Globally significant contributions to invasion science

Arsenic threat to communal areas in South Africa

Revealing gene flow from bones and teeth

South Africa's climate: 50 years of change

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Erratum

In the article that appeared on pages 106–112 of Volume 110(5/6), the labelling of Figure 2a (p.108) was incorrect: the label 35° in the centre of the x-axis should have been 0°.

Reference:

Garstang M, Coleman AD, Therrell M. Climate and the mfecane. S Afr J Sci. 2014;110(5/6), Art. #2013-0239, 7 pages. http://dx.doi.org/10.1590/sajs.2014/20130239

What's so bad about sound opinions?

The release of the World Economic Forum's (WEF) *Global Information Technology Report 2014: Rewards and Risks of Big Data* in June has received varied responses in South Africa. The Report's central focus is, as it states, global information technology – and the readiness of countries to avoid the risks, and benefit from the very considerable rewards, associated with 'big data'. As part of the analysis presented in the Report, the general quality of education systems, and of maths and science education in particular, are scored – a small part of the overall assessment, but (of course) telling in themselves. The Report placed the general status of South Africa's education system at 146 out of 148 countries, and the maths and science education at 148 out of 148. By comparison, Swaziland was placed at 81 and 91, respectively, and Zambia at 38 and 76.

The Minister of Science and Technology, Naledi Pandor, is quoted as saying that the Report's findings were 'based mainly on perceptions, rather than testing of the learners'[1], while the Department of Basic Education (DBE) issued a media release stating[2]:

> *The Report is not a credible or accurate reflection of the state of education in South Africa. This Report falsely insinuates* [sic] *that South Africa's maths and science education is ranked as the worst in the world. The DBE rejects this finding as it is based purely on the opinions or perceptions of selected executives.*

Adrian Schofield, a Fellow and Professional Member of the Institute of Information and Technology Professionals of South Africa, has offered a more nuanced view[3]:

> *The DBE is right about the Report being based on the opinions of selected executives, and only a handful of them. Without some rigorous investigation of how they are selected and what sort of sample cross-section they represent, it is impossible to gauge how much reliance to place on their responses. Even if we are satisfied with the sample, they still only represent business interests, and it would be better to include other stakeholders in the sample, together with a data-based analysis of pass marks and pass rates.*

Schofield does not argue, however, that the findings are 'grossly inaccurate'. He suggests that many people agree that the average quality of education in South Africa is abysmal. 'If we can achieve the halfway point in the Network Readiness Index, we should be able to achieve at least that in education.'[3]

The original source of the education data used in the Report – the WEF's *Global Competitiveness Report 2013–2014* (October 2013) – shows, however, that the methods used by the Executive Opinion Survey (which provides the information to the WEF) are spelled out with care, as are the techniques (such as Mahalonobis distance and univariate outlier tests) used to determine data outliers. Of course, it remains true that the survey reflects the views of just one sector of society – that of business leaders – but, as Schofield points out, this does not necessarily mean that the results of the survey are entirely ('grossly' in his words) incorrect.

To be fair, however, it makes sense that we should consider the 'testing of learners' mentioned by Minister Pandor. Unfortunately, South Africa is not one of the adjunct countries covered by the Organisation for Economic Cooperation and Development's wide-ranging Programme for International Student Appraisal, but has been included in the Trends in International Maths and Science Study (TIMSS). The test, based on each country's own curriculum, was conducted for Grade 8 learners in 42 countries, and for Grade 9 learners in 3 countries – including South Africa. South Africa would have ranked 41 out of the 42 countries for both maths and science, despite having the advantage of being one grade up. The next TIMSS assessment will take place next year and it will be instructive to revisit the South African results when they become available.

Nor is this the entire story: there are other indicative measures of the state of maths and science education in South Africa. Between 2009 and 2013, the number of students writing the maths and science exams dropped by 17% for both subjects, and of the 43% who wrote the maths exams in 2013, only 26% scored results over 50%. In addition, the 2013 Annual National Assessment results revealed that only 39% of Grade 6 learners and 2% of Grade 9 learners in South African schools were able to score more than 50% in maths tests. So while the overall National Senior Certificate results are 'improving' each year, the critical disciplines, when it comes to tertiary education and employment, are actually growing worse each year – for although the percentage pass rates in maths and science are creeping up, the number of students writing the exams is declining.

There can be little doubt that this situation is a major contributing factor to youth unemployment. There are, of course, demand-side challenges to be taken into account – but low levels of skills, numeracy and literacy have a critical role to play. In 2007, 2.7 million young people between the ages of 18 and 24 were 'not in employment, education or training' – the NEETs. By 2010, the number had grown to 3.2 million; both figures include young people who did not even make it as far as Grade 12. This year, STATS SA reported that close to two-thirds of young people were unemployed for a year or longer, while young people account for 90% of those who are unemployed and have never worked before. In his address on Youth Day this year, Deputy President Cyril Ramaphosa informed his audience that

> *the youth are particularly vulnerable to unemployment, poverty, inequality and low skills levels. More than a third of young South Africans in the labour force are unemployed. Youth unemployment is probably the single most critical challenge facing South Africa today.*[4]

As far as higher education goes, the implications are equally dire. The pool of Grade 12 graduates who qualify for major disciplines in the natural, applied natural, and social sciences is diminishing at the very time that the country needs more and more graduates from these areas.

Why, then, the fuss about the data published in the *Global Information Technology Report 2014*? There are measures, indicators, and social and economic circumstances that bear out the 'mere opinions' and their implications. Surely the appropriate responses, especially from government, would have been – we are probably not that bad, but bad enough, and we need to address the problem seriously. Perhaps the opinions of a limited number of well-informed people are not that far off the mark after all, and we need to act rather than rail against bad news.

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The ABCs of an NRF rating

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I have now been awarded virtually every NRF (National Research Foundation) rating reasonably available. Many years ago at the start of my academic life I received a 'Y' label; I have recently been awarded an 'A' rating. My most recent rating came as a pleasant but unexpected surprise, motivating me to think, more deeply than might otherwise have been the case, about NRF ratings. More particularly, I thought about what an NRF rating means, not only to me personally, but also to the research community of South Africa.

I have been known to be quite critical of the NRF rating process in the past. I continue to maintain that it is a system that bears some important flaws. However, I also recognise that it is a system that has value. Because it is used extensively and in various ways by academic institutions in South Africa, it is not likely to be abandoned in the foreseeable future. As a Deputy Dean for Research in a science faculty, I have to admit that consideration for promotions and other awards is made much easier where candidates have NRF ratings. Clearly, by providing an independent evaluation of accomplishment, apparently free of internal political considerations and other nuances, NRF ratings save considerable time and effort for universities. The system is, however, harsh and in some cases provides a skewed view of accomplishment. It is, therefore, imperative that we do not allow NRF ratings to define us as scientists, nor allow this 'label' to limit our goals and aspirations.

Much has been written regarding the fact that our perceptions define our reality. Scholars who are told they have higher IQs often achieve better results; sometimes despite the fact that their IQs are not quite as high as they think they might be! Likewise, an NRF rating should not unduly influence the kind of research one does or how one goes about this process. The fact that the ratings are inevitably perceived as hierarchal does unfortunately lead to strange perceptions among scientists, which often are quite damaging. As noted at the outset, I started off my career with a Y rating, which led to my second rating in the C category. My understanding of this system is that the NRF's expectation is that Y-rated researchers are likely to move to the C category and that those few young scientists in the P category will likely move to B category when they next apply for rating. I thus seemed to be progressing reasonably well.

