidar data (~10 points per metre) were acquired at by an ELMAP-V instrument and high-resolution colour imagery (~13 cm pixels) were acquired by a 46MP Nikon D850, both integrated onto the SAEON Airborne Remote Sensing Platform. BioSCape's airborne dataset is unique in its spectral and spatial resolution, covering much of the electromagnetic spectrum at ~2–15 m ground sample distance (Fig. 2). BioSCape's imaging spectrometers provide data in nearly 1000 well-resolved bands from 350 nm (UV) to 12,000 nm (TIR) at a resolution of 3.5 nm in the UV range to 5 nm in the SWIR range and 17.6 nm in the TIR range. The addition of coincident full-waveform large-footprint lidar acquisitions (1064 nm-wavelength laser) as well as discrete return lidar (1030 nm laser pulse) complement the optical measurements. Accompanying the airborne measurements are numerous satellite acquisitions, including 240 scenes from EMIT[24], 101 from ECOSTRESS[25], 1,051 from Sentinel-2[26], 168 from Landsat[27], and historical GEDI coverage[28]. BioSCape thus represents one of the few combined field, airborne, and orbital spectral and structural datasets available. While the airborne data is collected once off, it will serve as a powerful resource to explore the boundaries of remote sensing for biodiversity measurement across diverse aquatic and terrestrial ecosystems, and through time via links with ongoing satellite acquisitions[29].

Why South Africa?

BioSCape is focused on the Greater Cape Floristic Region (GCFR) of South Africa. The GCFR is home to astonishing levels of biodiversity, wicked conservation challenges[30,31], and a well-developed and progressive

