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EDITED BY
Sandra MacFadyen,
Stellenbosch University, South Africa

REVIEWED BY
Judith Botha,
South African National Parks, South Africa
Hayley Clements,
Stellenbosch University, South Africa

*CORRESPONDENCE
Fatima Parker-Allie
F.Parker@sanbi.org.za

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A conceptual approach to developing biodiversity informatics as a field of science in South Africa

Fatima Parker-Allie[1,2*], Mark J. Gibbons[2] and Douglas M. Harebottle[3]

[1]South African National Biodiversity Institute, Foundational Biodiversity Science, Cape Town, South Africa, [2]Biodiversity and Conservation Biology Department, Faculty of Natural Science, University of Western Cape, Cape Town, South Africa, [3]Risk and Vulnerability Science Centre, School of Natural and Applied Sciences, Sol Plaatje University, Kimberley, South Africa

In South Africa, as in other parts of the world, *Biodiversity Informatics* (BDI) has been identified as a young field of science that lies at the nexus of several disciplines, including informatics, biology and mathematics/statistics. Being such a new and dynamic field, there are challenges in the recruitment, training and retention of personnel that can support *inter alia* the mobilisation, management, coordination, and utilisation of biodiversity information for key conservation and biodiversity outcomes. The lack of human capital also place at risk the implementation of (e.g.) the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES), and hinders attainment of the Convention on Biological Diversity post-2020 framework targets. There is a clear demand for broad efforts to build human capital in the field. Using our experiences in South Africa, we provide a framework for establishing BDI as a field of science in developing countries and look at the potential building blocks towards this broad objective, including the need and requirements for the establishment of a Centre for BDI. We explore this concept against a backdrop of the South African government's 2019 White Paper on *Science, Technology and Innovation*, and the associated Decadal Plan, both developed under the auspices of the *Department of Science and Innovation*. We also reflect on efforts in the broader landscape to look at the establishment of BDI curricula.

KEYWORDS

biodiversity informatics, framework, science–policy interface, science technology & innovation (STI) policy, universities & higher education institutions, capacity development, training & development, elearning

Introduction

The South African science landscape has evolved dramatically since the dawn of democracy through government's commitment to transform the inward-looking and embattled sector into a system that is innovative, flexible and responsive to the needs of our society (DST, 2007). South Africa's prospects for improved competitiveness and

economic growth rely, to a great degree, on science and technology. Its ten-year innovation plan (DST, 2007) is built on the foundation of the *National System of Innovation*, and recognizes that the country needs to take further steps to becoming a knowledge-based economy in order to meet its developmental objectives (Manzini, 2012; DSI, 2021): the *National System of Innovation* is an organising framework for policies and institutions supporting the knowledge economy. In this review, South Africa's role in the Global Biodiversity Information Facility (GBIF) and the potential role that *Biodiversity Informatics* (BDI) can play in meeting a stronger *Science, Technology and Innovation* agenda ((DST, 2019; DSI, 2021) is explored (see Box 1).

The field of BDI deals with the interrelated challenges of collection, collation, integration, analysis, prediction, and dissemination of data and information related to the diversity of life on Earth (Hobern et al., 2012; Hardisty et al., 2013; Walters & Scholes, 2016). It is a field that has been massively enhanced following developments in information technology (Berners-Lee, 1999), which have led to exciting new opportunities for data consolidation and interchange (Chapman, 2005). Today, BDI is regarded as the application of informatics techniques to biodiversity data, with much of biodiversity informatics resting on physical objects that ground the digital information i.e., specimens of organisms (Parr and Thessen, 2018).

In the last two decades there has been an unprecedented increase in the acquisition of actual biodiversity data and data types, driven by mobile-cellular applications, sensors, mass digitization and next generation sequencing. More recently, public participation in research ("community science") has led to an increase in the mobilisation of biodiversity data. One such initiative is the United States National Science Foundation's iDigBio (Integrated Digitized Biocollections) which has mobilized more than 120 million specimens held in national institutions, and similar efforts are continuing in parallel across the world (Nelson and Ellis, 2018). New observation-based records collected by community science platforms have proliferated (eBird has >1 billion records whilst iNaturalist has >58 million (Auer et al., 2022; iNaturalist Contributors, 2023), outpacing museum specimen digitization by orders of magnitude (Chandler et al., 2017; Troudet et al., 2018).

The infrastructure (knowledge management systems) linked to BDI-based research, such as GBIF or the *Ocean Biodiversity Information System*, enable users to navigate and put to use vast quantities of biodiversity information. This can be used to advance scientific research in areas such as (e.g.) agriculture and conservation (GBIF Secretariat, 2022b), while species distribution modelling (Anderson et al., 2016) allows for the management of alien species (Faulkner et al., 2014) and understanding the possible impact of climate change on biodiversity (Burrows et al., 2019) and human health (Peterson, 2009).

The accessibility of data serves the economic and quality-of-life interests of society, and provides a basis from which our knowledge of the natural world can grow rapidly in a manner that avoids duplication of effort and expenditure (OECD, 1999; Parker-Allie et al., 2021). While opportunities abound for this new and dynamic field to impact many areas of science linked to human well-being, there is a critical need for increased capacity enhancement precisely because it is an emerging field – especially so in South Africa and other developing countries (Schalk, 1998; Sarkar, 2009; Parker-Allie et al., 2021).

The global context for biodiversity informatics

Global changes, including those with a socio-economic, geopolitical, scientific, technological, or environmental basis, have profound implications for the *National System of Innovation* in South Africa. Inter- and transdisciplinary knowledge is increasingly important, as research becomes progressively more data-driven (OECD, 2013a; Visalli et al., 2020), with greater access to existing information being facilitated by an open science approach (UNESCO, 2021). The success of South Africa's response to the Fourth Industrial Revolution will depend on how well we exploit the pivotal role of information and communication technology (ICT) and harness the potential of big data (DSI, 2022). With the increase in data volumes, velocity and types, data have become a core asset that can create a significant competitive advantage and drive innovation, sustainable growth and development (OECD, 2013a).

Box 1. Growing the knowledge economy through enhanced STI efforts

Data can be described as key elementary units of new knowledge, with data-driven initiatives like the South African National Biodiversity Institute – Global Biodiversity Information Facility (SANBI-GBIF) strengthening South Africa's role for enhanced activities in *Science, Technology and Innovation*. Knowledge provides the basic capital for innovation, through generation, accumulation and exploitation (OECD, 2013b). Economic growth is driven by innovation, and the key driver for innovation is "high-end" human capital. In South Africa, there is a need to significantly strengthen both the production of human capital and the institutional environment for knowledge generation and this can best be done with the collaborative assistance of international partners (DST, 2007). This especially as a growing percentage of the wealth in the world's largest economies is created by knowledge-based industries that rely heavily on human capital and technological innovation (Hadad, 2017; Department of Science and Technology, 2019).

