

Invasion science for society: A decade of contributions from the Centre for Invasion Biology

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Biological invasions are a growing problem worldwide. In 2004, the South African Department of Science and Technology, through the National Research Foundation, established a Centre of Excellence for Invasion Biology, with the primary goal of providing scientific understanding and building capacity in the field of biological invasions. South Africa is an extraordinary natural laboratory for the study of biological invasions, and the Centre for Invasion Biology (C-I-B) has capitalised on this situation. During its first decade, the C-I-B generated over 800 publications, and produced almost 200 graduates at honours, master's and doctoral levels. The C-I-B has therefore made a considerable contribution to building human capacity in the field of biological invasions. Substantial advances have been made in all aspects of invasion science, which is not limited to biology and ecology, but includes history, sociology, economics and management. The knowledge generated by the C-I-B has been used to inform policy and improve management practices at national and local levels. The C-I-B has emerged as a leading institute in the global field of invasion biology, with several unique features that differentiate it from similar research institutes elsewhere. These features include a broad research focus that embraces environmental, social and economic facets, leading to a diverse research programme that has produced many integrated products; an extensive network of researchers with diverse interests, spread over a wide geographical range; and the production of policy- and management-relevant research products arising from the engaged nature of research conducted by the C-I-B.

Introduction

Invasion biology is a branch of science that addresses the causes and consequences of introducing alien organisms to new environments, where some are able to persist and spread unaided, often with substantial negative consequences. The invasion of natural and modified ecosystems by alien species is a growing problem worldwide.¹ The ongoing and accelerating redistribution of species for agriculture, forestry, horticulture, recreation and the pet trade provides a pool of alien species from which invasive species are recruited. The magnitude and diversity of opportunities for accidental introduction have also grown dramatically with the rapid expansion in global travel and trade since the industrial revolution. The problem is exacerbated by human-mediated ecosystem disturbance, and changes in the world's climate and biogeochemical cycling, which makes ecosystems more susceptible to invasion by alien species. Many introduced species provide enormous benefits to the country's socio-economic development, but a small and growing proportion have a net negative effect. There is ample scope for research towards understanding where introductions will have adverse impacts, and how these risks should be managed and regulated.

Of the thousands of alien species that have been introduced to South Africa over the past 360 years, hundreds have become invasive. Those species that do invade can pose substantial threats to South Africa's ecosystems and the services that they deliver.^{2,3} They can reduce water supplies⁴, increase erosion⁵, exacerbate wildfires⁶, degrade rangelands⁷, threaten the health of people and livestock⁸, reduce productivity in agriculture⁹, and impact negatively in many ways on the country's remarkable biodiversity². The economic damage caused by these invasions has been estimated at over ZAR9 billion per year¹⁰, and is growing as invasive species spread, and as more species are introduced and become invasive^{3,11}.

The imperative to address biological invasions has several drivers at international and national levels. South Africa is signatory to several international conventions, the most important of which is the Convention on Biodiversity. Article 8(h) of the Convention requires contracting parties, as far as possible and as appropriate, to 'prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats or species'. The International Plant Protection Convention aims to secure coordinated, effective action to prevent and to control the introduction and spread of pests of plants and plant products. This agreement requires a single, national government authority to be in charge of specific responsibilities regarding phytosanitary control (in South Africa, this body is the Department of Agriculture, Forestry and Fisheries). At a national level, several additional policies imply a need to address biological invasions, including the 12 Presidential Outcomes, the National Development Plan, the National Biodiversity Framework of the Department of Environmental Affairs, and the Department of Science and Technology's 10-year Global Change Grand Challenge, all of which recognise the need to support sustainable development by protecting the environment from, *inter alia*, biological invasions.

In 2004, the South African Department of Science and Technology (DST), through the National Research Foundation (NRF), established six inaugural Centres of Excellence (CoEs) after wide consultation and a highly competitive selection process. CoEs are physical or virtual centres of research which concentrate and strengthen existing capacity and resources to address issues of national and international importance, enabling researchers to collaborate across disciplines and institutions on long-term projects that are locally relevant and internationally competitive. The goal of CoEs is to enhance the pursuit of research excellence and to develop trained scientific capacity for the country. Internationally, the CoE model has become a common research funding instrument, having already been established in Australia, Canada and the USA.

We present a brief review of the contributions of one of the six inaugural CoEs (the Centre for Invasion Biology, or C-I-B; www.sun.ac.za/cib) to the development of invasion science, following its first decade of activities. We examine the inputs that were required to establish the C-I-B, the outputs of research and training over the past 10 years, and the influence of this work in advancing the broad field of invasion science, and of implementing its findings in practice. These impacts are illustrated by means of examples at international, national and local scales.

Unique opportunities

South Africa can be viewed as an extraordinary natural laboratory for the study of biological invasions. The country has been particularly affected by biological invasions for a range of reasons. There is a long history of colonial occupation, dating back 360 years, which has led to a large number of alien species being introduced. There is also a remarkable diversity of ecosystems, including mediterranean-climate shrublands (fynbos), karoo arid shrublands, grasslands, savannas, thicket and forest, rivers, estuaries, temperate and sub-tropical marine ecosystems, and remote offshore islands, all of which currently harbour populations of well-established and diverse invasive alien species and emerging invaders.¹² The South African government allocates substantial funding towards the management of this problem.¹³ The combination of diverse ecosystems that all have particular suites of invasive alien species (some of which have been there for centuries) and well-funded management initiatives, has created particular needs for science-based solutions and trained capacity. The C-I-B has capitalised on this situation by initiating research across all of the country's varied ecosystems. Invasion biologists have to understand how natural ecosystems are structured and how they function, and how this structure and function is changed when ecosystems are invaded. This provides a novel 'lens' through which fundamental ecological questions can be viewed and addressed, and a unifying theme that can bring together scientists from different backgrounds. In addition, a focus on invasions requires research to extend beyond the narrower fields of biology and ecology, and to embrace sociological and economic aspects of the problem that must be understood to develop effective policies and management solutions. This has led to the scope of the work being broadened from 'invasion biology' to 'invasion science', and has allowed the C-I-B to develop unique solutions that have had impact at international, national and local scales.