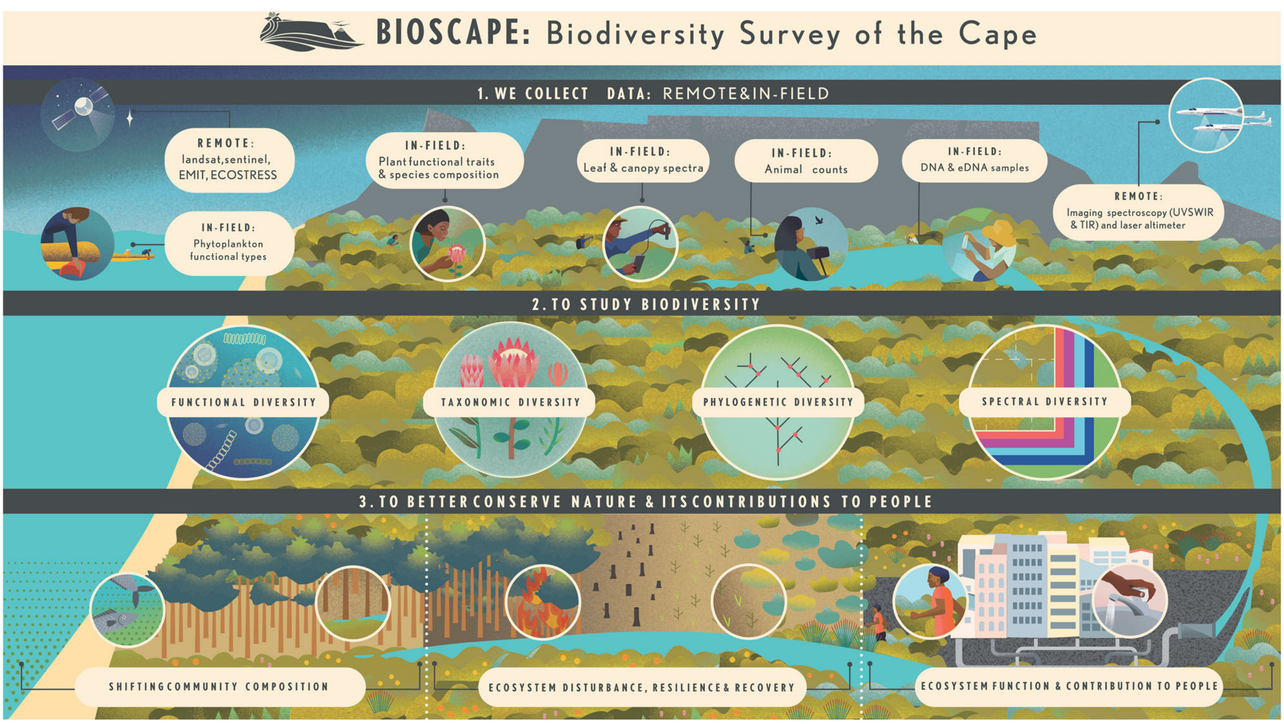

Fig. 1 | BioSCape is an integrated remote sensing and field campaign. Airborne data were acquired contemporaneously with a variety of field measurements of biodiversity. These data are processed through models and algorithms to produce products that inform our understanding of functional, taxonomic, phylogenetic, and spectral dimensions of biodiversity. Applying these biodiversity data products will help inform the measuring and management of biodiversity resources and nature's contribution to people (Artwork created by J.Silver under contract with BioSCape).

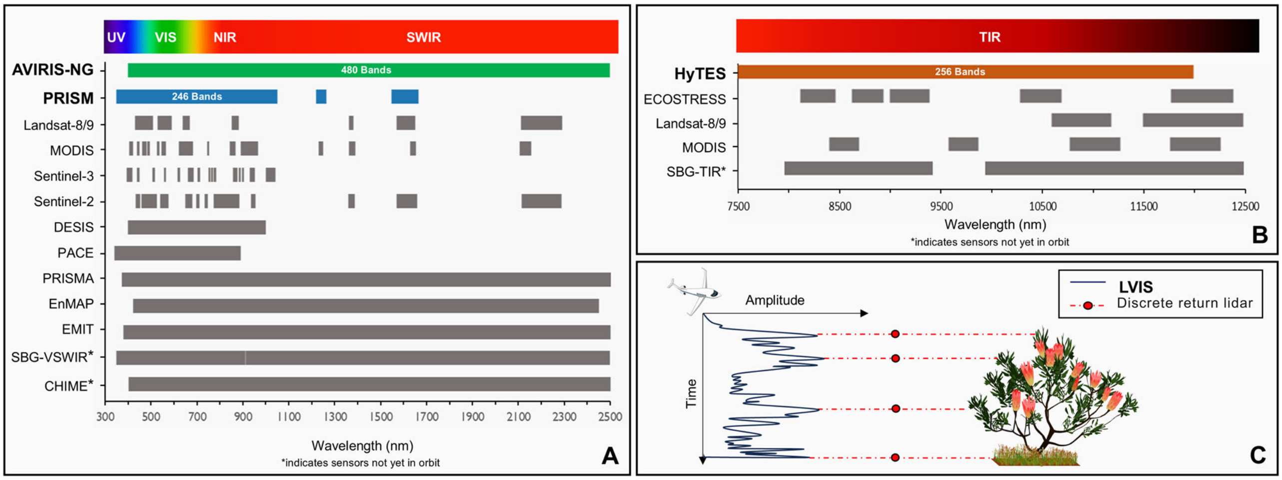

Fig. 2 | BioSCape's airborne dataset includes spectroscopic measurements across the electromagnetic spectrum and full waveform lidar measurements. This figure summarizes the key spectral characteristics of BioSCape's three imaging spectrometers and compares them with commonly used instruments with free and open access data policies, and anticipated future missions. **A** Data were collected across the electromagnetic spectrum, from 350 nm (UV) to 2500 nm (SWIR) using AVIRIS-NG and PRISM and **B** from 7500 nm to 12 000 nm (TIR) using HyTES, at a resolution of 3.5 nm in the UV range to 5 nm in the SWIR range and 17 nm in the TIR range. **C** Full waveform airborne lidar data were also acquired using the LVIS instrument. LVIS measures the full distribution of returned laser pulses to the active sensor, capturing more information about topography and vegetation structure than standard discrete return airborne lidar sensors, which typically capture 1-4 discrete points from a single laser pulse. (Artwork in 2c created by A. Ibrahim and J.Flora under contract with BioSCape).