In the "Scientific Impact of Nations", King (2004) made a correlation between the economic wealth of 31 nations and their "citation intensity", where citation intensity was used as a proxy for investment in science and technology. In King's (2004) study, South Africa was clustered with Brazil, South Korea, Russia, China and Poland at the lower end of the spectrum. This demonstrates that if South Africa wishes to increase its economic growth, it needs to prioritize an increased investment in research capacity and development output (DEA, 2016; DST, 2019; DSI, 2021). One of the methodologies that can be used to measure readiness for the knowledge economy is the Global Knowledge Index. This index builds on the Knowledge Economy Index (World Bank, 2012), and measures the knowledge performance of countries based on a country's general "enabling environment", and six other components. The latter include the levels of (1) pre-university education, (2) technical and vocational education and training, (3) higher education, (4) research, development and innovation, (5) ICT, and (6) the economy.

Initiatives such as GBIF fully support these philosophies as they enable vast amounts of data to be published in an open access manner through a knowledge management platform. South Africa's membership to GBIF encourages efforts to grow capacities in BDI. This intergovernmental mega-science, data-driven initiative provides a solid foundation for South Africa to implement its capacity development efforts in BDI, building as it does on the fact that training and capacity development are integral to GBIF's Implementation Programme (GBIF, 2022a).

At the global level the Global Biodiversity Informatics Outlook (Hobern et al., 2012) provides a framework for BDI, as it aims to harness the immense power of information technology and an open data culture to gather unprecedented evidence about biodiversity and so inform better decision-making. It proposes action in four key areas i.e. data, culture, evidence and understanding (Hobern et al., 2012). This framework, can be applied to the national biodiversity landscape, to help focus BDI effort and investment.

National mandates and initiatives to support biodiversity data mobilization and growing biodiversity informatics science in South Africa

The South African National Biodiversity Institute (SANBI), as a knowledge management institute, has a mandate to "collect, generate, process, coordinate and disseminate information about biodiversity and sustainable use of indigenous biological resources and maintain databases" in line with the National Environmental Management: Biodiversity Act, No. 10 of 2004. It supports data sharing and harmonising the sharing of biodiversity data through efforts such as knowledge-brokering (Godfrey et al., 2010), which it effects between its network of partners.

In support of this mandate, a Memorandum of Understanding (MoU) was signed between national government and GBIF in 2004. The establishment of the South African GBIF Node, initially called the South African Biodiversity Information Facility, represented a commitment by national government to the sharing and publishing of biodiversity data and to support open science and open access philosophies (The African Open Science Platform, 2018; UNESCO, 2021).

Growing human capital in biodiversity informatics

BDI is a new and rapidly evolving field of science and as such there are enormous challenges in the recruitment and retention of experienced personnel in biodiversity information management: newly recruited staff often arrive in the workplace without the adequate/appropriate combination of skills required (GreenMatterZa, 2009). The *Biodiversity Human Capital Development Strategy*, for the biodiversity sector (produced through stakeholder engagement by SANBI and the Lewis Foundation, which is one of the largest private funders of conservation activities in South Africa) has identified several skills, as being of "absolute scarcity". These include, not exclusively, database developers and managers, modellers, curators of biodiversity collections, Geographic Information Systems specialists and technicians and statistical ecologists. ICT specialists and technicians with biodiversity skills, such as systems analysts, web and multimedia developers, applications programmers and database designers and administrators (SANBI and Lewis Foundation, 2010; Rosenberg, 2012), are also thin-on-the-ground. These skills are core to BDI science, and their scarcity has been recognised by the South African Department of Science and Innovation, which has committed to supporting the development of this area of work.

In this paper, we review the efforts that SANBI and its strategic partners have taken to develop human capital in BDI and we provide an account of the processes, philosophies, and approaches that we have taken as a country. South Africa has leveraged its role in big data initiatives like GBIF and drawn from its participation in science–policy platforms, like the *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES) to advance this field of work. The opportunity for South African institutions to look at synergies between BDI tools and techniques, aligned to IPBES efforts around knowledge and data catalysis is also possible, thereby strengthening the ability for BDI to support science–policy endeavours. We believe that the model followed here holds much promise as a template for other countries to also develop a BDI agenda. In the South African context, some important policy drivers are in place, including national mandates, while several interventions were also needed, to drive a stronger human capital agenda for BDI and to grow the field of science. These are elaborated below.

Strategic high-level interventions to support efforts in BDI

In building capacity in BDI, several strategic high-level interventions have been implemented, with some clear outputs (Table 1). In 2007, the first Biodiversity Information Management Workshop was held, thereby initiating the development of a community of practice in biodiversity information management (Figure 1, Table 1). The workshop allowed participants to understand the needs of the community in relation to biodiversity data and how it is being managed across organisations. It also provided an opportunity to discuss community approaches around data sharing and publishing, and how ultimately these data could be analysed and used. Consultations with the community continued at the newly established annual Biodiversity Information Management Forum (BIMF) and later at the Joint Biodiversity Information Management and Foundational Biodiversity Information Programme (BIM-FBIP) Forum. These activities served to provide a national platform to discuss highlights, opportunities and challenges with regards to biodiversity data, data standards, biodiversity information systems, data publishing and data use.

In 2010, a Data Handover Event was held by the national Node to celebrate the publication of millions of primary biodiversity data

TABLE 1 Timeline of SANBI led activities and approximate related costs supporting the Capacity Development in Biodiversity Information Management/BDI (2007–current).