Inputs, research framework and goals

Unlike some of the other initial CoEs, the C-I-B was established *de novo* with the aim of providing the scientific understanding required to reduce the rate and impacts of biological invasions in a manner that improves the quality of life of all South Africans. The mission of the C-I-B is (1) to undertake research and education in the causes, effects and consequences of biological invasions for biodiversity and ecosystem functioning; (2) to remain at the forefront of research regarding biological invasions, biodiversity and ecosystem functioning by pursuing research excellence and interdisciplinary collaboration and by encouraging local, regional and international exchanges; (3) to enhance the national and international societal relevance of the C-I-B by producing high-quality, relevant research, and graduates who are sought after; and (4) to remain relevant to the needs of the community, focusing on South Africa in the context of trends shaping Africa and the world. Funding comes from a core grant from the DST, through the NRF, with substantial co-funding from Stellenbosch University as host of the C-I-B's administrative hub and partners. Additional funding is sourced through research collaboration agreements with a range of national and international sources, most notably the Department of Environmental Affairs' Working for Water Programme.

During the first 10 years, annual funding has grown from about ZAR3 million in 2004 to over ZAR12 million (USD1.13 million) in 2012 (Figure 1). This funding has been used to support a wide spectrum of activities designed to meet five key performance areas (KPA's): research; education and training; networking; information brokerage; and service provision. In accordance with the DST's 10-Year Global Change

Research Plan for South Africa, the C-I-B's approach to meeting its KPA's has been explicitly:

- strongly interdisciplinary, actively seeking out expert partners;
- directed at making a contribution to the international knowledge base while remaining locally relevant;
- aimed at advancing a better understanding of the functioning of South Africa's ecosystems to inform efforts to respond effectively to changes;
- aimed at bridging the gap between the natural and social sciences;
- policy relevant; and
- directed at biological invasions as a primary focus, but also at climate change and other facets of global change, taking into consideration contemporary debates and discussions.

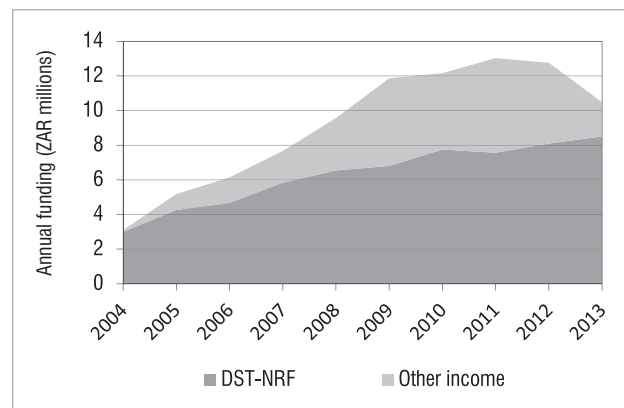


Figure 1: Funding to the Centre for Invasion Biology from the Department of Science and Technology (DST) through the National Research Foundation (NRF), and other sources, between 2004 and 2013. 'Other income' refers to contract funding which varies annually.

The C-I-B has also recognised its duty to change the demographic profile of its students, in common with other CoEs and in line with broad government policy. The C-I-B has thus actively sought to attract students from historically disadvantaged backgrounds into the research and capacity-development programme. This has been challenging, as the broad field of biology is often not perceived as offering an attractive or lucrative career, especially among the target group of prospective students.¹⁴ Despite this perception, the C-I-B's graduates and former employees are employed in a broad spectrum of institutions and sectors within and outside South Africa, reflecting the diverse and high-level skills gained by invasion biologists.

The management of biological invasions is complex, demanding a robust and holistic understanding of the many and varied aspects of invasion and its various stages, and of appropriate management responses to those processes. The C-I-B has adopted a research framework to guide the allocation of resources and to ensure that all facets of this complex problem are addressed effectively (Figure 2). By engaging in a spread of activities across this framework, the C-I-B covers the full spectrum of research required to fully understand biological invasions and to explicitly link research outputs to the development of policy and the improvement of management.

The C-I-B is centred at Stellenbosch University, with a second satellite hub at the University of Pretoria. The network of core team members is based at several South African universities and institutions. Over the life of the C-I-B, these institutions have included the Universities of Cape Town, Johannesburg, KwaZulu-Natal, Pretoria and Venda, Walter Sisulu University, the Council for Scientific and Industrial Research, the City of Cape Town, South African National Parks, the South African Institute for Aquatic Biodiversity, and the South African National Biodiversity Institute. This inter-institutional arrangement allows for a broad range of