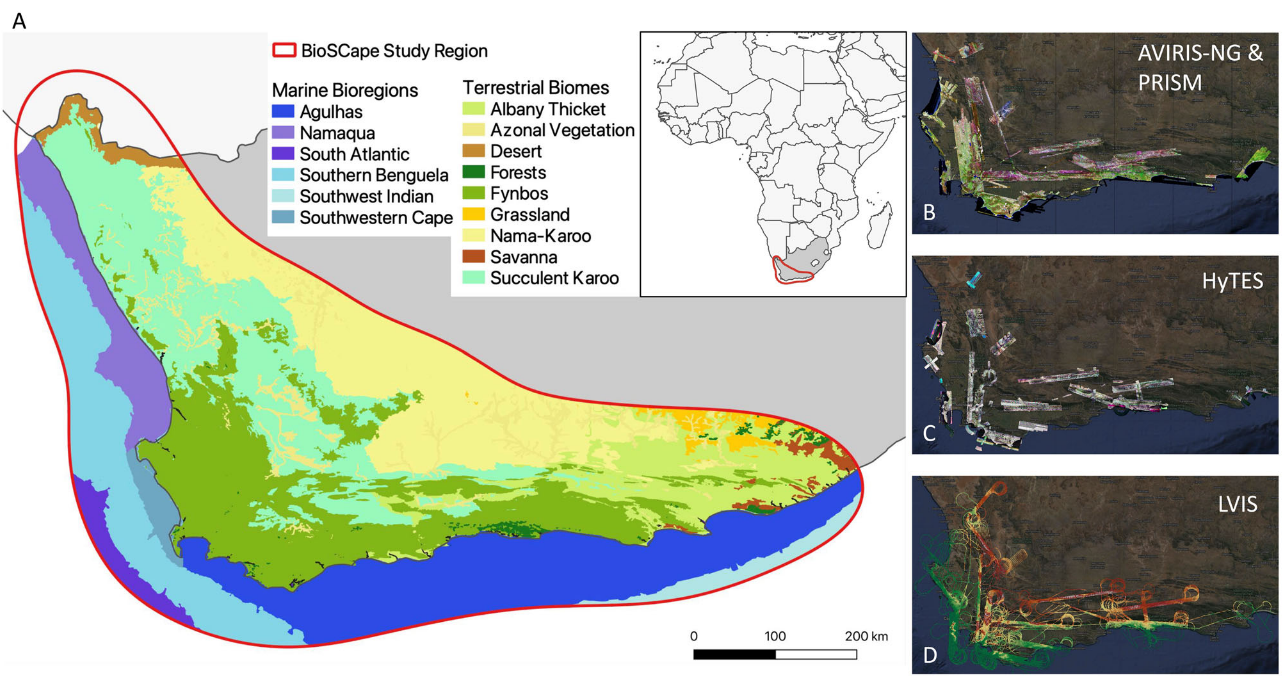

Fig. 3 | BioSCape collected airborne data across several terrestrial biomes and marine bioregions. **A** Terrestrial biomes and marine bioregions of the BioSCape study area (the Greater Cape Floristic Region) in the South-Western corner of South Africa and (**B**–**D**) Airborne data coverage by four of the airborne instruments over the study area. (**B**–**D** are screengrabs from the BioSCape Data Portal, popo.jpl.nasa.gov/mmgis-aviris/?mission = BIOSCAPE).

biodiversity research and conservation community[32,33], together providing fertile ground for local impact and global lessons.

A megadiverse mesocosm of global challenges

The GCFR includes the intersections of eight terrestrial and six marine biomes and is known for its extreme topographic and environmental heterogeneity (Fig. 3). It is home to two of the world's richest biodiversity hotspots, containing some 11,500 species of vascular plants, of which 78% are endemic to the region[34,35]. The GCFR is also where the cold Benguela and the warm Agulhas Currents meet, leading to regional peaks in marine biodiversity and some of the highest levels of marine endemism globally, with up to a third of about 13,000 marine species being endemic[36–38]. The GCFR's freshwater aquatic systems also display high amounts of endemism in their fish, frogs, and invertebrate fauna and are listed among the World's 200 Significant Ecoregions[39].

Like many regions worldwide, the GCFR needs to support human development while conserving its biodiversity in the face of climate change. The region is increasingly drought-prone and the oceans are experiencing rapid warming of offshore ocean currents and upwelling intensification with further increases in ocean temperature, ocean acidity, and storm frequency predicted[40–42]. Climate change effects are compounded by significant and somewhat stochastic community reorganization after disturbance by fire or hydrological shocks and by pressure from dense human populations[43,44]. As a result, the GCFR has the second highest documented number of vascular plant extinctions in the world, over half of marine and coastal ecosystems are threatened, and nearly half of marine fisheries are over-exploited or collapsed[38,45].