Year	Activity	Outcome	Approximate Costing (ZAR)
2007	The start of national engagements through the Biodiversity Information Management Forum (BIMF), with the aim to harmonise biodiversity information sharing	Capacity Enhancement in BDI and the development of a community of practice in biodiversity information management.	R100,000
2008–2011	Through annual BIMF meetings the idea of building BIM capacity was further supported and strengthened	In 2010 as an outcome of the BIMF discussions SANBI was elected to drive the development of a Centre for BDI, in an endeavour to build capacity in the field	R400,000
2009	A skills profile for Biodiversity Information Management was developed by SANBI		
2010	DST recommended for the development of a Center for Biodiversity Information Management, at the South African Biodiversity Information Facility instead of the acronym (SABIF) data handover event.		R200,000
2010	SANBI's Human Capital Development Strategy Report for the Biodiversity Sector was developed	Biodiversity Information Management skills critical to scarce skills in South Africa	
2011	Training coordinator for BIM Directorate funded by the South African Biodiversity Information Facility (3 years)	• A Learning Network Strategy developed for BIM • Training events were coordinated	R1,100,000
2012	A Priority Skills Report [GreenMatter, 2012] was developed	Biodiversity Information Management components was listed as part of the absolute scarce skills areas, within the top 21 priority skills for South Africa's Biodiversity sector	
2012	SANBI signed an MoU with University of Western Cape (UWC) on the 31st of March 2012, which outlined intended areas of cooperation in teaching, research, technical and policy-related biodiversity issues. Also, to look towards the establishment of a postgraduate research hub.	• High level support from the Deputy Minister of Science and Technology, the Vice Chancellor of UWC and Chief Executive Officer of SANBI • Two academics were in place to support the initiative. One as champion and other costed through a Memorandum of Agreement (MoA)	R1,000,000 SANBI R1,000,000 UWC (co-funding)
2012	SANBI secured funding for two post-doctoral students to work on BDI curricula and development of a research strategy and developing Biodiversity Information content and tools.		R1,400,000
2014	Appointment of first post-doctoral fellow	Focus Area: South African BDI Research Strategy	R100,000 (Running Costs)
2015	Appointment of second post-doctoral fellow	Focus Area: BDI content and tools	R100,000 (Running Costs)
2015	SANBI-GBIF led two sessions at the GBIF Nodes meeting entitled: "Towards a Curriculum for BDI"	• SANBI identified to drive the process for a GBIF endorsed Global Curricula for BDI • A Taxonomic Data Working Group (TDWG) – GBIF Interest Group was established	R60,000
2016	Capacity development Session at Joint BIM-FBIP Forum	• Community engagement and additional interest and support for the roll-out of a Centre identified	R50,000
2020	Appointment of SANBI-GBIF MSc Student (Registered at University of KwaZulu Natal)	• Project title: The phylogeographic diversity and connectivity of intertidal sponges as well as determination of whether substrate type influences species settlement along the East of South Africa	R288,000
2020	Appointment of SANBI-GBIF MSc Student (Registered at Rhodes University)	• Project title: Freshwater Amphipoda in South Africa: diversity, distribution and taxonomic review	R288,000
2020	Appointment of third Post-doc	Research focus: BDI Research and Curriculum Development (Biodiversity Data Science)	R300,000
2021	Services rendered by training experts through both direct funding and in-kind contributions of individuals in terms of people time	• Capacity of stakeholders developed in BDI content areas	R250,000
2022	Funding available for 2 Postdoc appointments		R600,000
			R7,236,000

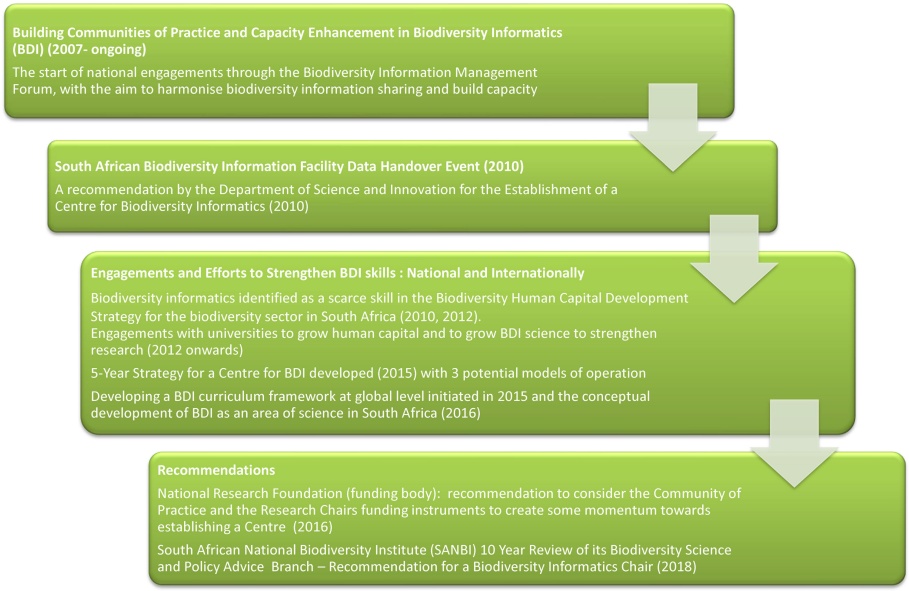

FIGURE 1
Processes, activities and outcomes put in place to support the advancement of BDI.

records to GBIF. Although this event recognized the rewards of investment in BDI by the Department of Science and Innovation (2005–2012), it also resulted in a recommendation being made by national government for the establishment of a Centre for BDI. To achieve this and to grow the field of BDI science, a holistic approach to capacity development was proposed as part of the SANBI-GBIF programme of work. This approach focused on (1) ensuring that relevant, high quality biodiversity information would be available for use by decision makers and managers, and (2) a coordinated network of partners with the commitment and capacity to digitise, share and use biodiversity information would develop. Following engagements with programmes such as GreenMatter[za], which is a national initiative focused on the promotion of human capital and skills development in the biodiversity sector (GreenMatterZa, 2009; Rosenberg, 2012; The Lewis Foundation and SANBI, 2021), it became clear that strategic interventions with other parties would be critical for success. The other parties have included academia, the biodiversity community and national government, as well as the National Research Foundation, which is the primary funding body for research in the country. Moreover, this holistic approach included a series of objectives and activities that are detailed in the discussion below (Figure 2), and a Five (5) Year Strategy for the establishment of the Centre was developed in 2015.

In May 2016, a facilitated session was conducted with the biodiversity science community, at the Joint BIM-FBIP Forum (Box 2). One of the outcomes of that meeting was a series of subsequent engagements with the National Research Foundation to discuss the requirements for a Centre for BDI (detailed later in this study). In line with this, and following an external branch review of SANBI in 2017 (Njobe et al., 2017), it was recommended that the development of a critical mass to enhance Research Leadership was needed. In response to this, a recommendation from SANBI was made in 2018, to explore the opportunity to develop a *Research Chair* in BDI.

Discussion

The need for increasing human capacity in biodiversity information management was identified by the scientific community in South Africa back in 2007 (Willoughby, 2008; GreenMatterZa, 2009; Coetzer et al., 2012), and it continues to be expressed at the annual joint BIM-FBIP Forum of stakeholders (FBIP, 2020). Efforts to support the need for enhanced capacity has been addressed in several ways, through the efforts of SANBI and the SANBI-GBIF Node over time. A holistic approach to capacity development has been developed (Figure 2), especially since efforts has predominantly focused on short-term, work-based training. The composition of participants has mainly been BDI practitioners, biodiversity scientists and personnel from research and government departments nationally, needing specific skills in their work or study area.

The holistic approach taken addresses activities across four strategic objectives (Figure 2): (1) growing relevant skills, (2) building a robust team, (3) improving the quality and use of information, and (4) growing an inspired and coordinated network. Such an approach was aimed at strengthening the national BDI human capital so that a larger pool of professionals would be available to support this growing field of work. It would additionally improve the quality, use and dissemination of biodiversity data and information, and it addresses several of the opportunities and obstacles identified by the Biodiversity Information Management community in the facilitated capacity building session held in 2016 (Supplementary Table 1). These are further elaborated below.