As an administrator of research, I all too often overhear colleagues speaking of having 'only a C rating'. This is very unfortunate as a C rating is neither trivial to achieve nor to maintain. For many (perhaps most) researchers, this is also a necessary step in the hierarchy of ratings that they must logically wish to climb. The exceptions here are those very few young researchers who achieve a P rating the first time they apply; the remaining majority achieve Y ratings the first time. In fact, a Y rating should be hugely celebrated as it is an indication that one has successfully taken a very important step towards a career in research.

After achieving a Y rating, it is important to act strategically in terms of research and thus to ensure a jump to clear the next hurdle and achieve a C rating. This requires an intensive effort and it is important that one achieves a sustained output for a 5-year period. Alexander Graham Bell is quoted as having said that genius is 1% inspiration and 99% perspiration. In this regard, achieving a significant research output involves focused and sustained research activity, which requires commitment to one's career and involves far more than the 40-h week that is typically defined as a normal effort for which one recieves a salary. The defining issue here is that being a research academic is a vocation – not a job. I believe that many researchers are confused by the fact that successful academics often seem to be having fun. There is a perception that fun cannot be equated to hard work. Certainly it is much easier to work very hard when one is in fact having fun. I am often heard to say that I am paid to have fun – at least most of the time! I clearly enjoy my academic life hugely, but I also work very hard. I am without question not paid to work as hard as I choose to do. Most of the time this is a choice I am very happy to make. My view (I understand that others might feel differently) is that there are many benefits to a successful research career that cannot be measured in monetary terms.

The jump to a B rating in the NRF system requires engagement with the international science community. For me, one of the really incredibly enjoyable aspects of my work is that I have been able to participate in an exciting global community of scientists. I have friends and colleagues in many parts of the world and they have substantially enriched my life and work. The Internet has made this engagement easier and the network of people with whom I communicate is truly international. These networks take time to establish and they require that one engages in research problems that are significant to one's discipline, globally.

I am often confronted with researchers who tell me that their particular research interests are really only important to South African situations. Generally I find that this belief is as a result of a misplaced understanding of what the important research questions are or how one chooses to align our research (which might be focused on a local problem) with interests in the global arena. The problem I see in South Africa is that as researchers, we can be inordinately inward looking; it is commonly easier to publish research in local journals and to attend local conferences. This should not imply that I do not support national journals and society meetings, they clearly have their value; but all too often I see that a local perspective defines the totality of many South African researchers. In this regard, they choose not to elevate their research to the global arena and while their research might be very good, it is unlikely to ever be seen by the international community. And the consequence here is that these researchers will never be challenged by the international peer-review system, which admittedly can be very tough, to become world players. In terms of NRF ratings, the outcome is that some academics who are actually excellent researchers never make it into the B-rated researcher ranks.

There are many myths regarding the need to be an independent researcher and these myths have important implications in terms of NRF ratings. For example, it is often suggested that if one works in a team, one's input is not fully appreciated; and that one might forever languish in the shadow of some senior professor. As is true

for many myths, there is some truth in this contention. It is sometimes difficult to determine the relative inputs of individual researchers in a team. However, my experience has been that those researchers in teams who 'pull their own weight' are in fact quite readily recognised as a driving force behind certain activities in a team. Indeed, there might be a lag of a year or two before this recognition rises to the surface. However, if one considers the time and effort that is required to establish an entirely independent research group, the relatively short lag phase before being recognised as a key member of a team, seems quite reasonable.

As is often said of accomplishment, 'Rome was not built in a day' – this sentiment is equally true for a research career. A significant academic profile takes years to establish. I know from my own experience that there have been times along the way that I have felt a sense of frustration that the quality of my research has not been fully appreciated. However, looking back I recognise that this is because it really does take time for the research community to appreciate the research that one has done. And in many cases, one commonly receives recognition for research, years after the work was done.

My work is conducted as part of a large research team; and shortly after completing my PhD, I began to collaborate with my husband. In this regard, my only mistake was that I took my husband's name when we married. I had no idea at the time that we would work together in such a successful team, but the result has often been confusing, for both of us and for others. The fact that we both have A ratings says a lot for what two researchers can achieve together. While we are not unique in South Africa nor elsewhere in the world, our situation is unusual. As a firmly committed feminist, I believe that women often accept more of a supporting role in a marriage. This is especially the case when children are part of the package. In this regard, I urge young professional couples to understand the consequences of the choices that they make and to consider the 20- to 30-year horizon at which point children have grown up. It is at this point that I find many female colleagues are no longer particularly pleased about the choices that they believed they needed to make when they were younger.

Achieving the various levels of NRF ratings is similar to the ABCs of literacy. It is a process that involves hard work and sustained effort over time. In his article 'The secret of success', Michael Bond[1] highlights the fact that success cannot be attributed solely to IQ, ability or geographical or socioeconomic advantage. These can all be part of the mix, but another ingredient – which he calls 'grit' – concerns determination, time, effort and also 'staying power'. Do I have the grit to maintain my current NRF rating? I would like to think that I will be able to maintain at least my current level of accomplishment. But to do this I will need to ensure that my profile and productivity, at the very least, matches its current level. But I also believe strongly that one's focus should not be on a particular rating but rather on enjoying one's research in such a way that the experience is enjoyable and that the effort is not painful, neither to oneself nor to others. An academic career is a wonderful privilege and it can be hugely rewarding. Succeeding is akin to 'catching and riding a wave' – substantial effort is required but the results can be invigorating and enormously satisfying.

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South Africa – A global player in the battle against alien plant invasions

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The 4th International Symposium on Weeds and Invasive Plants was held in Montpellier, France, from 19 to 23 May 2014. Hosted by the European Weed Research Society, the symposium was attended by 152 delegates from 33 countries (including South Africa). The Society provided financial support to several delegates (including the author) to facilitate their attendance.

Initiated in 2006 and held every 3 years in a European country, this symposium has in the past highlighted important subjects such as ragweed management and how society deals with invasive species. The 2014 meeting focused mainly on the management of invasive plants and aimed to strengthen global interactions and to facilitate exchanges to bridge the gap between the science (researchers) and the action on the ground (managers and action agencies in the field). For example, an extra session offered during one of the evenings – on the establishment of global biocontrol research centres and the maintenance of effective global collaborations in this field – was aimed at ensuring an unobstructed flow of biocontrol agents between 'donating' and 'receiving' countries.

Overview of presentations

The three-and-a-half-day programme of 53 oral and 89 poster presentations, plus a midweek fieldtrip, was well structured and allowed for good international collaborations to be initiated, as the meeting took place at a single venue with no parallel sessions and minimal disturbance. Authors of posters were given an opportunity to present the key messages of their posters to the audience: an opportunity which is rarely afforded at most conferences in which posters are simply left as wall displays with the result that they receive almost no exposure.

The seven sessions were relevant to invasive plant research and management in the 21st century, with important messages being delivered by all the keynote speakers as they introduced each session. The sessions were: (1) Invasive plants in Mediterranean regions, (2) Invasive plants in aquatic and riparian ecosystems, (3) Biology, ecology, evolution and impacts of invasive plants, (4) Invasive plant management: Biological and integrated control, (5) Ragweed – a joint session with COST Action SMARTER (sustainable management of *Ambrosia artemisiifolia* in Europe), (6) Human perceptions of invasions and (7) New tools for weed risk assessment (WRA) and for early detection and rapid responses (EDRR). Each of these sessions had some relevance for South Africa, with the last session having the most relevance for South Africa's national Invasive Species Programme (ISP) based in the South African National Biodiversity Institute (SANBI).[1] The keynote address during this session, delivered by Dr Dane Panetta[2], on eradication – a word often misinterpreted by the scientific community – was particularly insightful, as eradication is the ultimate goal of the SANBI ISP. He stressed the importance of establishing the full extent of the problem before commencing an eradication attempt. Hence SANBI ISP, which includes surveillance as part of its mandate, is obviously heading in the right direction. Furthermore, he highlighted two species attributes as important factors to consider for eradication: (1) time to reproduction and (2) propagule persistence. Research conducted by the SANBI ISP should include these two factors wherever possible. It was sad to learn from him that the Australian *Chromolaena odorata* eradication project, which many had considered to be a world leader in this EDRR approach, had been terminated in 2006.