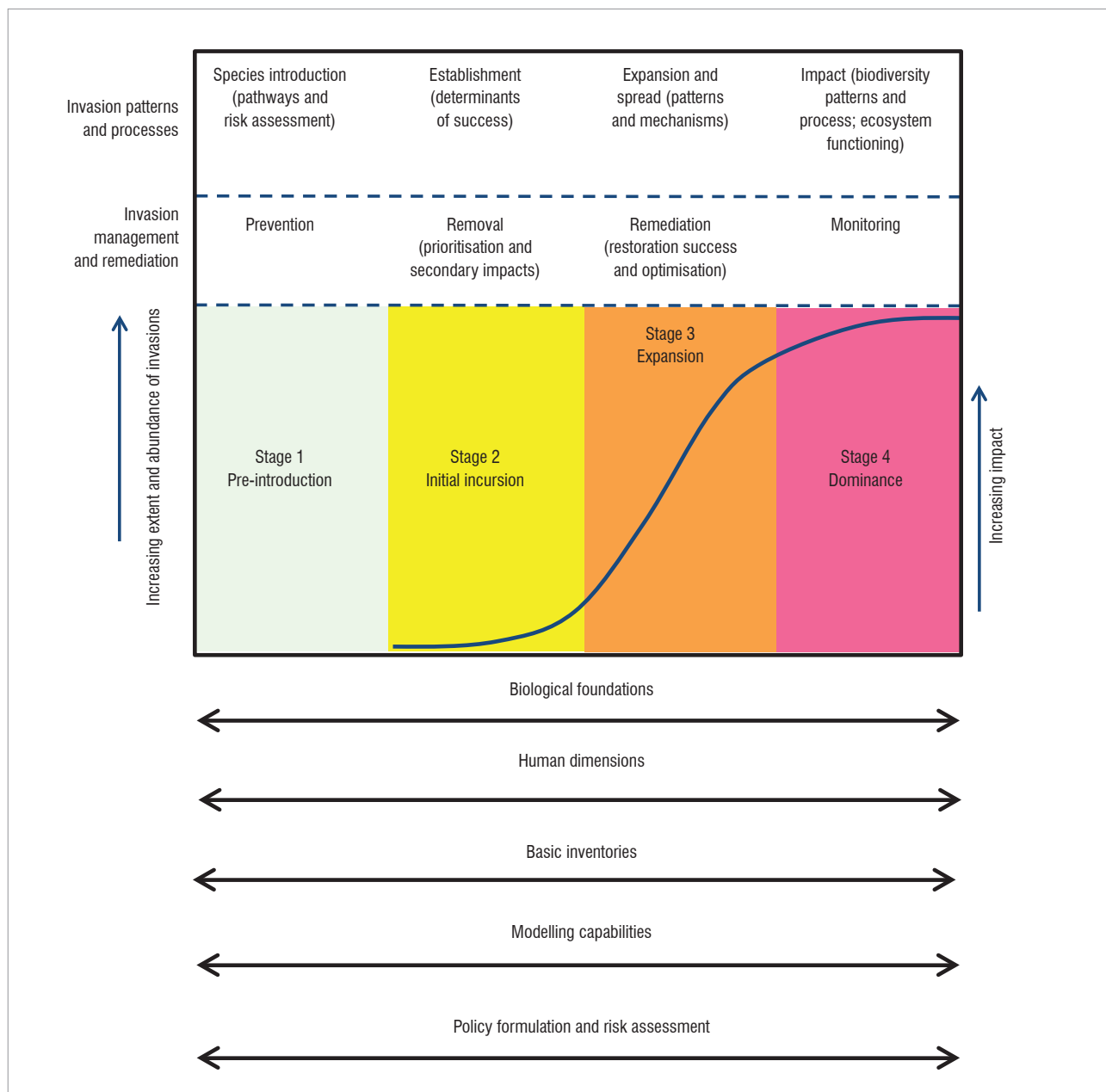


Figure 2: A framework used by the Centre for Invasion Biology to guide relevant and comprehensive research on biological invasions. There are four stages of invasion, dependent on the extent and abundance of the species concerned: pre-introduction, initial incursion, expansion, and dominance. At each stage, it is necessary to consider the patterns and processes that drive invasions, as well the management and remediation responses required to reduce the spread and impacts of invasive alien species. Cross-cutting issues that apply to all stages of invasion are indicated by the arrows below the box.

research interactions involving a wide diversity of research associates, postdoctoral fellows and students (Table 1). The C-I-B also collaborates with other organisations involved in invasion biology. Internationally, these organisations have included the Canadian Aquatic Invasive Species Network; the Institute for Biological Invasions at the University of Tennessee, USA; the Laboratorio de Invasiones Biológicas at the Universidad de Concepción in Chile; the Centre for Advanced Studies in Ecology and Biodiversity, Pontificia Universidad Católica de Chile; the British Antarctic Survey, Biodiversity and Macroecology Group, Department of Animal and Plant Sciences, University of Sheffield; and the Institute of Botany, Academy of Sciences of the Czech Republic. Other collaborators have included the Working for Water Programme of the Department of Environmental Affairs, Iziko Museums, the Flower Valley Conservation Trust, the Table Mountain Fund, the Drakenstein Trust and the Millennium Seedbank Project of the Royal Botanical Gardens at Kew.

The C-I-B reports to a Board which currently comprises 14 members from eight South African and two international institutions active in the environmental and conservation fields.

Outputs

The C-I-B's research, education and training KPAs are assessed in two broad categories: publications and graduates. Research papers published in peer-reviewed journals are given prominence in the C-I-B's research KPA, where there is a requirement for a minimum number of such papers to be published annually. This target (currently set at 60 papers per year) has grown over time, but the actual output has always exceeded the annual target. Since its inception, the C-I-B has, as of June 2014, published a total of 841 papers in Web of Science (formerly ISI) indexed journals, representing a significant contribution to global understanding in the field of invasion biology (Figure 3a). The

Table 1: The numbers of different categories of team members of the Centre for Invasion Biology between 2004 and 2014

Category	Definition	Number in any given year		
		Minimum	Maximum	Current (2014)
Core team members	Researchers actively working on a broad range of invasion biology and environmental sociology topics. Core team members are funded, and they undertake to publish in peer-reviewed outlets and to supervise postgraduate students.	14	26	23
Additional hub support staff	Staff providing administrative and technical support to core team members, postdoctoral fellows and students within the C-I-B's hubs.	2	21	15
Research associates	Partners who are active in the field of biological invasions, but not necessarily involved in academic research or student training. Research associates benefit through access to the C-I-B's national and international networks, events and information systems, but are not funded.	0	19	19
Postdoctoral fellows	Recent PhD graduates appointed on short-term (1–3 year) fellowships to conduct research on invasion biology.	6	13	10
Postgraduate students	Registered students pursuing studies that will lead to honours, master's or doctoral degrees.	7	78	61

impact of these papers is reflected in the >13 400 citations (Figure 3b), with an h-index of 52 (i.e. 52 papers have been cited 52 or more times each¹⁵). Invasive species feature prominently in these publications, which address a wide range of topics from evolution and ecological processes to conservation and management (Figure 4). In addition to publications in the peer-reviewed literature, C-I-B activities have led to the production of several synthesis volumes and many semi-popular texts that have both increased understanding in the field, and raised awareness of the issue among a wider audience (Table 2, Figure 5).

In 2004, the Invasive Species Specialist Group of the International Union for the Conservation of Nature (IUCN) published a list of '100 of the world's worst invasive alien species'³¹. Publications arising from the C-I-B have addressed 21 of these '100 worst' species (including one aquatic and eight terrestrial plants, four fish, two mammals, two birds, and two aquatic and two terrestrial invertebrates), indicating the wide coverage of research at the C-I-B.