A region of challenges and opportunities

The megadiverse GCFR presents a challenge for remote sensing of biodiversity. On land, the high plant richness is the result of the radiation of a limited number of lineages, which, together with convergent evolution of similar traits among different lineages, has resulted in large numbers of species that are difficult to distinguish[46,47]. From a remote sensing perspective, this is aggravated by shrubs being small enough that multiple individuals, and possibly multiple taxonomic groups, are often present in a single pixel. The extreme topography of the region also makes post-processing of remote sensing data difficult and can compromise data quality. In aquatic environments, the optical characteristics and complexity of freshwater and marine environments vary wildly based on nutrient availability and excess. These issues, combined with variations in sediment loads and dissolved organic carbon concentrations that are driven in part by highly localized vegetation and land cover characteristics and land-to-sea biogeochemical transformations, make the applicability of globally-calibrated algorithms challenging for the region[48–50]. A lack of aquatic bio-optical datasets in the global south confounds these challenges. In selecting the GCFR, we hope to push the best available technology and theory up to and beyond its current limits, thereby highlighting areas for future research that will result in even broader utility.

Local impact and global lessons

South Africa is a well-known early adopter of systematic conservation planning and has been relatively successful in operationalizing scientific findings into government policy and decision-making[51]. The local scientific community is deeply engaged with research that speaks to the information needs of stakeholders, and BioSCape has strongly emphasized incorporating local knowledge from its inception[33,52]. We expect that BioSCape's data products will feed into the GCFR's established pathways from science to application. In doing so, we hope that BioSCape can help set an example of science diplomacy and research for good.

Expected Contributions

All BioSCape data products will be Open Access, and will be accessible through a cloud computing environment throughout the analytical stage of the project. In addition to the regularly delivered Level 1 and 2 airborne data products, BioSCape is also producing Level 3 orthomosaics of surface reflectance from AVIRIS-NG and PRISM, relative heights from LVIS, and possibly surface temperature and emissivity from HyTES. These orthomosaics will be co-registered to a common grid with a common spatial resolution (5×5 m, with select regions at 2×2 m). This level of data harmonization is unprecedented for an Open Access multi-sensor airborne campaign and we hope will set a new standard for data accessibility[53]. BioSCape's data analysis workflows, including airborne data harmonization, will also largely be open source and made available with publications and/or on public GitHub repositories versioned with a DOI, and all data will be made available through the Oak Ridge National Laboratory Distributed Data Archiving Centre[54]. This will increase interoperability of data products and the reproducibility of the science. In this section, we summarize how the campaign is using data optimized for usability to test the limits and potential of remote sensing for global biodiversity applications.

The spatial resolution of BioSCape pixels, while finer than any spaceborne spectroscopic measurements to date, are typically coarser than the individual organisms being studied and result in pixels with mixed spectral signatures. While one can often identify the endmembers (species or cover types) contributing to the mixed signal using spectral unmixing (e.g.[55], another approach is to look at the diversity of spectral signatures across a window of pixels. Spectral diversity has been shown to predict functional and phylogenetic diversity as well as ecosystem function, although there are limitations to this approach[56–58]. Methods like Intrinsic Dimensionality (ID), that allow us to estimate spectral diversity without training data, are some of the few viable approaches to map biodiversity at a global scale using comparable metrics across geographic regions[59–62]. Measures of spectral beta diversity can be combined with statistical techniques such as Generalized Dissimilarity Modeling or Spatial Generalized Dissimilarity Mixed Modeling to explore drivers of spectral turnover or to estimate spectral gamma diversity[63,64]. ID has been used to estimate diversity in marine phytoplankton communities and tropical forest and desert landscapes, but it has never been extensively calibrated with field observations, with multiple sensors, and across environmental or diversity gradients[61,65]. BioSCape represents the largest application of ID to field data and will help us delineate what this promising method can do for remote sensing of biodiversity at the global scale.