Presentations in this session demonstrated that a few (<10) countries now have at least some kind of prioritisation tool or national screening process for proposed new alien plant introductions, but it seems that the majority of countries are stuck in the 'damage control' phase in which established weeds are being continuously contained or maintained, and very few have had the opportunity to try to eradicate newly arrived ('emerging') alien species before they have had a chance to become well established. South Africa is one of these fortunate countries, and the poster presentation by Lalla[3] demonstrated the progress that has recently been made towards the eradication of an emerging invasive succulent.

Other similarities to South Africa were challenges in communicating about invasive alien plants, not only to the general public but also to governmental policymakers[4-7], and the use of modern technology (smartphones, websites, apps, etc.) in enticing the general public to become 'citizen scientists'[8]. It would have been a good information-sharing opportunity for South African experts on these topics to have attended and shared our experiences. For example, the websites initiated by two metropolitan governments – the eThekwini municipality and the City of Cape Town – differ slightly from their international counterparts, in that they only feature *emerging* invasives, thus inviting locality reports for only this limited number of species for which we have rapid response capacity – with the aim of preventing over-reporting of already widespread, well-established invasives which results in less immediate control actions and eventually in demotivated 'spotters'.

It was evident from the session on human perceptions, that we as scientists need to realise our weakness as communication or sales experts, and, if resources permit, these aspects of our programmes should be outsourced to the relevant experts in order to get our messages across. In this light, the recently initiated South African project on assigning isiZulu common names to invasive alien plants is novel and is an exciting leap in the right direction – a representative of the multi-stakeholder working group of this project at the conference would have been most beneficial.

Biocontrol was highlighted as important in the sustainable management of invasive plants, and a recent shift of people's perceptions to accepting this method has now begun. Particularly fascinating, was Dr Dick Shaw's talk on the success obtained by simply substituting the word 'biocontrol' with 'natural control' in engagement with the media.[9] The excellent work of some South African biocontrol researchers was mentioned on several occasions,

but unfortunately none of them were in attendance. Dr Asad Shabbir's research on the effects of climate change on biocontrol agents was insightful,[10] and indicates the need to realise potential consequences of climate change for the efficacy of the many established biocontrol agents in South Africa.

Dr Joe Caffrey's keynote address[11] in which he highlighted the success of controlling an aquatic weed of South African origin (*Lagarosiphon major*) in Ireland, using natural fibre called 'jute'[12], could possibly benefit South African management of the emerging alien aquatic *Hydrocleys nymphoides*, only known to occur in one dam from the KwaZulu-Natal midlands in which chemical control is not an option.

The use of the genus name *Reynoutria* (instead of *Fallopia*) at this conference may need to be reflected in the national list of invasive species soon to be published under the South African *National Environmental Management: Biodiversity Act* (NEMBA, 2004). There were a number of presentations on invasive alien species in this genus,[13-15] and links have been established with these authors to assist South African weed taxonomists with their identification queries.

Insights gained from the dedicated session on ragweeds (*Ambrosia* spp.) could help South Africa as we embark on a national battle against a related invasive alien plant species: *Parthenium hysterophorus*. The fact that the *Ambrosia* species and *P. hysterophorus* both give rise to serious human health problems as a result of their highly allergenic properties, provides the South African authorities with some useful precedents as to how best to develop their awareness campaigns, among other considerations.

Knowledge of what are currently the most globally important weeds will benefit South Africa as these species will be put onto a watch list of potential invaders for the country if they do not already feature on such lists. In addition, international collaborations with those scientists researching species that are already a problem in South Africa could benefit South African invasive alien plant management. Some of these species are: *Acacia* sp.[16], *Ailanthus altissima*[17], *Ambrosia* sp.[18-22], *Carduus nutans*[23,24] and *Cytisus scoparius*[24], *Fallopia* (=*Reynoutria*) sp.[13,25], *Genista monspessulana*[24], *Hypericum* sp.[24], *Ludwigia* sp.[26], *Lythrum* sp.[23], *Melaleuca quinquenervia*[27], *Oenothera glazioviana*[28], *Parthenium hysterophorus*[29,30], *Pueraria* sp.[31,32], *Rubus* sp.[33] and *Verbascum thapus*[34].

It is envisaged that abstracts and presentations will be uploaded onto the conference website (http://invasive.weeds.montpellier.ewrs.org/default.asp) in the near future. Authors also have the opportunity to submit papers for a special issue (or section) of the *Weed Research* journal. This will be very beneficial in global information sharing, and to initiate or build on current interactions between invasion scientists who share particular interests.

Conclusions

South African invasion experts, such as Dave Richardson, Ian Macdonald, John Wilson, Julie Coetzee, Martin Hill, Terry Olckers and others, are well known in the international invasion biology scene. People rate South African expertise in the field of biocontrol very highly; the high-calibre invasion biology research of the Centre for Invasion Biology, headquartered in Stellenbosch University, is also making us a world player. Several delegates recalled with considerable pleasure their participation in the International Weed Science Congress held in Durban in 2004, and the International Symposium on Biological Control of Weeds held at Kruger National Park in Mpumalanga earlier this year.

South African attendance and participation at international conferences is expensive, but the benefits obtained often outweigh the costs. The value of face-to-face interactions among people of similar interests cannot be overstated, nor can the opportunity to showcase South African research to the world. South African scientists need to realise their worth on the global front in invasion biology and should view participation at such international conferences as an investment, rather than simply as a cost.

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The spark of life: Electricity in the human body

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A captivating read, *The Spark of Life* presents an inclusive and magnetic account of electricity in the human body. With story-like accounts of the history of electrical discovery and its role players, lucid reviews of school biology, and absorbing descriptions of discoveries at the cutting edge of neuroscience, this book has something in it for everyone. Ashcroft's persuasiveness leaves the reader both convinced of and fascinated by the essential role of electrical signals in our cells – these are what make us truly alive.

The opening pages of the book introduce the reader to its star player: the ion channel. These proteins, found in the membranes of every cell on earth, are the focus of the author's research as a Professor in Physiology at the University of Oxford. In her own words:

> *From the lashing of the sperm's tail to sexual attraction, the beating of our hearts, the craving for yet another chocolate, and the feel of sun on your skin – everything is underpinned by ion channel activity.*

Each chapter that follows includes reference to the fundamental role of ion channels in just about every aspect of our physiology.

A tribute to the scientists and engineers who were instrumental in the illumination of animal electricity, the finer details of how ion channels generate electric currents in our body, and the structure and function of nerve fibres form the book's foundation. Later chapters give specific attention to the workings of the synaptic gap, the 'ins and outs' of chemical neurotransmission at the neuromuscular junction, and the heart as a 'pump controlled by electricity'. The significance of ion channels is solidified by accounts of their function in photosynthesis, water regulation in our bodies, fertilisation and cell death and in underpinning various clinical conditions such as cystic fibrosis and diabetes. The later chapters form somewhat of a climax, exploring how ion channels in our sense organs dictate the way in which we see the world around us, and how sensory experience is transformed into electrical impulses that our brains can interpret. In the penultimate chapter, the discussion extends beyond the purely functional. Here the reader will discover how the wiring of the brain influences thoughts, consciousness, emotions and personalities. The book ends with a peek into the future – including prospects of creating artificial memory and controlling computers directly with our minds.