Postgraduate training is a core function of the C-I-B and funds are made available to students in the form of bursaries, running costs for research projects and travel grants. The education and training KPA stipulates that at least 50 postgraduate students should be supported each year, and that at least half of the students should be women, and half should be black. The periods of study are also monitored, with a requirement that, on average, master's and doctoral students should graduate within 2.5 and 3.5 years, respectively. During the first decade of activity, 97 students graduated with 4-year BSc or honours degrees, 60 with master's degrees and 35 with doctoral degrees (Figure 6). The average duration of study was 2.5 and 4.1 years for master's and doctoral graduates, respectively; the failure to meet the 3.5-year target for the completion of doctoral degrees reflects the unrealistic nature of this target.³²

Graduates of the C-I-B have found employment in a wide range of sectors, including in government, science councils, parastatal organisations, NGOs, tertiary education institutions, and the private sector. There has thus been a growing contribution to human capacity in the field of researching and managing biological invasions, not only in South Africa but also in other African countries. Graduates of the C-I-B do not only provide capacity in the field of invasion science, they also raise awareness of the problem of biological invasions, and grow the discipline in their respective spheres of influence.

Contributions to invasion science

Research conducted at the C-I-B has addressed invasion patterns and processes, and their management and remediation, at all stages of the introduction-naturalisation-invasion continuum (Figure 2). The C-I-B has made substantial contributions to invasion science on multiple fronts (Table 3). The term 'invasion science' was proposed to describe the full spectrum of fields of enquiry pertaining to alien species and biological invasions. It embraces invasion biology and ecology, but increasingly draws on non-biological lines of enquiry, including economics, ethics, sociology, and inter- and transdisciplinary studies.³³ Some contributions have built on research initiated pre-C-I-B, but many others chart new directions in invasion science, drawing on the special problems and opportunities in South Africa. For example, work on tree invasions has addressed key questions and sought new solutions at a range of scales from genes to ecosystems, merging results from detailed biological studies with investigations of human perceptions and other socio-economic

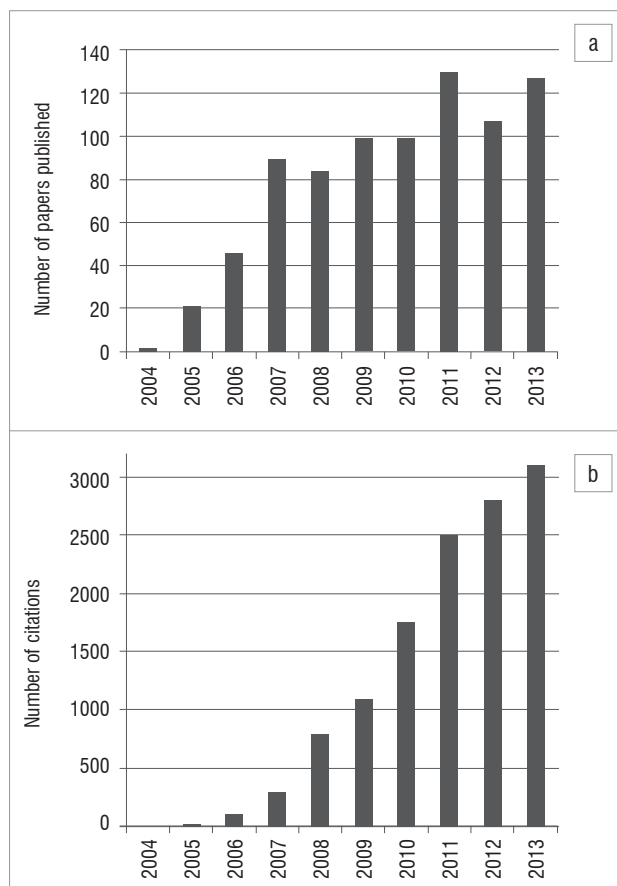


Figure 3: (a) The number of papers published each year in Web of Science (formerly ISI) indexed journals during the first decade of research by the Centre for Invasion Biology and (b) the annual number of citations to papers published by the Centre for Invasion Biology.

Table 2: Examples of scientific compilations that have advanced understanding and raised awareness of biological invasions in South Africa and globally

Subject	Format	Scope	Issues addressed
Global synthesis of invasion ecology	International workshop, and publication of a book ¹⁶	30 chapters by 51 authors from 9 countries	Charles Elton's pioneering book on the ecology of invasions by animals and plants was published in 1958. This synthesis conference marked the 50th anniversary of Elton's publication, and examined the origins, foundations, current dimensions, and potential trajectories of invasion ecology.
Plant invasions: theoretical and practical challenges	International conference on plant invasions (EMAPI 10) and publication of journal special issue ¹⁷	15 papers by 48 authors from 10 countries	The Ecology and Management of Alien Plant Invasions (EMAPI) conference series is the premier international forum for this field. The C-I-B hosted the 2009 event which attracted 263 delegates from at least 29 countries. The journal special issue contains papers on advances and challenges in theoretical and practical dimensions of plant invasion science.
Ecology and management of introduced Australian <i>Acacia</i> species	Workshop and publication of a special issue of an international journal ¹⁸	21 papers by 112 authors from 14 countries	This review explored how evolutionary, ecological, historical and sociological factors interact to affect the distribution, usage, invasiveness and perceptions of a globally important group of plants.
Ecology and management of tree invasions	Workshop and publication of a special issue of an international journal ¹⁹	16 papers by 36 authors from 12 countries	The papers summarise current knowledge on tree invasions and identify the most important challenges facing researchers and managers. The papers span disciplines, geographical regions and taxa and provide novel insights on pathways and historical perspectives, detection and monitoring, determinants of invasiveness, function and impact, and the many challenges that face managers.
Management of riparian ecosystems in invaded landscapes	Simultaneous publication in a national journal of work arising from a project on targets for ecosystem repair in invaded riparian zones ²⁰	14 papers by 26 South African authors	The ultimate aim of this project was to produce guidelines and tools to improve management of invaded riparian ecosystems.
Plant invasions in protected areas	Publication of edited volume in Springer's 'Invading Nature' book series ²¹	28 chapters by 79 authors from 20 countries	The first comprehensive global review of alien plant invasions in protected areas, providing insights into advances in invasion ecology arising from work in protected areas. There are extensive practical guidelines for managers, based on experience from around the world.
Links between marine and terrestrial ecosystems in oceanic islands	Publication of an edited volume arising from collaborative research by the South African National Antarctic Programme ²²	14 chapters by 24 authors from 7 countries	An overview of the structure, functioning and interactions of marine and terrestrial systems at the Prince Edward Islands. Demonstrates how global challenges, including climate change, biological invasions and over-exploitation are playing out at regional and local levels in the Southern Ocean.
Raising awareness of biological invasions and related conservation issues	Popular scientific books written for a broader audience ²³⁻²⁸	Accounts compiled by between one and four authors	The accounts included an overview of animal invasions and comprehensive accounts on dragonflies and introduced molluscs; a popular science book on invasions and their impacts on South Africa; and popular science books on the ecology and management of islands in the Southern Ocean.
The use of fencing in conservation and land management	Publication of an edited volume ²⁹	16 chapters by 43 authors from 10 countries	An evaluation of the positives and negatives of fencing in conservation and wildlife management, including case studies from around the world.
Re-introduction of top-order predators	Dedicated symposium at the annual meeting of the Society for Conservation Biology, and publication of a book ³⁰	19 chapters by 33 authors from 9 countries	An assessment of the ecological, social, political and genetic challenges of re-introducing top predators to environments where they have become locally extinct.