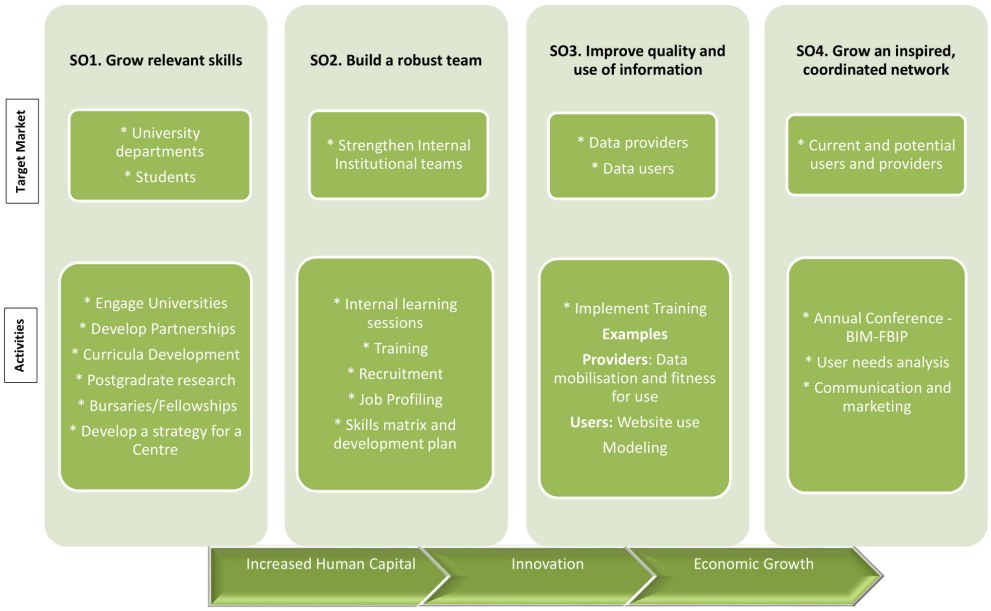

FIGURE 2
A holistic approach to capacity development.

Strategic objective 1. Grow relevant skills in biodiversity informatics

To deliver on this objective, engagements with institutions of Higher Learning are essential (Parker-Allie et al., 2021). Universities provide the existing, enabling physical infrastructure (buildings, lecture halls, laboratories, equipment), the student population and the opportunity to implement a BDI curriculum as a part of undergraduate and postgraduate degree programmes. Capacities can also be developed through research project activities, which often form a key part of postgraduate degrees.

Discussions with universities to support capacity development in BDI, through the establishment of Centres focussed on Biodiversity Information Management activity, have also been conducted (Harebottle et al., 2016). Such centres have the potential to rapidly grow the field of BDI and will have a marked impact for *Science, Technology and Innovation* through the generation of increased MSc and PhD outputs. These centres will also lead to the production of research-led publications, and have innovation and economic outcomes (Department of Science and Technology, 2007; Department of Science and Technology, 2019). As noted earlier, a Five (5) Year Strategy for a Centre for BDI has been developed (Harebottle et al., 2016), and this addresses some of the challenges and opportunities outlined previously (Box 2). Table 1 shows a detailed breakdown of activities and investments over time.

The Five (5) Year Strategy provides detailed guidelines with regards to potential models for a Centre, as well as the requirements and outputs. Three models for a Centre are proposed, with various hosting and co-hosting options by academic institutions, research entities (e.g., SANBI) and partnership links with research organizations and other institutions (Figure 3). The Five (5) Year Strategy (Harebottle et al., 2016) also provides a framework for the development of content and curricula suitable for a BDI honours degree (a postgraduate specialisation following an undergraduate degree) or an extended elective module. Strategic partnerships have already been established (via MoUs and/or collaboration agreements) with the University of Western Cape, the University of Sol Plaatje and University of Cape Town to support capacity development endeavours(Figure 4). These efforts have resulted in the appointment of postdoctoral students, the provision of fellowships and the development of research projects focused on the use of open data, through various data pipelines. BDI course content has also been developed to support undergraduate and postgraduate modules at the University of the Western Cape and Sol Plaatje University (Sol Plaatje University, 2020). Additional efforts to strengthen engagements with academia will continue, especially to support efforts to grow research outcomes and to grow capacities at various levels like MSc and PhD.

Strategic objective 2. Grow a robust internal team

Having a robust internal team that will support capacity development for BDI is essential. A job skills profile was conducted by SANBI in 2012 to understand the skills, scope of jobs, and roles and responsibilities that would be required to adequately support national needs. While this exercise was partly initiated in response to the recruitment of personnel into the organisation and/or sector, it also allowed SANBI and partners to improve the sharing and harmonisation of data, as well as the analysis and publishing of said data. At a more global level, this type

Box 2. National stakeholder engagements and efforts towards the development of a Centre for BDI

The Joint BIM-FBIP Forum in 2016 was attended by over 50 national participants (SANBI, 2016; Supplementary Table 2). Here, SANBI-GBIF led a facilitated session focusing on a holistic approach to capacity development in BDI. This focused on both academic engagements with universities and training programmes/events for professional skills development, with the long-term vision for exploring the requirements, potential opportunities, contributions, and obstacles for establishment of a Centre for BDI. The key objectives of this session were twofold, 1. to determine the issues that delegates thought needed to be unlocked to realise a fully operational Centre for BDI, 2. To determine the key opportunities to move the Five (5) Year Strategy for a Centre towards implementation.

The issues/concerns and opportunities identified by the participants were classified into nine focus areas (Supplementary Table 1). These included: 1 funding, 2 relevant skills required, 3 the need and opportunity, 4 interest and communication, 5 content, 6 partnerships and collaborations, 7 science–policy interface, 8 regional collaboration and 9 institutional buy-in, career relevance and private sector opportunities.

Funding was identified as one of the biggest constraining factors with investments required for infrastructure, sustainability and scholarships, as well as for research into emerging areas and for catalysing affiliations with other institutions. While a key challenge, funding was also recognised as a potential opportunity and it was advised that a fund-raising strategy should be developed. It was also suggested that the opportunity should be leveraged, where institutions were already providing funding for research and postgraduate studies.

The lack of persons with the necessary skills to develop such a Centre, to train students and develop training materials that could also be used to "train-the-trainers" was flagged as critical. In the context of developing potential new multidisciplinary BDI modules, the global curriculum for BDI was discussed, and it was agreed that opportunities for knowledge transfer, international collaboration, exchange programmes and experiential learning should be addressed.

Building collaborations and partnerships between committed partners was considered key to success, and it was suggested that SANBI's network of partners should be leveraged to effect this, especially with tertiary institutions. This would provide, at the very least, experiential learning opportunities. In line with this, it was suggested that co-hosting options should also be considered, to develop a network of collaborators with university partners. Other collaborations identified included partnerships with the science–policy interface Directorate of the national Department of Forestry, Fisheries and the Environment, to mainstream biodiversity data into decision-making. Additionally, exploring avenues or prospects with the private sector was also suggested.