Both the expert in the field and the layperson will appreciate the way in which Ashcroft uses the unique angle of the ion channel to elegantly contextualise modern neuroscience in a manner that makes it truly come alive. How ion channels in our nerve cells create electrical impulses, why eating a puffer fish might kill you, what exactly happens during a heart attack, how taste is detected and deciphered, how prosthetic arms can be controlled by thought alone and how memories are generated and stored – this book is filled with a plethora of attention-grabbing facts.

Beyond the facts, the author also takes the opportunity to describe how neuroscience has shaped her philosophy. According to this philosophy, 'we are no more than the integrated electrical activity of our brain cells', and 'free will...is merely an illusion...a construct of the brain'. On a lighter note, Ashcroft makes wide and frequent use of humour. In one instance she describes how the beat of the Bee Gees hit 'Staying Alive' helps trainee doctors perfect the rhythm used in CPR, while 'Another One Bites The Dust' provides an equally perfect (but far less appropriate) training aide.

From the intricacies of the K_{ATP} channel to electroconvulsive therapy, Ashcroft demonstrates a unique ability to make complicated science both comprehensible and appealing. In so doing, she exemplifies the purpose of popular science literature: bridging the gap between scientific research and literature and the territory of cultural and political dialogue. Helpful diagrams and portraits depicting fascinating classic experiments make for a more enjoyable and easy-to-follow read. In the field of neuroscience, in which new information is constantly being unearthed, books like *The Spark of Life* are invaluable.

Overall, I found this book to be a wonderful read and it comes with my highest recommendation. Should you choose to read it, you are bound to expand your knowledge and have fun doing so.

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 supplies[4], increase erosion[5], exacerbate wildfires[6], degrade rangelands[7], threaten the health of people and livestock[8], reduce productivity in agriculture[9], and impact negatively in many ways on the country's remarkable biodiversity[2]. The economic damage caused by these invasions has been estimated at over ZAR9 billion per year[10], 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 (KPAs): 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 KPAs 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.

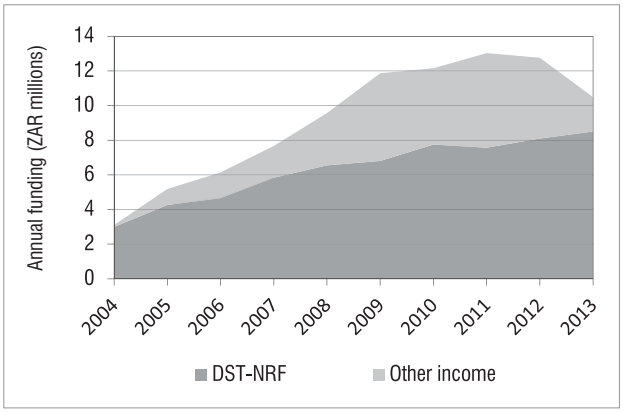

Figure 1: Funding to the Centre for Invasion Biology from the Department of Science and Technology (DST) through the National Research Foundation (NRF), and other sources, between 2004 and 2013. 'Other income' refers to contract funding which varies annually.

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

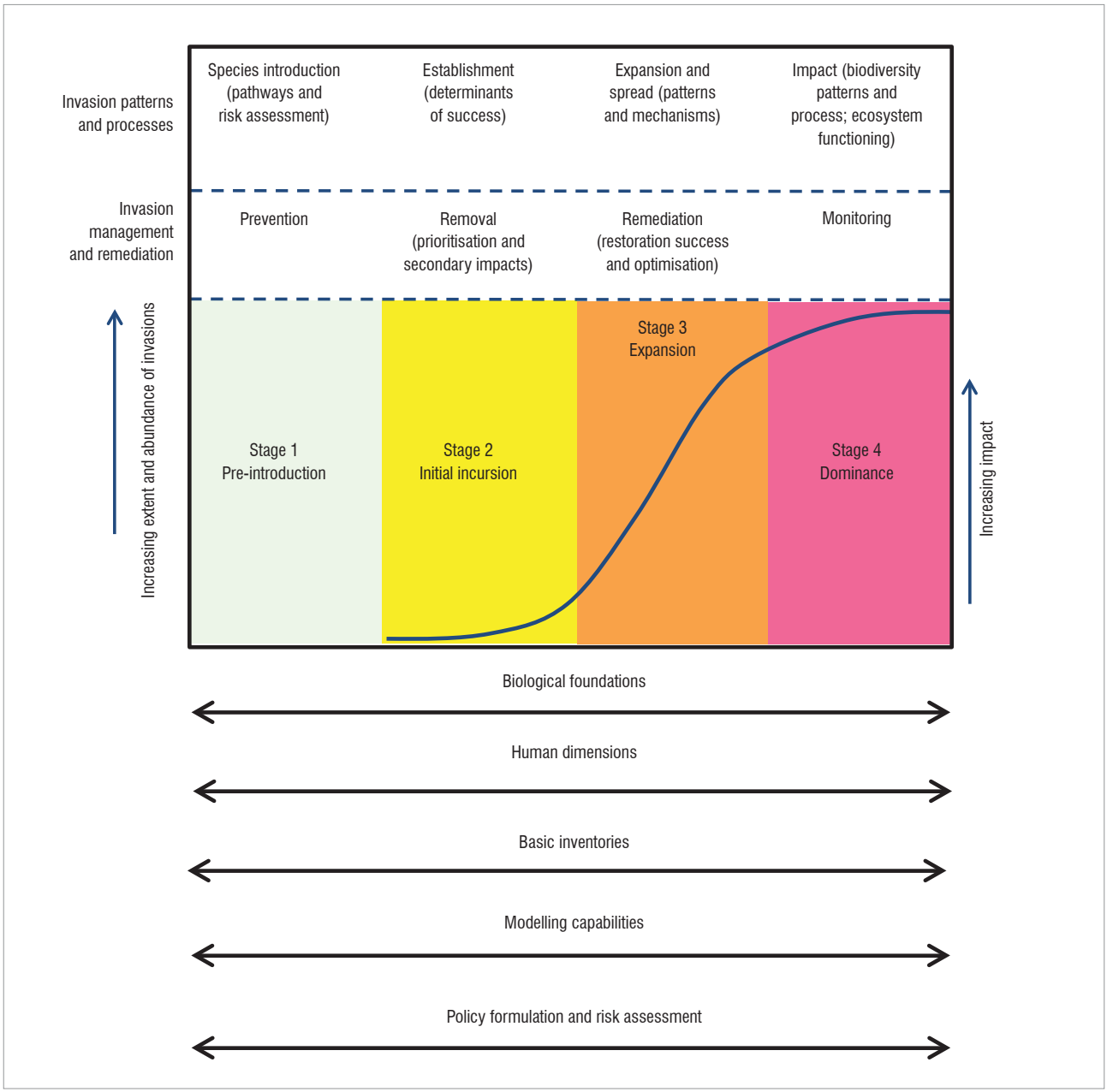

Figure 2: A framework used by the Centre for Invasion Biology to guide relevant and comprehensive research on biological invasions. There are four stages of invasion, dependent on the extent and abundance of the species concerned: pre-introduction, initial incursion, expansion, and dominance. At each 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 each[15]). 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).