aspects, and drawing new insights by contrasting the South African situation with examples from other parts of the world.¹⁸ Numerous studies have addressed diverse aspects of the invasion ecology of Australian *Acacia* species; this group has proved very useful as a model system for focusing research on many dimensions of invasion science.³⁴ Another important area of research pioneered at the C-I-B is macrophysiology – the investigation of variation in physiological traits over large geographical, temporal and phylogenetic scales.³⁵ Several studies have highlighted the importance of physiological tolerances in determining range limits and the population structure of invasive species.³⁶

High-impact contributions to invasion science have been made to all elements of the framework in Figure 2 and for all the main taxonomic groups of invaders (the bias in favour of plants is in line with the global dominance of botanical work in the literature on biological invasions),³⁷ and across all biomes and ecosystem types in South Africa. Key fields in invasion science that are under-represented in the C-I-B's research output are biological control and the ecology and management of alien microorganisms. The C-I-B has intentionally not undertaken basic

research in these fields, because both have their own well-resourced research programmes in South Africa.^{14,38} However, in both cases, C-I-B research has added important insights. For biological control, C-I-B research outputs have, among other things, demonstrated the crucial need to reduce seed production to contain key invasive plant species³⁹; assessed the overall contribution of biological control to the management of invasive alien plants and the protection of ecosystem services in South Africa⁴⁰; and identified the exact provenance of invasive species using molecular ecology to facilitate better host matching for biocontrol agents⁴¹. For microorganisms, the role of mutualistic associations between bacteria and plant roots that facilitate invasions by alien legumes has been explored in several studies.⁴²

Influence at an international level

The C-I-B has emerged as one of the leading institutes worldwide that conduct research on invasive species as their primary focus. The research carried out at the C-I-B has been influential in shaping the global development of invasion science, as evidenced by the production

of hundreds of publications that have been cited thousands of times (Figure 3, Tables 2 and 3). Some examples of the influence of the C-I-B's research at an international level are outlined here.

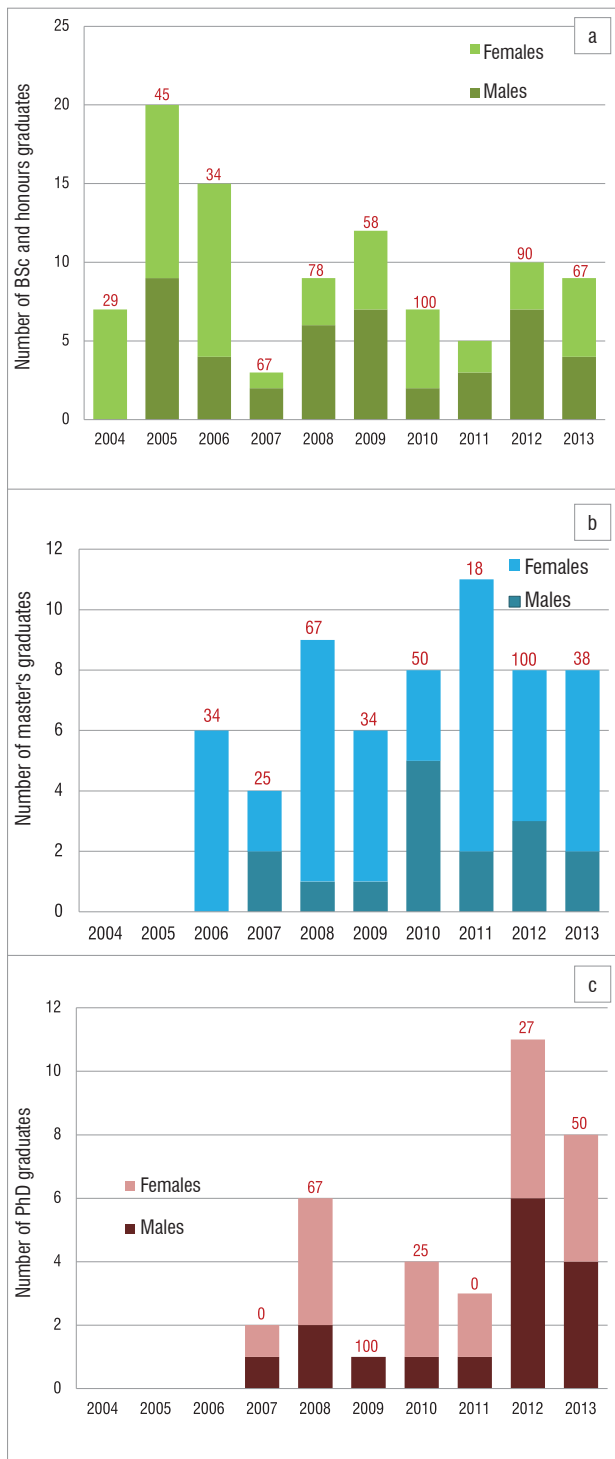


Figure 6: The number of C-I-B-supported students who graduated between 2004 and 2013 with (a) a 4-year BSc or honours degree, (b) master's degree and (c) doctoral degree. Numbers above the bars indicate the percentage of black graduates. The C-I-B is not a degree-awarding institution and degrees are awarded by participating universities.