Spectral signatures are inherently a combination of the underlying structure and chemistry of the system; put another way, functional traits define the spectroscopy of plants. Pixels with similar spectral signatures, so called "spectral species"[66,67], and their associated functional traits can be mapped across a landscape[68]. In land plants, certain functional traits can be mapped using empirical relationships derived between field-measured trait values and associated airborne spectral reflectance values[69,70]. This approach works for single sites and can work for regions, but it struggles to scale further since the calibration relationships can be site-, and sensor-, or date-specific[69]. The challenge of parameterizing spectra-trait relationships that are applicable globally is further exacerbated by the geographic bias in imaging spectroscopy data acquisition. To date, very little imaging spectroscopy has been acquired on the African continent. BioSCape provides a unique opportunity to test the potential impact of this geographic bias and will compare similar ecosystems across continents and assess both the difference in calibration equations and the accuracy of these equations to map functional traits from remotely sensed imagery[71]. The BioSCape AVIRIS-NG acquisitions, the first from this sensor on the African continent, are well placed to be compared to the extensive acquisitions along the West Coast of the United States - which has, in parts, a similar climate and vegetation biome to the GCFR. Once functional traits have been mapped, they can be clustered and examined with environmental variables and structural data to better understand the drivers of biodiversity and inform conservation decisions[72].

Leaf spectra have been demonstrated to correlate with plant phylogenetic history[73]. Phylogenetic diversity does not perfectly align with functional diversity due to trait convergence, which causes different lineages living in similar environments to develop similar functional traits. When evaluated with spectral and functional diversity, phylogenetic diversity can provide deep insight into the drivers of functional trait variation across abiotic gradients and spatial scales[74]. The links between spectral, functional, and phylogenetic diversity have been explored for the BioSCape study region using leaf-level data[56] but can now be tested using airborne and satellite remote sensing data. The astonishing levels of taxonomic diversity and yet surprisingly low variation in physiognomy in this biodiversity hotspot will test the limits of these methods[47].

In aquatic environments, remote sensing of biodiversity is challenging as vegetation and phytoplankton are often partially or entirely submerged in water, interfering with their spectral signature. In coastal and inland waters, high concentrations of suspended sediments or coloured dissolved organic matter (CDOM) also make it difficult to detect and discriminate between different plant and phytoplankton functional types[75,76]. Adding to this challenge, the water leaving signal is a very small component of the overall signal received by the sensor (usually less than 10%)[77]. To resolve phytoplankton and plant functional types, a sensor must have a high signal-to-noise ratio to detect small changes to water-leaving radiances and distinguish these from the water and atmospheric radiance measurements. Additionally, the sensor needs to capture high spatial resolution data, since freshwater floating plants and marine kelp may be limited in their extent, and data must be collected with relatively low solar zenith angles to avoid sunglint from impeding the signal[78–80]. BioSCape's data over coastal and inland waters has a high spatial (~1–15 m) and spectral resolution and excellent signal-to-noise ratios, with PRISM having a ratio of 500 or more to one at 450 nm. By coupling PRISM and AVIRIS-NG on the same platform, BioSCape made simultaneous spectral measurements across the UV to the SWIR, which may enable improvements in corrections for sunglint and aerosols to enhance remote sensing detection of aquatic biodiversity. When coupled with the near-simultaneous acquisition of thermal imaging spectroscopy from HyTES, this is the first time that such detailed radiance measurements have been collected by multiple spectrometers concurrently with field measurements at the confluence of major oceanic currents and over freshwater bodies.

Detecting change in biodiversity is difficult, as any departure from expected radiance or reflectance values needs to be attributable to a change in community composition or ecosystem function rather than a background change in the atmosphere or water column values. One can use first-principle physical laws to address this attribution challenge by using radiative transfer models (RTMs) to generate synthetic background or baseline measurements of a system[81,82]. RTMs' synthetic measurements can be compared to measured radiance and reflectance values to help disentangle disturbance signals from background noise. RTMs are especially useful for remote sensing of phytoplankton communities, where differentiating signals from the water column and the target communities is difficult[83]. RTMs are also useful in terrestrial plant communities where there is high natural variability through space and time and thus departures from the "natural" state of the ecosystem can be hard to detect unless one has a suitable model of the expected signal of a "natural" state[84,85]. In inland and coastal waters, BioSCape's innovative combination of sensors will facilitate development and testing of new machine learning algorithms, making an essential contribution to water quality measurement and monitoring[86]. On land, BioSCape will use 3D RTMs to develop synthetic reflectance datasets for several different vegetation types that will be compared to terrestrial and airborne lidar and airborne imaging spectroscopy datasets[87]. These next-generation RTMs can assist in detecting alien plant invasions and abnormal post-fire vegetation recovery trajectories, as well as provide baseline datasets for various functional and structural trait measurements.