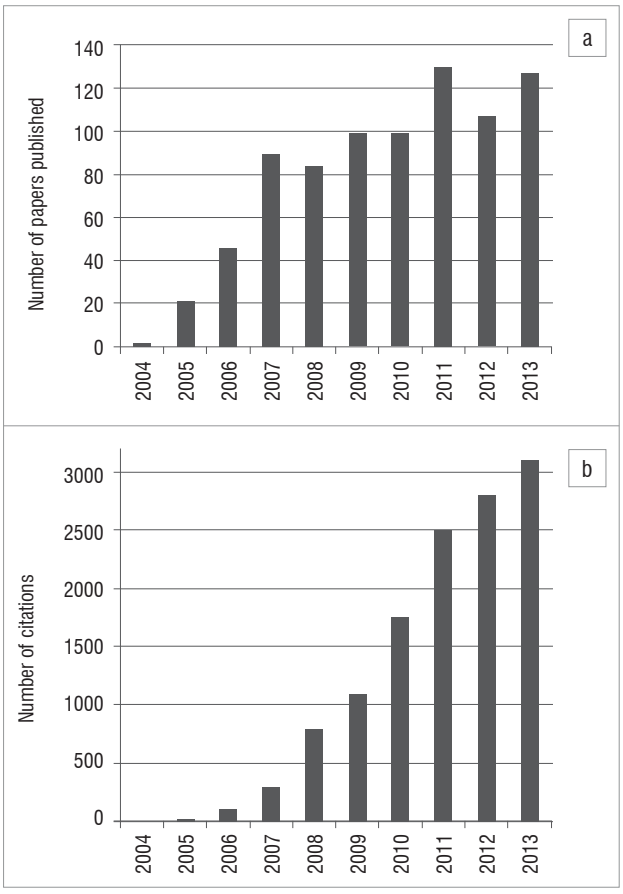

Figure 3: (a) The number of papers published each year in Web of Science (formerly ISI) indexed journals during the first decade of research by the Centre for Invasion Biology and (b) the annual number of citations to papers published by the Centre for Invasion Biology.

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 4: Word cloud derived from the 20 most highly cited papers published by the Centre for Invasion Biology between 2004 and 2013. The size of words is proportional to the number of times they appear in the titles, keywords and abstracts of these papers.

Figure 5: The Centre for Invasion Biology ensures contact with dispersed members by holding an Annual Research Meeting, which all core team members and all postgraduate students are required to attend (top right). In addition, focused international gatherings are convened to address and synthesise topics of importance and global interest: (top left) participants at a workshop on introduced Australian *Acacia* species; (middle left) participants at a workshop on the ecology and management of tree invasions; (bottom) participants at a workshop at which a global synthesis of invasion ecology was undertaken to mark the 50th anniversary of the publication of Charles Elton's pioneering work on invasion biology (see Table 2 for details).

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 *Acacia* 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 species[39]; assessed the overall contribution of biological control to the management of invasive alien plants and the protection of ecosystem services in South Africa[40]; and identified the exact provenance of invasive species using molecular ecology to facilitate better host matching for biocontrol agents[41]. 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.

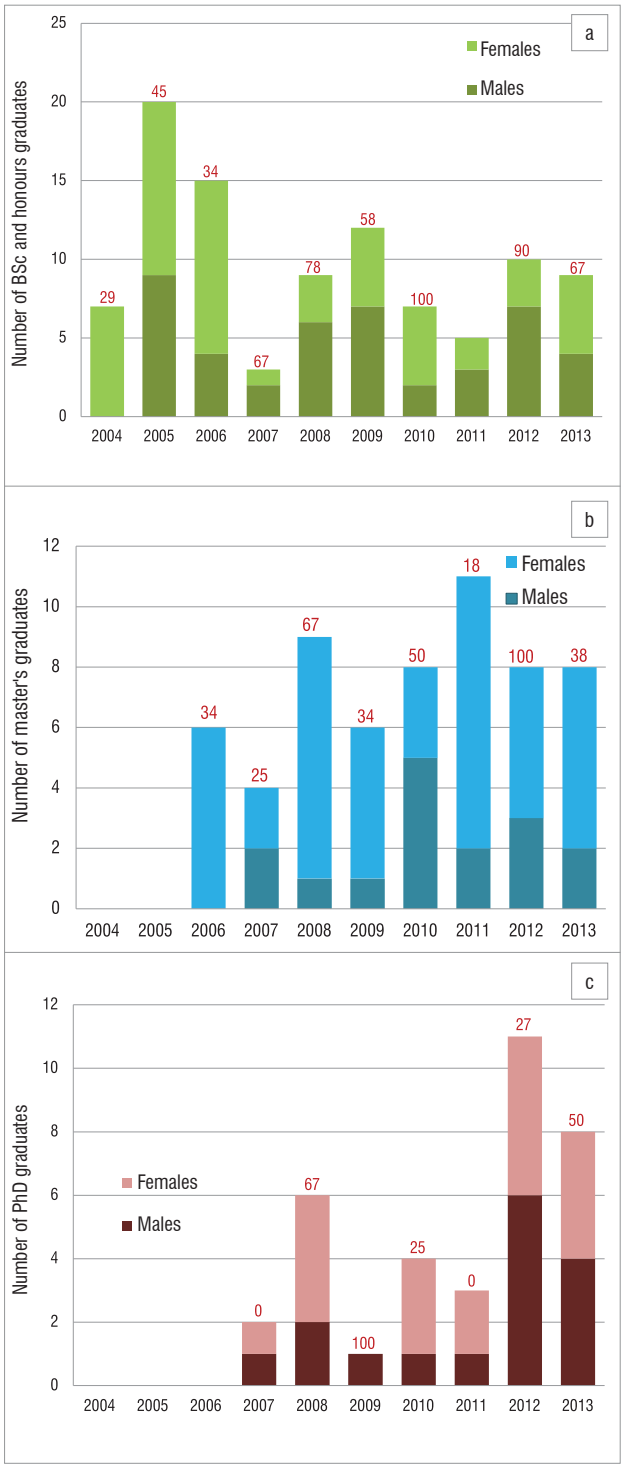

Figure 6: The number of C·I·B-supported students who graduated between 2004 and 2013 with (a) a 4-year BSc or honours degree, (b) master's degree and (c) doctoral degree. Numbers above the bars indicate the percentage of black graduates. The C·I·B is not a degree-awarding institution and degrees are 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 2014[49], 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 *Acacia* 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.
	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 development	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.
	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.
Overarching research	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.
	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.
	Basic inventories	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.
	Development of a modelling capability	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 species[50] 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 Programme[13] (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 invasions[19] 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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Golden Gate Highlands National Park: Killing the goose laying golden eggs? Comment on Taru et al. (2013)

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In their recent commentary published in the *South African Journal of Science*, Taru and colleagues[1] highlighted the possible shortcomings of the approved management plan[2] of Golden Gate Highlands National Park (GGHNP). Although they can be commended for their critical efforts to evaluate policies within an adaptive management framework, many of their concerns were grounded on fragile factual foundations. Consequently, despite their good intentions, their specific recommendations seem to be misconstrued. It is not necessarily our aim to defend the management plan of GGHNP, nor do we believe that it is faultless. Instead, in this brief essay, we will firstly highlight some of the factual inaccuracies in the evaluation by Taru and colleagues and, secondly, point out some considerations that were not plainly addressed in their original commentary.