Extensive research over the past 10 years has established the C-I-B as a centre for knowledge generation relating to the biology and conservation of the Antarctic. South Africa's involvement in the Antarctic Treaty and presence on that continent, as well as its ownership of the sub-Antarctic

Prince Edward Islands, make the country a key player in Antarctic policy relating to conservation and management practices. The C-I-B has conducted research for the South African National Antarctic Programme of the NRF and the Department of Environmental Affairs (DEA), as well as for international bodies.^{43,44} The research has addressed all levels of Antarctic conservation, from fundamental research to management planning and the production of handbooks for tourists.^{22,24,26} The research has been taken up in plans for protected area management and Antarctic Treaty System policy and position papers. The C-I-B (through its former Director, Prof. Steven Chown) also provided considerable service to the Scientific Committee on Antarctic Research (SCAR), by representing SCAR annually at the Committee for Environmental Protection (CEP) of the Antarctic Treaty System, and by ensuring that the CEP was provided with the scientific advice it solicits from SCAR and/or which SCAR considers significant for management of the Antarctic Treaty area.

Further work of international relevance has been focused on the development of Headline Indicators to measure progress made towards the Millennium Development Goals and the Convention on Biological Diversity's target of reducing the rate of loss of biodiversity by 2010. The C-I-B was contracted to develop and populate indicators of 'trends in invasive alien species'. Until 2010, no fully developed indicator for invasive alien species was available that combined trends, used a standard set of methods, and addressed a range of species groups, ecosystems and regions. This absence prevented the objective assessment of this key trend worldwide, particularly in the context of the commitment of the Convention on Biological Diversity's signatories to 'achieve by 2010 a significant reduction in the current rate of biodiversity loss at global, regional and national level as a contribution to poverty alleviation and to the benefit of all life on Earth'. Following the development of the indicators,^{45,46} the research team contributed to an assessment (using 30 indicators of biodiversity change) of the global effort to achieve the 2010 biodiversity target. The outcomes of this assessment showed that the rate of biodiversity loss has not been significantly reduced.⁴⁷ This assessment attracted much attention, with numerous articles on many international news sites. Another key intervention was the major contribution from the C-I-B to a new scheme for ranking the impacts of invasive species. This scheme was designed to have a similar structure and logic to the widely adopted IUCN Red List for categorising extinction risk so that it could potentially be integrated with existing Red Listing practices and policies.⁴⁸

The C-I-B's research has also influenced many international policy documents. An example is the Fourth Global Biodiversity Outlook (GBO-4; www.cbd.int/en/gbo4) document prepared by the Convention on Biological Diversity. The technical background document provides the basis for the main GBO-4 report, to be launched in Korea in October 2014. Almost 10% of references cited in Chapter 9 (Aichi Target 9 – Invasive alien species) of this document were published by the C-I-B.

Influence at a national level

The C-I-B has made substantial inputs to the development of policy relating to biological invasions in South Africa. For example, the C-I-B incorporated key research findings from its own programmes and from the international literature into the formulation of the regulations of the *National Environmental Management: Biodiversity Act* relating to alien and invasive species. Several core team members participated in a task team assembled by the DEA to develop objective, science-based lists of alien and invasive species; to compile a risk-assessment framework based on international best practice and advances in invasion biology in South Africa; and to participate in the drafting of the regulations. Outcomes from diverse C-I-B research were used in the process, and expert insights ensured that the regulations were grounded in international best practice from the fields of invasion biology and environmental management. Such impact is reflected in the overall structure and content of the regulations, which were published in January 2014⁴⁹, and are currently undergoing public review.

In 2014, the C-I-B also co-led, with the Council for Scientific and Industrial Research, the development of a National Strategy for Dealing with Biological Invasions in South Africa. This comprehensive strategy,

Table 3: Fields of research within the discipline of invasion science, and brief descriptions of key contributions to the development of these fields by the Centre for Invasion Biology (C+I-B). The fields of study are as defined in the C+I-B's guiding framework (Figure 2). Expanded details of the key contributions, with citations to relevant papers, are provided in Supplementary table 1 online.