It was recommended that career pathing processes by institutions should be implemented at a strategic level. This includes accessibility to clear development pathways for technical versus academic positions. It was also indicated that the institutions themselves need to recognise and buy-in to the need for information managers, enabling clear opportunities for graduates. Hence, there needs to be a link between supply and demand. Additionally, exploring avenues or prospects with the private sector was also suggested.

of exploration was also conducted for the bioinformatics field of science (Welch et al., 2014).

Strategic objective 3. Improve the quality and use of information

Given that the world is increasingly becoming more data-driven (IEAG, 2014; The Economist, 2016), it is critical that we improve the quality and use of data in the science of BDI. The target markets for training activities can be identified as data providers/publishers and data users. To best support these communities, and various research, data analysis, publishing and use options (Asase and Peterson, 2016; Peterson et al., 2018; Freeman and Peterson, 2019), training has been identified as critical. This will enable the mobilization and publishing of high quality data which is fit-for-use (Hill et al., 2010; Chapman et al., 2020) and comprehensive in terms of taxonomy, geographic and temporal scope.

In this regard, a number of targeted capacity development opportunities have been offered by SANBI and the SANBI-GBIF Node since 2008 (Supplementary Table 3). The topics covered have included biodiversity data standards, species distribution modelling using R, improving fitness-for-use of biodiversity data, data management and cleaning, biodiversity georeferencing etc. (Figure 5). More generally, training opportunities provided by GBIF have also been taken advantage of, when available. These have included those associated with the *Biodiversity Information for Development* Initiative e.g., those hosted and supported by the JRS funded *Africa Biodiversity Challenge* initiative and SANBI-GBIF (GBIF, 2017), (GBIF, 2018). These courses include the Biodiversity Data Mobilisation (GBIF, 2018) and the Data Use for Decision Making. The content for the latter course has been adapted, from the original course (GBIF, 2022b); GBIF Secretariat, 2022a), and evolves as GBIF enhances the curriculum following these training events. A list of training events can be found in Supplementary Table 3.

Other SANBI implemented initiatives such as the Foundational Biodiversity Information Programme (FBIP) have provided funding opportunities for partner institutions to conduct biodiversity related training workshops (Supplementary Table 4). This investment into the training and capacity building efforts supports the need raised at the facilitated session of 2016 (Supplementary Table 1).

SANBI-GBIF has also put in place an eLearning Platform (SANBI-GBIF, 2022), which can be accessed through the SANBI-GBIF website. This platform aims to be a repository of BDI course contents offered by the Node. Agendas, academic course content, lecture presentations, videos, scripts for relevant informatics software programmes, are made accessible for re-use and for subsequent training. This will enable stakeholders to pick up modules that are relevant for specific training needs. Following a registration process, stakeholders can access SANBI-GBIF training content and materials for topics such as "Fitness for Use of Biodiversity Data", "Species Distribution Modelling", and "Data Management and Cleaning supporting Science, Policy and Sustainable Development". The scope of the training will increase as more training events and courses are rolled out.

At the global scale, training courses, resources and materials, especially those related to the GBIF nodes have been summarised elsewhere (Parker-Allie et al., 2021). But there are others, such as training in Data Carpentries and BDI (Peterson and Ingenloff, 2015) that also support the development of fundamental data skills needed to conduct research, and so provide researchers with high-quality, domain-specific training covering the full lifecycle of data-driven research (management, analysis and use).

A "train-the-trainers" mechanism to grow local expertise has also been employed since 2012 and is ongoing. The two areas of

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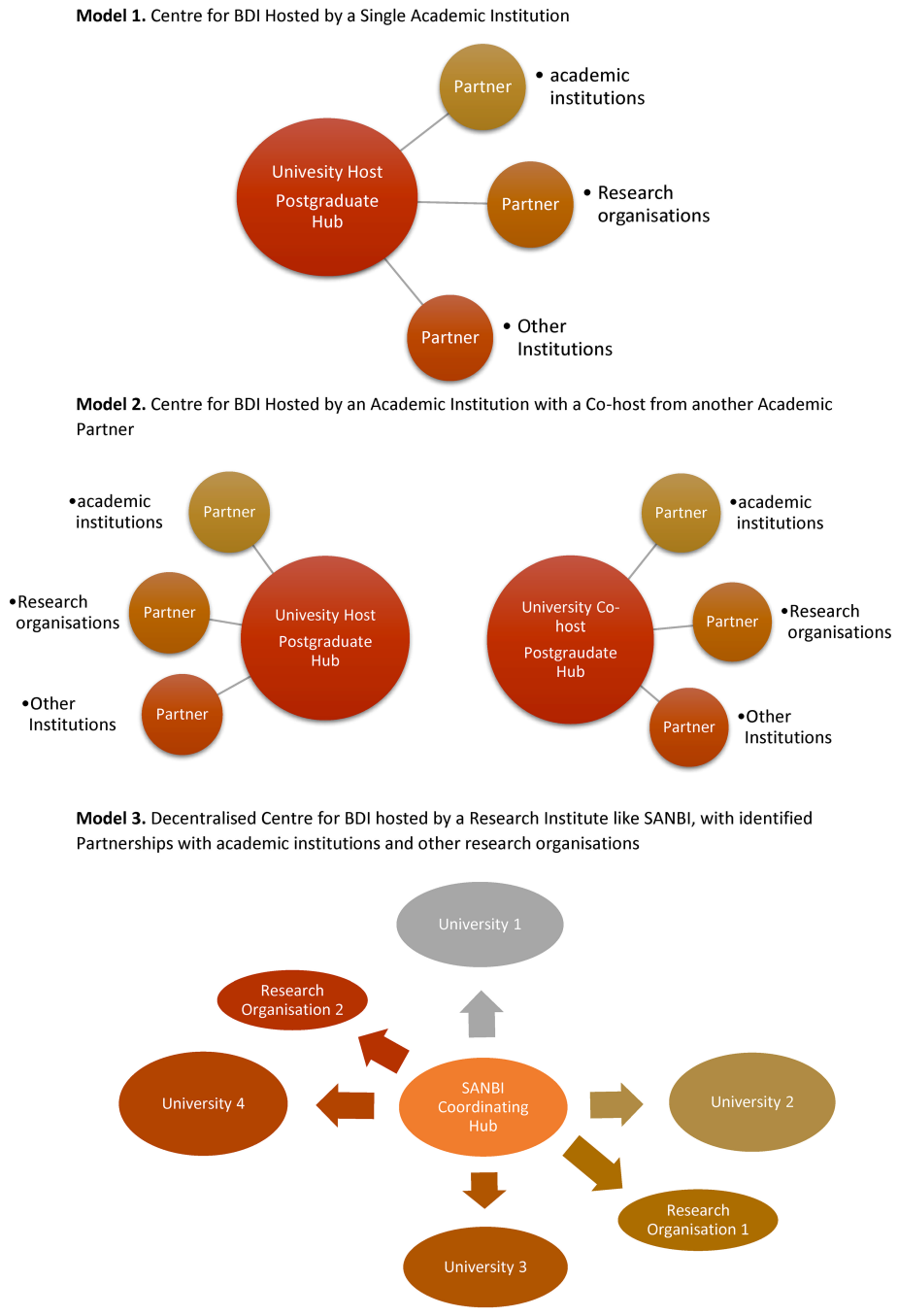