Taru and colleagues pointed out flaws in the approved management plan of GGHNP but, unfortunately, many of their criticisms seem to contradict what is actually written in the document or what is happening on the ground (Table 1). While we acknowledge that they may have been questioning the *adequacy* of specific sections of the management plan, rather than highlighting their *absence*, Taru and colleagues did not make it clear where and how their opinions differed from what had already been addressed by the management plan. As such, it was difficult to gain an accurate picture of the reality at GGHNP based on their assessment.

Table 1: A list of criticisms made by Taru and colleagues[1]

Criticism	Reality
The management plan does not adequately consider that local communities are deprived by the absence of a local museum showcasing the palaeontological and cultural heritage of GGHNP.	This concern is addressed in Section 2 (page 2) of the management plan: 'A world-class interpretive centre that will tell the story of the African dinosaurs is in the planning stages'. Despite not yet having a museum, GGHNP has committed to environmental education in the region (Section 10.4.3.; pages 41–42), which currently involves more than 4000 individuals annually.[9]
With the exception of a few individuals who graze their livestock, local community members have not benefitted from activities within GGHNP.	In accordance with Section 17(j–k) of the South African *National Environmental Management: Protected Areas Act (NEMPA) Act 57 of 2003*, GGHNP is legally obligated to be a key contributor to the local economy and livelihoods of communities. This is covered in Section 10.4.4 (pages 43–45) of the management plan.
The management plan needs to address a socially oriented benefit sharing scheme to reduce the illegal harvesting of resources in GGHNP.	In line with Sections 17(g–h) and 41(2)(f) of NEMPA, the management plan addresses the importance of sustainable resource use in GGHNP (Section 10.2.3., pages 34–35). This section specifically emphasises the importance of a co-management approach with various stakeholders to enhance human well-being.
The public participation process used in the development of the management plan was 'not from a grassroots but an elitist level'.	Appendix 3 of the approved management plan outlines the multiple stages of the public consultation process. This process included representatives and members of the public from the local (Maluti-a-phofung) and district (Thabo Mafutsanyane) municipalities as well as the University of the Free State, amongst others.
The management plan does not adequately define combative measures against the illegal grazing of livestock within GGHNP.	The fact that livestock still graze in the most sensitive high-altitude grasslands, is because of a lack of enforcement and not a strategic oversight; Section 10.2.2.4 (page 33) of the management plan highlights the negative effects of livestock grazing on natural biota, and identifies actions and responsible parties for the removal of species from GGHNP.
The fire management policy requires revision and immediate research into the environmental consequences of fire.	Although a valid concern, this statement trivialises a widespread problem throughout the region by implying that veld fires are a result of the absence of research and lack of information. Nevertheless, Section 10.2.2.2. (pages 30–31) of the management plan addresses the fire management strategy of GGHNP, which includes the prevention, monitoring and fighting of fires. Staff currently monitor fire frequency and are actively involved in fighting uncontrolled fires (as many as 76 uncontrolled blazes annually[9]).
The ability to maintain water quality and quantity is being jeopardised as the ecological integrity of the wetlands in GGHNP are being threatened by erosion and alien vegetation.	GGHNP aims to ensure that the park and its surrounds produce high-quality water. This is addressed in Section 10.2.1 (pages 27–28) of the management plan, which highlights the importance of flow regulation, wastewater management, the spread of alien invasive species and excessive erosion.
The management plan fails to demonstrate mechanisms of traffic control. Uncontrolled use of the R712 road through GGHNP – which is dominated by freight transport from Durban to Maseru (Lesotho) – is a missed opportunity for revenue collection.	Section 7 (page 19) of the management plan explains that access to the park via the R712 cannot be restricted as it is a public road. However, road signs at the intersection with the R711 near Clarens indicate that the road through GGHNP is not suitable for heavy freight vehicles. Moreover, the primary freight route from Durban to Maseru is along the N5 via Bethlehem, not through GGHNP.
The management plan does not stress the importance of developing a GIS database for the spatial locations of important geological and heritage features.	Section 10.4 (pages 38–40) of the management plan focuses on establishing the best ways to promote tourism through the proper management of geological and heritage features of GGHNP. These strategies include the updating of pre-existing databases.
Access to GGHNP should be restricted to visitors who check in at control points and pay for access permits.	Access to GGHNP is already limited in all zones except the high-intensity zone along the R712 road (Sections 6 and 7; pages 15–18). This control involves self-reporting at the Glen Reenen Rest Camp or the Golden Gate Hotel where an access permit is obtainable (the fee was ZAR36 per person in December 2013). Overnight visitors are also required to check-out on departure.
Fossilised eggs and foetal skeletons discovered in the park[3,4] were shipped away to distant museums; wasting an excellent learning opportunity in the region.	The removal of fossils without a permit is forbidden by Section 35 of the South African *National Heritage Resources Act 25 of 1999*. It is not possible to legally remove fossils anywhere in South Africa without informing the proper authorities. Scientists who have removed fossilised eggs followed the correct procedures and were granted permission by the South African government to do so.

In their commentary, Taru and colleagues also called for the accelerated documentation of all the palaeontological[3,4], geological[5,6] and cultural[7] features of GGHNP using geographic information systems (GIS) and suggested that this activity would promote tourism in the region. They went on to imply that the revenue generated by increased tourism could be used to accelerate social and economic development in the poverty-stricken QwaQwa region (Maluti-a-phofung local municipality). This implication is supposedly based on the view that the short-term generation of capital could act as a catalyst for secondary economic growth in the region, which, coincidentally, aligns with the views expressed on page 5 of the approved management plan. Unfortunately, this reasoning is based on incomplete evidence: neither the management plan nor Taru and colleagues' evaluation considered the continuous outflow of tourism-generated revenue from the region. In a preliminary appraisal of tourism in the town of Clarens within the Maluti-a-phofung local municipality, Atkinson[8] found that less than 5% of tourism-generated revenue was actually spent within the local municipality, while the greatest proportion of income was spent either in the adjacent Dihlabeng local municipality (37%) or in other cities and provinces (59%). This finding suggests that accelerated tourism will not necessarily alleviate poverty in the QwaQwa region. Moreover, the palaeontological, geological and cultural (i.e. rock art) features in GGHNP all degrade naturally[5,6] and increased human exposure will only accelerate this degradation. In this sense, these natural features should be viewed as a finite stock, rather than a sustainable generator of long-term revenue. Given that the revenue created by increased exploitation might just flow out of the region without uplifting local communities, the suggestion by Taru and colleagues is akin to the fable of the farmer who kills the goose that lays the golden eggs: they are potentially sacrificing a small, but steady income for the prospect of a large and immediate pay-off that may never materialise.

We recommend that GGHNP rather take a proactive role in poverty reduction by continuing, and perhaps expanding, their efforts in environmental education. Currently, more than 4000 individuals benefit from these educational programmes each year[9] and, according to the budget outlined in the management plan, these programmes require annual investments of ZAR1.45 million. Despite these costs, however, such efforts are invaluable in a region in which just one in four people over the age of 20 has completed secondary school education.[10] Moreover, environmental education was listed as the primary reason for visiting the park by inhabitants of QwaQwa and Clarens[11], so this education-centred strategy could help build ties between park management and local communities. Whether our suggestions are in line with the long-term objectives of GGHNP or not, we feel confident that they are more sustainable than the fast-tracked exploitation recommended by Taru and colleagues. Their strategy is potentially damaging to the integrity of GGHNP and would not necessarily translate into modest, let alone sustainable, local economic growth. Instead, such an economic-centred view of natural resources as a source of capital could accelerate environmental collapse and cause immeasurable harm to people in the long term.[12]

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A concise review of the applications of NiTi shape-memory alloys in composite materials

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Composite materials have increasingly been used in construction and in the aerospace and automotive industries because they are lightweight, strong and corrosion resistant, and because their anisotropic properties can be controlled; maintenance costs are also low. However, there is a growing demand for improved composite materials which have 'smart' capabilities, that is, they are able to sense, actuate and respond to the surrounding environment. Shape-memory alloys (SMAs) possess sensing and actuating functions. Embedding SMAs into composite materials can create smart or intelligent composites. Amongst the commercially available SMAs, NiTi alloys – in the form of wires, ribbons or particles – are the most widely used because of their excellent mechanical properties and shape-memory performance. These materials have found application in broad fields of engineering and science as a result of their superior thermomechanical properties. Here we review the use of NiTi SMAs in applications such as vibration control, shape control, position control and adaptive stiffening.