Element of framework	Field of research	Brief description of C+I-B contributions
Patterns and processes of invasion	Pathways of species introduction	Pathways include the combined processes that result in, or drive, the introduction of alien species from one geographical location to another. The C+I-B has conceptualised the role of dispersal pathways (notably the contributions of propagule pressure, genetic diversity and the potential for simultaneous movement of co-evolved species) in determining the success of introductions of species to new regions. The C+I-B has also studied the introduction and dissemination of a range of organisms and different spatial scales in detail, notably for the Antarctic, and for ants, marine organisms, reptiles, amphibians and plants (notably Australian <i>Acacia</i> species, and the roles of horticulture, biofuels, roads and rivers).
	Determinants of success of species establishment	Not all introduced species will become invasive, and it would be extremely useful if invasive potential could be predicted before introductions are made. The C+I-B has advanced this understanding for numerous groups, including birds, terrestrial invertebrates and vascular plants. Such work has provided key insights for assessing the risk of further introductions. Phenotypic plasticity (the capacity of organisms to change their phenotype in response to changes in the environment) has been explored mainly for invertebrates, but also for plants.
	Patterns and mechanisms of species expansion and spread	Understanding the way in which alien species spread is crucial for developing appropriate management responses. Macroecological studies have explored the relationship between native and alien species diversity, and the link between human population density and alien species distributions. Studies have also shed new light on the invasion dynamics and options for management for birds, marine organisms, reptiles, amphibians and terrestrial plants. The role of propagule pressure in mediating invasions has been explored in many studies, covering many taxa and contexts.
	Impacts of invasions on biodiversity patterns and processes, and ecosystem functioning	Invasive alien species can have serious negative impacts on biodiversity and ecosystem services, but documented accounts of these impacts have until recently been scarce. The C+I-B has made substantial contributions in this area, ranging from local to national scales. These studies include those in the Antarctic and Prince Edward Islands, in fynbos, karoo and savanna biomes, and in freshwater and marine ecosystems.
Management and remediation of impacts	Preventing the introduction of new invasive species	One of the most effective ways to reduce the risk of biological invasions is to stop them before they happen, either by preventing high-risk species from entering the country or by intercepting them at the border. Many of the C+I-B's studies have contributed knowledge to inform screening systems to identify species that pose a high risk of invading South African ecosystems. These studies have included the use of niche-based modelling to map high-risk source areas, the compilation of global lists of invasive species ('invasive elsewhere' is one of the most robust predictors of invasive success), and the risks of moving species to Antarctica and between sub-Antarctic islands.
	Removing newly established populations of potentially harmful invasive species	If populations of invasive alien species are detected early, eradication (removal of all individuals in the country) can be considered. Internationally, eradication has been shown to be highly cost-effective. It requires dedicated and focused effort, but little money relative to reactive management. It is also important to detect new invasions and evaluate these in the context of any utilisation. The C+I-B has studied several invasive plant species that still have limited distributions and where eradication is potentially feasible.
Policy development	Reducing impacts and ecosystem restoration	Considerable attention has been given to developing sustainable protocols for restoring ecosystems following the removal of invasive species. Key insights for restoring fynbos and riparian communities after the clearing of invasive trees have emerged from the C+I-B's work. The overall effectiveness of national-scale alien plant clearing programmes has also been assessed.
	Monitoring the extent and impacts of widespread invasive species	Once alien species have come to dominate ecosystems, management options are reduced. It is important to be able to identify such areas, and the C+I-B has applied remote sensing and other methods for mapping, assessing and monitoring the extent of invasions, and standardising the metrics to be used.
	Policy formulation	Ultimately, work at the C+I-B is intended to lead to knowledge that will underpin the development of sound policies for management. The C+I-B has published accounts of frameworks or protocols for prioritising invasive species and/or areas for management based on the evaluation of their impacts and/or other considerations. The C+I-B was also a key player in the development of legal regulations for the management of invasive species, and in the drafting of a national strategy for dealing with biological invasions in South Africa.
Overarching research	Risk assessments	Formal risk assessments are a central component of policies and legislation for the management of invasive species. The C+I-B has contributed to the conceptual development of risk assessment methodologies for invasive species management, and to the implementation of risk assessment for specific applications in South Africa and Antarctica.
	Biological foundations	Understanding the impacts of invasive species demands a fundamental understanding of the functioning of the ecosystems they invade and the diverse drivers of change in these systems, as well as the interactions and synergies between these drivers. To this end, the C+I-B has conducted many studies which have contributed to the improved understanding of South African and Antarctic ecosystems, and of global biodiversity.
Basic inventories	Human dimensions	Many studies have addressed the numerous complex ways in which human requirements drive introductions of alien species, and how humans perceive alien and invasive species and rationalise the need to manage invasions and the options for doing so. Studies have examined the drivers of invasions, for example commercial forestry, the pet and nursery trades, and recreational angling. Several key case studies were exploited to elucidate the range of human perceptions regarding invasive species and options for their management, which is especially challenging when invasive species (such as trout or trees used in commercial forestry) also have commercial or other value.
	Development of a modelling capability	Many studies at the C+I-B have contributed to inventories and species lists for a range of native taxa and ecosystems. Three long-term transects (in the Cederberg, Sani Pass area and the Soutpansberg) have yielded substantial contributions with respect to bats, spiders and other invertebrates. Other contributions have been based on detailed surveys of marine ecosystems; the application of molecular methods to detect cryptic species; an assessment of cryptogenic marine species; studies to resolve questions of species identification, and the combination of meticulous field surveys, interviews and the examination of introduction records and collections. DNA barcoding has emerged as an important tool for resolving a range of species identification issues in invasion biology.
		Many types of models have been developed and used at the C+I-B for the study of different aspects of invasion science. These include models used in theoretical analyses of evolutionary processes and population dynamics, through to models applied to provide support to management. Many studies have applied bioclimatic, species distribution or 'niche-based' modelling.

based on the inputs of 19 authors (more than half of whom were from the C-I-B) and numerous workshop participants, addresses all aspects of the management of biological invasions, covering all taxa and all stages of invasion. In developing this strategy, the C-I-B worked closely with the DEA to ensure that the best science-based practices were incorporated, while at the same time ensuring that these would be practically implementable in the South African socio-political context. The strategy is to be released shortly by the DEA. The C-I-B was also contracted by the DEA to review international best practice in the field of risk assessment for invasive species⁵⁰ and to prepare guidelines for the implementation of risk assessment methods as part of national protocols for preventing the introduction of new invasive species.

In 2008, the C-I-B was also involved in the development of an Invasive Species Programme within the South African National Biodiversity Institute (SANBI's ISP). One of the main aims of SANBI's ISP was to focus on incursion response (stage 2 in Figure 2). This unit, funded by the Working for Water Programme¹³ (the branch of the DEA responsible for managing invasive alien species), was designed to (1) detect and document new invasions, (2) provide reliable and transparent post-border risk assessments and (3) provide the cross-institutional coordination needed to successfully implement national eradication plans.⁵¹ The establishment of SANBI's ISP marks a substantial departure from historical practice, where the introduction of alien species was only considered insofar as it would affect agricultural productivity and human health, and where the impacts of alien species on the broader environment were only considered reactively. The C-I-B will continue to be a key research partner for SANBI's ISP, enabling them to meet their broader mandate of reporting on the state of invasion nationally, managing data on biological invasions, and coordinating risk assessments.

Research conducted at the C-I-B has also improved on-the-ground invasive species management. Since its establishment in 2004, the C-I-B has been a key research partner of Working for Water. Since 2008, a large part of the research efforts of the C-I-B have been guided by a formal collaboration with Working for Water on research and capacity-building entitled 'Integrated management of invasive alien species in South Africa'. The partnership has produced numerous research outputs, including several economic assessments of the costs and impacts of invasive species^{2,3,40} that have been crucial for justifying the expenditure of public funds on natural resource management initiatives like Working for Water. The partnership has also trained postgraduate students (37 degrees have been completed) in a range of disciplines related to conservation biology, environmental management and invasion ecology, and provided regular training to employees of the Working for Water Programme.⁵²

Impacts at sub-national or local levels

The C-I-B is integrally involved in outreach activities aimed at developing interest, capacity and awareness in biodiversity and biological invasions. These activities range from exhibitions to training courses, providing expertise where it is requested, and learning lessons from real-life practice.