FIGURE 3
Three proposed models for the Centre for BDI, with various hosting and co-hosting options by academic and research organizations.

focus have been in biodiversity data geo-referencing and biodiversity data management. In 2012, an initial workshop was supported by the VertNet international team of experts, who also supported a follow-up geo-referencing workshop. Training was provided to more than 30 participants, and a small core team of local trainers have conducted subsequent training. These local trainers already had skills in geo-referencing and were then also able to act as trainers and support more training events (FBIP, 2021). The same mechanism was also employed for the establishment of a core team training in the field of Data Management.

Strategic objective 4. Grow an inspired and coordinated network of partners

The fourth strategic objective has been to grow an inspired and coordinated network of partners, and the annual BIM-FBIP Forum

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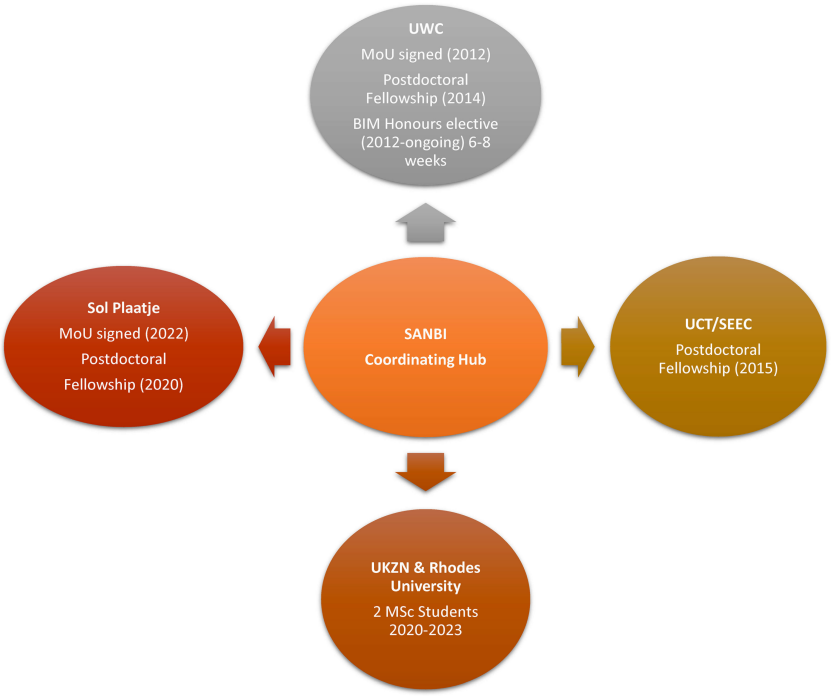

FIGURE 4
Strategic partnerships and progress in developing BDI as a science.

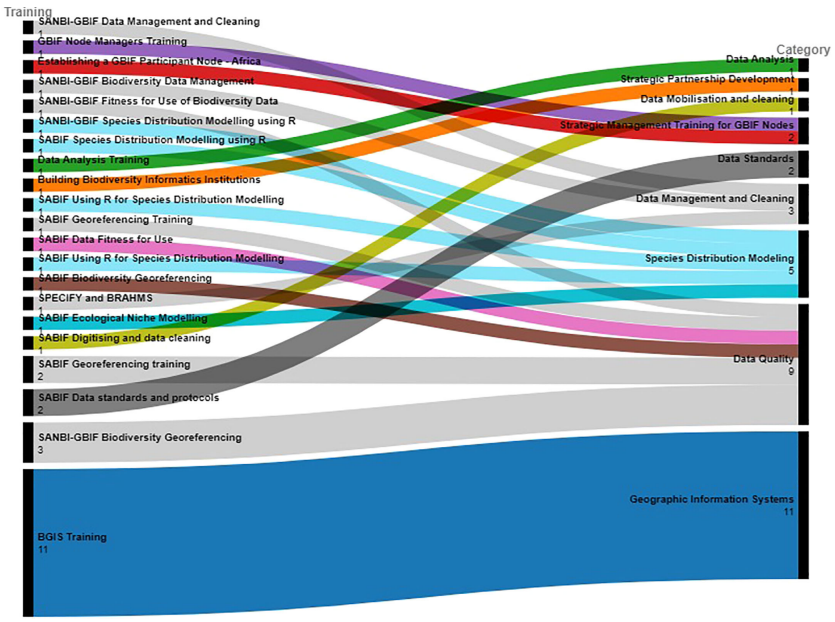

FIGURE 5
Training workshops/short courses offered or supported by SANBI (Biodiversity Information Management Directorate) and SABIF/SANBI-GBIF Programmes over time. The numbers represent the number of training events offered over time. The training events were categorised into data content areas on the left.

provides a platform for engagement to this end (see above). To further support the coordination of BDI, training events and stakeholder workshops are often held alongside the Forum (SANBI, 2016; SANBI, 2019; FBIP, 2020).

Having a national platform to engage stakeholders and share experiences is important to ensure ongoing engagement between partners and the growth of BDI programmes and endeavours. More recently, these Forums have also been instrumental in connecting the biodiversity science and information management community to the *Science, Technology and Innovation* agenda (Box 3). In 2019, the theme for the BIM-FBIP Forum was "Biodiversity Open Data Supporting Open *Science, Technology and Innovation*". Here the aim was to look at how to grow efforts and galvanise the thinking of the community, in-line with the objectives of the White Paper in *Science, Technology and Innovation*. It aimed to prepare and ready the community for effective engagements in the DSI Decadal Plan when this came into play. It was identified that there are several initiatives funded by the DSI i.e., SANBI-GBIF, the *Foundational Biodiversity Information Programme* and the *Natural Science Collections Facility*, as well as many activities taking place in line with this. Thus, in part of the Forum it was identified to look at how the concepts presented in the *Science, Technology and Innovation* White Paper could be taken forward strategically, within institutions, across institutions and more broadly i.e., regionally and globally.