Introduction

Composite materials are increasingly used in construction and in the aerospace and automotive industries because they are lightweight, strong and corrosion resistant and their anisotropic properties can be controlled.[1] The high specific stiffness and strength characteristics of composites have increased their application in various engineering structures over other engineering materials.[2] However, there is a growing demand to improve on composite materials to enable 'smart' capabilities, that is, so they can sense, actuate and respond to the surrounding environment.

Shape-memory alloys (SMAs) are metallic alloys that can undergo reversible martensitic phase transformations as a result of applied thermomechanical loads and are capable of recovering permanent strains when heated above a certain transformation temperature.[3] SMAs possess sensing and actuating functions and have the potential to control the mechanical properties and responses of their hosts as a result of their inherent unique characteristics of shape-memory effect and pseudoelasticity.[4] When integrated into structural components, they can potentially perform sensing, diagnosing, actuating and repair or healing functions, thereby enhancing the performance characteristics of their hosts. Amongst the commercially available SMAs, NiTi (nickel-titanium) alloys are the most widely used because of their excellent mechanical properties and superior material characteristics regarding shape-memory performance, good processability, good corrosion resistance, cyclic stability, wear resistance and biocompatibility, which allows them to be used in the biomedical field.[5,6] We present a concise review of the applications of NiTi SMAs in composite materials and the ways in which their performance characteristics can be improved.

General properties of NiTi shape-memory alloys

NiTi SMAs can exist in two crystal phases: (1) the stronger austenite (or parent) phase which is stable at high temperatures and (2) the softer martensite (product) phase which is stable at low temperatures.[7] The NiTi SMA in its martensitic phase can be easily deformed because of its relative softness. The austenite phase has a well-ordered body-centred cubic structure that presents only one variant. The martensite phase has a lower symmetry and may exist in multiple variants depending on the type of phase transformation. Therefore, although there are several ways by which martensite can be formed out of austenite, there is only one route by which the martensite formed will revert to austenite. The understanding of the characteristics of NiTi SMAs such as SME and pseudoelasticity, is important in the design and implementation of NiTi-based devices.

Shape-memory effect

Shape-memory effect (SME) is a phenomenon by which SMAs that have been permanently deformed can recover their original configuration after being heated above a certain transition temperature. SME is based on the reversible martensitic transformation of the SMA between an austenitic phase and a martensitic phase by the application of heat or stress.[8]

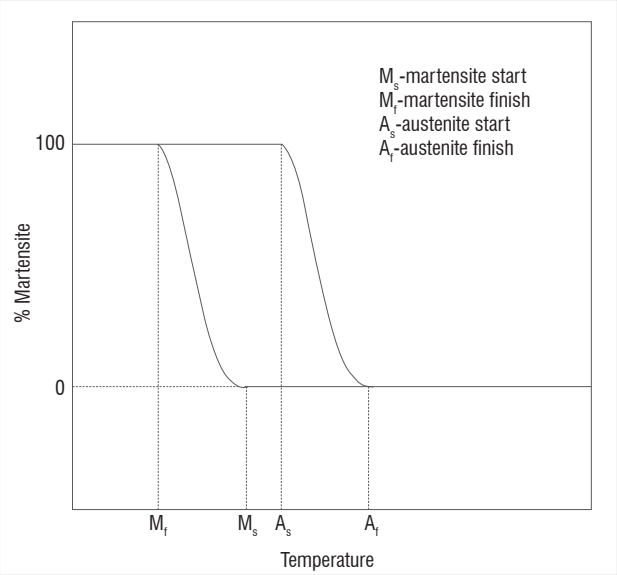
The forward thermoelastic transformation occurs when the alloy in the parent austenitic phase is cooled through the transformation temperatures – martensite start (M_s) and martensite finish (M_f) – to produce martensite. The reverse transformation occurs when the alloy is heated through the reverse transformation temperatures – austenite start (A_s) and austenite finish (A_f).[10,11]

One-way shape-memory effect

One-way SME (or pseudoplasticity), schematically shown in Figure 2, begins from the high-symmetry austenitic phase. After cooling to martensite, the material undergoes permanent deformation, and then reverts to its undeformed shape when heated above the transition temperature.

The one-way SME is geometrically illustrated in Figure 3. The austenite is cooled below M_f to form twinned martensite. Upon the application of stress, detwinned martensite is formed. When the detwinned martensite is heated above A_f, it returns to the austenite phase and its original shape. In NiTi SMAs, a strain of up to 9% can

be completely recovered (free recovery) and recovery stress between 500 MPa and 900 MPa can be generated (constrained recovery) during this process.[12]



Source: Liang et al.[9]

Figure 1: Illustration of martensitic reverse transformations.

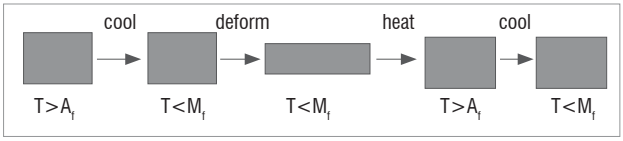
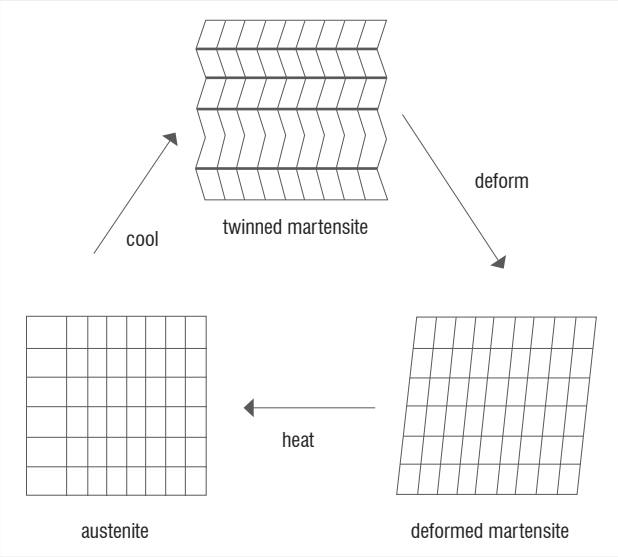


Figure 2: One-way shape-memory effect.



Source: Duerig et al.[13]

Figure 3: Microscopic illustration of the shape-memory effect.

Two-way shape-memory effect

The two-way SME, schematically illustrated in Figure 4, is the preferential creation of certain variants of martensite that are energetically more stable and depend solely on temperature. Two-way SME is achieved by a thermomechanical treatment known as training in which the SMAs are 'made' to remember a predetermined geometrical shape at high temperature (greater than A_f) and another shape at low temperature (lower than M_f).[14] The SMA is severely deformed at a temperature below M_f. When the deformed martensite is heated above A_f, the SMA reverts to its original shape and, upon subsequent cooling, it returns to the deformed shape.