Early in the life of the C-I-B, ants were identified as a suitable group of organisms on which to base an innovative outreach and awareness-raising project, entitled *limbovane* (the isiXhosa word for ants). This project was conceived by Steven Chown and Kevin Gaston, and established by a grant from the Darwin Initiative (Department for Environment and Rural Affairs, UK). It involves pupils and teachers in biodiversity science at 25 secondary schools in the Western Cape (Figure 7). *limbovane* has benefited science education and conservation^{53,54} by (1) improving understanding of biodiversity among Life Science pupils and teachers; (2) establishing a monitoring and inventory protocol for an ecologically important and poorly understood taxonomic group (ants), and (3) generating valuable information on the diversity and distributions of native and alien invertebrates. Biodiversity was not explicitly included in the South African secondary school curriculum before 2006, but this changed with the South African National Curriculum Statement for Grade 10–12 Life Science, which introduced a major component dealing with biodiversity, continuity and environmental change. When

the new curriculum was launched, a substantial knowledge gap became evident, as teachers were either not well-equipped to teach the concept and practice of biodiversity science to pupils or had not received formal training in this relatively new field. *limbovane* filled this gap, provided important additional support to teachers and pupils, and generated key data.⁵⁵

The C-I-B initiated a collaboration with the Flower Valley Conservation Trust to provide practical guidelines for the wild flower industry in the Western Cape.⁵⁶ The sustainable use of floral resources will help to secure valuable natural resources and provide a sustainable income for flower farmers on the Agulhas Plain and ultimately elsewhere in the Cape Floristic Region. The fact that these areas are severely threatened by invasive alien plants, and the need for protocols for sustainable management that took these threats into account, provided the rationale for the involvement of the C-I-B. Harvesting wild flowers is an important economic activity in the Cape Floristic Region, especially on the Agulhas Plain which has higher flower harvesting levels and generates more income than any other fynbos area. The Agulhas Plain is recognised as a biodiversity hotspot, but this biodiversity is being severely affected by alien plant invasions, agriculture and urban development, as well as escalating pressure from the wild flower industry on natural plant populations. The guidelines provided by the C-I-B have been used in a Code of Best Practice for the use of fynbos resources, which will improve the sustainability of all flower farming operations. Protocols were also developed for the explicit integration of economic incentives in the evaluation of restoration potential in the region.⁵⁷

The C-I-B's work has also provided fundamental information on the invasion ecology of the most important invasive alien plants in the Kruger National Park, South Africa's flagship protected area. Despite its large size, the park is long and narrow, with an extensive boundary with human-modified landscapes. Seven large rivers flow into the park from adjoining residential, agricultural and pastoral areas. Preventing alien plant invasions along river corridors and across the long boundary is a major challenge for conservation.⁵⁸ Until very recently, conservation managers in South Africa had little science-based evidence for making decisions about invasive alien species as a threat to biodiversity in protected areas. Although information was available for some protected areas, a more holistic and deeper understanding of patterns and processes of invasions was lacking. C-I-B-supported projects have greatly improved our knowledge of the extent, impacts and ecology of key invasive species in protected areas, and their findings have been incorporated directly into various management plans and policies.⁵⁹ The work has also informed the development of various protocols that are now in practice and have been transferred to other national parks in South Africa.⁶⁰

In 2006, the C-I-B prepared a detailed management plan for the Prince Edward Islands.⁶¹ This plan, which was drawn up for the Department of Environmental Affairs, drew on the extensive knowledge that had been generated regarding the ecology of the islands.²² The plan covered administration, historical and conservation management, and waste management, and had a strong focus on preventing the introduction of alien species and the eradication of invasive species that had established on the island. Implementation of this plan has placed the management of these islands on a sound footing.

Conclusions

The rationale for the establishment of a CoE for invasion biology, as for other CoEs, was to stimulate sustained research and to develop capacity, in a field adjudged to be of national importance. Both of these goals have been attained, as evidenced by the fact that set targets have been met or exceeded. The C-I-B has emerged as a leading institute in the global field of invasion biology, with several unique features that differentiate it from similar institutes that have a research focus. This includes a set of KPAs that required participants to embrace environmental, social and economic facets, leading to a diverse research programme and many integrated products. The make-up of the C-I-B (a managed network of researchers with diverse interests, spread over a wide geographical range) is another unique feature. Finally, the production



Figure 7: Participants in the C-I-B's *limbovane* project, aimed at raising awareness of biodiversity and conservation issues among school pupils. (a) Gaining field experience while collecting ants along a fynbos transect, (b) gaining insights into taxonomic techniques while using identification keys and microscopes to identify specimens and (c) interactions between two ant species (*Tetramorium quadrispinosum* and *T. solidum*). Ants are common in the environment, easy to collect, and mostly completely harmless to humans. They thus provide an ideal way to teach the concepts and practice of biodiversity science. (d) Pupils are provided with certificates on completion of the courses.

of policy- and management-relevant research products arising from the engaged nature of research conducted by the C-I-B sets it apart from other similar research entities elsewhere. Much of the research has been designed to meet specific needs identified by resource managers with whom researchers have regular contact.

A mid-term review of the performance of the C-I-B, conducted by an international panel in 2009, identified several positive features.⁶² The review pointed to the emergence of the C-I-B as one of the most influential entities in the field of invasion science globally. The C-I-B was also seen to be leading the world in certain aspects of this field, for example, in tree invasions¹⁹ and invasions on the Antarctic continent^{43,44}. The backing of the C-I-B's main host institution, Stellenbosch University, has provided an attractive location, excellent facilities and financial support, allowing the unit to establish a physical presence and a sense of identity. The output of the C-I-B, as measured by the publication of papers in peer-reviewed journals (the accepted primary measure of scientific productivity) was seen in the mid-term review as remarkable. This output has been substantially assisted by the maintenance of a large, active cohort of postdoctoral fellows and postgraduate students, who have contributed greatly to the research effort.

The achievements of the C-I-B include a substantial contribution to the development of invasion science nationally and internationally, the training of scientists to address the problems of invasions, and increasing awareness among diverse sectors of society. As a result, South Africa is currently seen as a globally significant player in this important field. This review provides evidence that the CoE approach has been successful, and has made great strides towards understanding and managing invasive species – but substantial challenges remain. The C-I-B will continue to be active in this field for at least another 5 years.

It is currently developing a strategy that will build on a solid foundation, and will find ways to continue its work in a sustainable fashion.

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