Global opportunities that support our biodiversity informatics work in South Africa

For many countries, especially developing countries, a case needs to be made for the investment of national resources towards participating in global initiatives. The value and subsequent impact need to be demonstrated. It is therefore imperative that participation at the global level provides value and makes an impact at the local level and vice versa, through the sharing of relevant information with stakeholders and appropriate work planning through implementation plans, to effect change. To demonstrate greatest value, it is imperative that countries are also able to inform the global agenda, and to fully contribute to and participate in global initiatives.

The GBIF Graduate Researchers Award provides an opportunity to raise awareness and increase the visibility of BDI, and the value of data mobilisation. The award fosters innovative research and discovery in BDI by graduate students, whose studies rely on GBIF mediated data, in countries participating in the GBIF network. To support national efforts to develop and grow BDI efforts and capacity, SANBI-GBIF has developed a national process to support the selection of candidates and has established a SANBI-GBIF Young Researchers Award Advisory Panel, to provide support and foster additional champions for this scarce skills area of science.

A partnership project entitled "BioDATA Advanced – Accelerating biodiversity research through DNA barcodes, collection and observation data", was approved for funding and is being led by the Museum of Natural History at the University of Oslo. This initiative is a collaboration between national GBIF Nodes from Norway, South Africa and the Altai State University (Russia), and is being funded by the Norwegian Agency for International Cooperation and Improvement of the Quality of Higher Education (DIKU). The project will offer young researchers academic mobility, as well as professional training in the study of biodiversity using modern methodologies in *inter alia* processing, publishing and using open data (University of Oslo, 2022). Eight courses in advanced biodiversity data skills are planned, and six student MSc and PhD internships will be provided. The courses are designed to create a network of exchange between professionals and students through targeted internships, in the participating countries and around the world.

Mainstreaming our data to support the science–policy interface

One of the opportunities highlighted by the South African community (Supplementary Table 1, Box 2) as contributing towards enhanced BDI endeavours is ensuring good partnerships

Box 3. National STI policy drivers towards change for biodiversity informatics

Two key policy drivers including the *Science, Technology and Innovation* White Paper (DST, 2019) and the *Science, Technology and Innovation* Decadal Plan provide key opportunities and an enabling framework for taking BDI capacity building efforts forward. The White Paper sets a vision for *Science, Technology and Innovation* to accelerate more inclusive and sustainable socio-economic development and improving the quality of life of its citizens. Here some key focus areas or goals provide the ideal mechanisms to support the development of BDI. This includes supporting a more digital society, targeted strategic internationalization, increasing funding across the *National System of Innovation*, expanding the research enterprise (e.g. increasing *Centre's of Excellence*, and *Research Chairs*) and transforming the human capacity for *Science, Technology and Innovation* (DSI, 2021).

The *Science, Technology and Innovation* White Paper, is based on an extensive review of the *National System of Innovation*, which is described as a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts that define new knowledge (DSI, 2021). Data and information are the building blocks of new knowledge (Chaim, 2013). With the huge volumes of data being mobilised through various new technological advances, it is imperative that we have the computational abilities and capacities in place to use, analyse and mine this data. This especially, towards ensuring outcomes related to societal grand challenges (DSI, 2021). Initiatives such as the FBIP are just one data intensive programme, providing investment in the generation of new data and knowledge, which ultimately informs policy aspects such as global change and the bio-economy (Foundational Biodiversity Information Programme, 2020). One such impactful outcome includes the work conducted through the SeaKeys consortium project, with data mobilised through this project contributing to the expansion of the South African coastal area under marine protection, from 0.4% to 5% (Save our Seas Foundation, 2019; Sink et al., 2019; Parker-Allie, 2021).

The *Science, Technology and Innovation* White Paper also sets out a long term policy direction for government to ensure a growing role for the sector in South Africa, and thereby supporting the objectives of the National Development Plan for 2030 (National Planning Commission, 2015). This policy aims to help South Africa benefit from global developments in rapid technological advancements and respond to the four societal grand challenges, i.e., climate change, future-proofing education and skills, re-industrialising the modern economy and future of society, as well as two *Science, Technology and Innovation* priorities (health innovation and energy innovation).

and alignment of biodiversity data and information with the Science–Policy Interface. South Africa, through SANBI-GBIF has supported the efforts of the IPBES, as a member of the Task Force on Knowledge and Data. As part of its workplan, the Task-Force has developed a Data Management Policy (IPBES, 2020b) to provide overarching guidance on the management of data and knowledge in current assessments and IPBES products. The policy is grounded in the principles of open science (UNESCO, 2021), accessibility, and building knowledge through partnerships. Efforts have also included the development of downloadable curriculum and webinars, to support IPBES authors, in the development of IPBES assessment chapters or other IPBES knowledge products (IPBES, 2020a). These modules cover topics ranging from data management policy, reports, active research data, tools, and examples (Seebens et al., 2022). Efforts relating to the management of active research data were also supported by SANBI-GBIF through the development of content and video presentation (Parker-Allie and IPBES task force on knowledge and data, 2020).

An additional objective of the Task Force on Knowledge and Data is the development of templates and guidelines for IPBES authors on knowledge gaps identification and knowledge catalysis, as identified in the IPBES 2030 Rolling Workplan (IPBES, 2019). Gaps will be used to engage and dialogue with research funders and programmers, to catalyse investment in priority research and data mobilization. In June 2022 as part of the Sustainability, Research, and Innovation Congress, which is a joint initiative of Future Earth and the Belmont Forum, dialogue workshops on the identification of knowledge gaps in the IPBES Global Assessment of Biodiversity and Ecosystem Services was conducted. These efforts are all relevant for mobilising data and knowledge at the national and regional level. Nationally, this also provides an opportunity to leverage funds from existing biodiversity programmes and prioritise these gaps identified through the IPBES Assessments.

At the national level, contributions to the data–science–policy interface are also ensured through ongoing engagement with the IPBES Focal Point, for inclusion into the IPBES Plenary Meetings. IPBES is also a standing item on the BIM-FBIP Forum Agenda, which is in-line with the recommendations from the Joint BIM-FBIP Forum in 2016, indicating that partnerships, synergy and alignment be sought with DFFE, and that data should be mainstreamed to support the science–policy interface and be used for effective decision-making. This engagement with IPBES also supports downstream activities with the scientific community to catalyse data mobilisation activities at national level to support data and knowledge gaps identified in the IPBES assessments, and ensuring alignment with the data and knowledge needs identified in the National Biodiversity Assessment (Skowno et al., 2019). Data gaps exist with the estuarine realm being identified as the most threatened realm in South Africa and freshwater fish identified as the most threatened species group in the country, and freshwater invertebrates identified as a challenge. The marine realm was also identified as lacking adequate taxonomic knowledge, limited occurrence records and a lack of abundance and long-term population trend data, insufficient knowledge of species life histories and ecology, limiting marine threat assessments (Sink et al., 2019; Skowno et al., 2019).