In the GCFR and other Mediterranean ecosystems, one of the most widespread changes in community composition and threats to biodiversity is the increase in the abundance of invasive alien plants[88]. Invasive alien plants decrease biodiversity by replacing indigenous plant species and disrupt the normal fire regime by altering fuel loads and fire severity and frequency[89,90]. Invasive alien trees in the region also alter ecosystem function by dramatically increasing water use and evapotranspiration while decreasing runoff and groundwater recharge[91–93]. Groundwater-dependent ecosystems provide many contributions to people, including ensuring water quality, and their sensitivity to invasive alien trees and groundwater abstraction is largely unknown as the linkages between surface and groundwater are highly complex[94]. BioSCape will combine spectral information with structural information to quantify and map alien invasive trees, flammable fuel loads, and water use efficiency across various invaded landscapes as well as groundwater dependent ecosystems in the region.

Changes in aquatic community composition can affect ecosystem function and services. For example, phytoplankton functional type and abundance are key determinants of water quality, kelp forests support healthy fish populations, remove nitrogen from the water column and may act as blue carbon stores, while estuaries play a role in coastal protection and maintenance of fisheries[95–97]. BioSCape will develop and apply algorithms for airborne spectroscopy to map phytoplankton functional types based on their accessory pigments and to map kelp forest extent and physiological condition. By developing these algorithms for multiple marine and, where relevant, inland water bodies across anthropogenic and environmental gradients, BioSCape will contribute towards harmful algal bloom and kelp forest monitoring efforts. Additionally, BioSCape will map estuarine biodiversity variables to make predictions about how these systems' contributions to people may change with changes in climate, especially sea level rise. All of these research objectives will have global applicability, but are especially important to address in water scarce regions with little redundancy in drinking water supply and in places with economically important fishing and aqua- and agri- culture industries, as is the case in the GCFR[98,99].

Understanding the complex links between biodiversity, ecosystem function, and nature's contribution to people requires not only different types of remote sensing data but also an abundance of high-quality field measurements. Technological advancements in field methods have changed the type and increased the amount of low-cost high-coverage biodiversity information we can collect. The novelty of these field biodiversity measurements means they have not yet been reliably related to remotely sensing biodiversity information. For example, multi-locus metabarcoding of eDNA from soils, sediment, and water can extend species identification to microorganisms and non-vascular plants, in addition to the vascular plants and vertebrates captured in traditional field surveys[5,15]. These molecular methods can facilitate new insights into the organization of ecological communities - for instance, eDNA samples collected in rivers can provide an integrated field-based measure of biodiversity across the entire watershed and can be better than traditional surveys at detecting small, rare, or otherwise cryptic species[100,101]. Genetic composition is the only Essential Biodiversity Variable class "not yet measurable from space"[7]. To address this gap, BioSCape will correlate ground-based eDNA estimates of allelic diversity with remotely sensed diversity metrics across multiple watersheds and along a gradient of human influence. Such an approach has been successfully trialed in California[5], and BioSCape hopes to advance this field significantly. Like eDNA, autonomous recording units deployed across a landscape allow us to gather biodiversity information about birds, frogs, and other potential indicator species over large areas quickly and at relatively low cost[16,102–105]. BioSCape will aim to link acoustic diversity with plant and structural diversity determined from airborne spectroscopy and lidar data. Both eDNA and acoustic diversity provide novel biodiversity information that, when paired with remote sensing data, has great potential to improve the accuracy of biodiversity measurement at regional to global scales.

Conclusion

Addressing biodiversity loss is a global priority and there is a clear need to improve our ability to map and monitor change. Due to its complexity, the GCFR represents one of the most challenging environments for remote sensing of biodiversity, but also presents myriad opportunities. BioSCape's findings will advance our understanding of biodiversity in South Africa and have far-reaching implications for global biodiversity science, inclusive international research projects, data-driven conservation, and effective ecosystem management. All BioSCape data are Open Access and will be made available through the Oak Ridge National Laboratory Distributed Data Archiving Centre[54]. The project's innovative methods and insights will help define the potential and the limits of biodiversity measurement and monitoring using remote sensing. In doing so, we hope BioSCape can guide the development of appropriate biodiversity proxies that can be observed from space, ultimately contributing to preserving our planet's rich biodiversity.

Data Availability

No datasets were generated or analysed during the current study.

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Competing interests

The authors declare no competing interests.

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