A roadmap for advancing biodiversity informatics and the way ahead

Partnerships and collaboration

This article has set out to provide an overview of the processes that have been undertaken to drive BDI efforts in South Africa, and therefore provides the baseline for a roadmap for the advancement of biodiversity informatics capacity development in the country. In line with some of the opportunities highlighted from the 2016 stakeholder workshop, partnerships with universities have been established and areas of cooperation have been identified. As has previously been stressed, research/academic expertise is the backbone of skills development and high-level partnerships need to be reinforced with additional capacity that can support teaching and research outputs, whilst leveraging internal staff capacities at the universities.

In 2012 an MoU was signed with the University of Western Cape and in March 2022, SANBI and the Sol Plaatje University signed an MoU for cooperation to strengthen efforts to grow the field of BDI science. Future efforts must focus on the development of courses and curriculum content to grow capacity in BDI and data science, to grow human capital through provision of bursary opportunities, internships, postdoctoral fellowships and the development of collaborative research projects.

Experiential learning opportunities through partnerships with Iziko Museums and the City of Cape Town Biodiversity Branch will be explored from 2023, using the Groen Sebenza internship initiative as a model. The latter is a job creation programme that aims to provide a bridge for graduate students leaving university into the work environment, and is funded by national Treasury (SANBI, 2013). With Groen Sebenza it is hoped to support research activities and to develop critical skills in BDI and collections' management in the process. Additional opportunities to expand experiential learning efforts will be through the BioData Advanced initiative, as mentioned above.

Establishment of the Centre and funding opportunities

To look at how a Centre for BDI could be established, a workshop was held in August 2016 which was catalysed by GreenMatter[za], and included SANBI and the Centres of Excellence team at the *National Research Foundation*. It was identified that a good instrument to move this work forward would be the *South African Research Chairs Initiative* that is funded by the national *Department of Science and Innovation* and the *National Research Foundation*. This initiative is aimed at strengthening the research and innovation capacity of public universities in strategic institutional niches of excellence. This appointed *Research Chair* would be catalytic in supporting student activity and would create momentum in this research area. The Terms of Reference for a *Research Chair* have been developed, and the process will be taken forward as the

opportunity for funding arises. Engagements between SANBI and the *Department of Science and Innovation* have otherwise been ongoing since 2022 to further identify mechanisms and instruments to move capacity building efforts forward.

Funding for bursaries and studentships

Some funding prospects exist by tapping into bursary opportunities available through the universities, SANBI (Joan Wrench Scholarship Fund) and the National Research Foundation. That said, we need to scale up our efforts in this regard by identifying and engaging with relevant players in the biodiversity science community, and by identifying suitable projects that will support BDI initiatives.

Curriculum and content development

To develop relevant content and materials, SANBI-GBIF has been developing modular re-usable course content and curriculum in component areas of BDI, as highlighted above. *The University of Western Cape* has successfully implemented a 6–8 week BSc Honours module focused on Biodiversity Information Management which has been available since 2012 as part of the Biodiversity and Conservation Biology Honours degree (Parker-Allie et al., 2021). Going forward, SANBI-GBIF will be developing a course in collaboration with GBIF-Spain that will investigate data mining approaches for impactful data use cases and stories (GBIF, 2022c). Other courses that are planned will be developed within the framework of the BioData Advanced initiative with a focus on the mobilisation of molecular, observation and natural history collection data (University of Oslo, 2021; SANBI-GBIF, 2021).

Challenges towards development of a Centre for BDI

While much has been achieved in pursuit of creating a Centre for BDI in South Africa, we have experienced a number of challenges, and we reflect on those here, because they may prove to be valuable to other countries that wish to embark on a similar journey. Our initial efforts were very ambitious, and they were aimed at ensuring high level support and buy-in from both government departments and institutions, and universities. While this was, and remains, of utmost importance, a three-pronged approach should perhaps have been taken. This would additionally have included engagement with a greater critical mass of research expertise to help drive efforts that would support capacity development, as well as a clear science plan. The latter ensuring a more targeted approach towards impactful research outcomes for both science and policy.

Our successes in growing BDI capacity/science since 2012 have largely been achieved through the existing series of programmes and initiatives of SANBI and the managed network. However, to be truly successful in the creation of a Center for BDI, several additional supportive components should perhaps have been in place. This includes: (1) A governance structure and identified leadership at various levels that could provide oversight and advisory support i.e., a Board and/or Advisory/Steering Committee including Working Committees depending on the need/s. (2) A clear funding strategy, with an approved budget and a plan for financial sustainability. (3) A clear science strategy and implementation plan for research and Human Capital Development, building in collaborators to lead research and teaching components. (4) A marketing and awareness raising plan to promote the ambitions and opportunities provided by the Centre. (5) A monitoring and evaluation plan that would ensure the Centre meets key performance areas, metrics, and targets. This would support administrative and business plan reporting related to outcomes/outputs to government.

Conclusion

This review article has highlighted our efforts towards the development of BDI as a field of science in South Africa. Although significant achievements have been made in enhancing capacity in BDI, we are not yet at the stage where a Centre has been established.

The study has provided some key lessons that can be implemented by other countries in pursuit of the same goal. For us, the following points are key, including: (1) The annual Forum has been invaluable in developing of a community of practice in BDI, as it provides all interested parties with an opportunity to openly discuss issues, to unblock challenges and to catalyse new projects and endeavours, through strategic engagement with other stakeholder groups. (2) A holistic approach to capacity development has enabled activities across several key strategic areas and target markets. (3) The implementation of platforms such as the SANBI-GBIF website and the eLearning platform, has provided local context, and access to the data published by the South African community, as well as access to the BDI course content implemented by the Node, respectively. (4) High level buy-in and support from national government. (5) Ongoing training events provide capacity development opportunities to learn a range of skills (6) A strong pool of research and teaching expertise in this field of science is lacking, thus there is a clear need for high level skills that could perhaps be enabled through funding for a *Research Chair*. (7) Strong institutional buy-in by host institution/s and associated sustainable resources is needed. (8) A critical mass of students and researchers involved in BDI is needed. (9) Internationalization efforts will be required to grow research and teaching capacities.

For South Africa, it is imperative that the value of the *Science, Technology and Innovation* policy agenda and the alignment with the DSI decadal plan be leveraged to ensure implementation with activities, outcomes and impacts related to the societal grand challenges i.e. futureproofing education and skills, human resources for STI, climate change, expanded and transformed research systems,

expanded and transformed strategic internationalisation, to establish a fully operational Centre and to grow biodiversity informatics as a field of science in South Africa.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

FP-A conceptualized this research and was the primary investigator and author. FP-A leads this research area of work for SANBI in collaboration with University Partners. MG provided critical thinking and strategic input into this research endeavour as a key university partner, and contributed towards the research paper. DH was also a key university partner in this work and was instrumental in the strategic thinking with regards to the Centre. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2023.1107212/full#supplementary-material

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