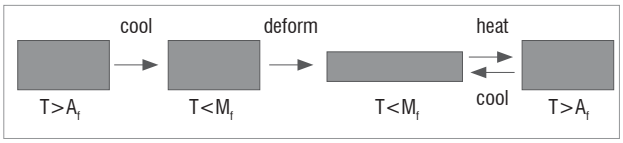
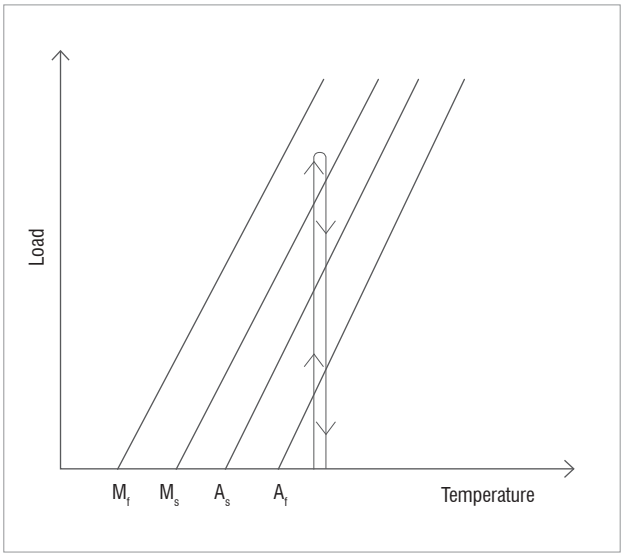


Figure 4: Two-way shape-memory effect.

Pseudoelasticity

Pseudoelasticity (also known as superelasticity) is the ability of the NiTi SMA to return to its original shape upon loading after substantial deformation.[15] This functional property of NiTi SMAs is present at almost constant deformation and constant temperature (Figure 5).



Source: SMA/MEMS Research Group[16]

Figure 5: Load diagram of the pseudoelastic effect.

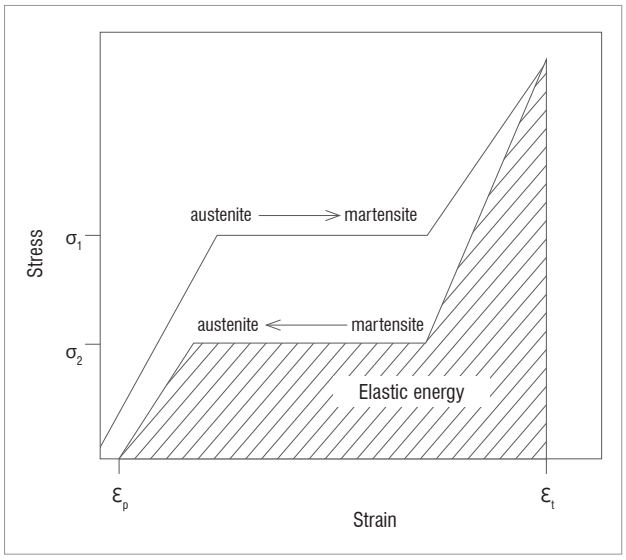
Generally, pseudoelasticity refers to the observed non-linear unloading characteristics, while superelasticity is associated with the stress plateau and inflection point upon unloading as shown in Figure 6.[17] Unlike the SME, in which martensite is formed when the SMA is cooled to below M_s, pseudoelasticity occurs when the SMA is composed entirely of the austenitic phase. Under the application of stress, the austenite is transformed to martensite and upon the removal of the stress the martensite reverts to austenite. The martensite formed via this transformation is known as stress-induced martensite.

Improvement on the properties of NiTi shape-memory alloys

Despite the excellent thermomechanical properties of NiTi SMAs, research has been conducted on methods to improve on their performance characteristics. It has been shown experimentally[18] that thermomechanical cycling and aging erases the non-homogeneous transformation and inconsistent yield strength of NiTi SMAs.

Uchil et al.[19] studied the stability of the R-phase during thermal cycling for near equiatomic, 40% cold-worked, NiTi wire samples using electrical resistivity measurements. The NiTi wire samples are heat treated at higher temperature ranges and show only M↔A transformation during the first cycle and M_s decreases along with the onset of intermediate R-phase. Uchil et al.[19] established that for NiTi, for any heat-treatment temperature above 420 °C in which only M↔A are present, the effect of thermal cycling on the transformation behaviour is identical. The number of critical cycles needed to stabilise the R-phase continues to increase

with an increase in heat-treatment temperature and this number tends to be a constant above 520 °C.



Source: Duerig and Zadno[17].

Figure 6: Stress versus strain characteristics showing superelasticity.

Applications of NiTi shape-memory alloys

The use of NiTi SMAs in engineering and science applications is a result of their unique characteristics. A considerable amount of work has been done in the area of embedding NiTi SMAs into composite structures, with the objective of obtaining a better understanding of the effects that embedded NiTi SMAs have on the material properties and behaviours of the resulting composite structures.[20] Philander[21] developed an engineering computational design tool that can be used for the design of NiTi SMA wire based smart or intelligent actuators that exploit SME for their operation.

Hybridised composite materials have the ability to alter their stiffness properties when the NiTi SMAs are activated. The hybridised composites can also be utilised in shape and position control as well as for vibration control. Whereas the active use of NiTi SMAs is based on the SME characteristics, the passive application, such as vibration damping, is a function of the pseudoelastic effect.

Vibration and dynamic response control

Baz et al.[22] studied the feasibility of using NiTi actuators in controlling the flexural vibrations of a flexible cantilevered beam by modelling the beam dynamics using the finite element method. They integrated the thermal and dynamic characteristics of the SMA to develop a mathematical model of the composite beam-actuators system. They confirmed that at the time of activation, when the beam is subject to step displacement, the actuator shrinks and exerts a force which provides the restoring control movement. They established that NiTi actuators are feasible for vibration control applications and can be extended to control higher mode shapes via implementing sophisticated control strategies such as a time-sharing strategy.

Ni et al.[23] investigated the vibration characteristics of laminated composite plates with embedded SMAs. They found that the natural frequency of the SMA-based composite plate is a function of the volume fraction of the SMA. At a temperature of about 100 °C, when the SMA is in the austenite phase, the natural frequency of the SMA-based composite plate is almost twice that of a laminated plate without an SMA implant. In the case of woven SMA-based laminated plates, they reported that the natural frequency increased by 1.8 times when compared to laminated plates without SMA implants. They established that the use of SMA wires and woven SMA mesh is an effective way to implement damping control in practical material structures.

Kim et al.[24] studied the vibration of thermally post-buckled composite plates embedded with NiTi SMAs. They reported that an increase in the volume fraction and initial strain of the NiTi SMA fibres resulted in a stiffer plate and hence increased natural frequencies, lower thermal deflections and higher critical temperatures. They also reported that, in the pre-buckled region, the presence of SMA in the composite plate increased its natural frequency as a result of the recovery stress of the SMA. However, in the post-buckled region, the natural frequencies of the SMA-embedded plates were lower than those without SMA. Nevertheless, they established that SMA fibres can be used to control the vibration behaviour of composite structures, modification of natural frequencies, critical temperatures and thermal deflections.

Turner[25] investigated glass–epoxy composite laminates embedded with 5% pre-strained NiTi SMA actuators under thermal and acoustic loads for dynamic response abatement applications. Turner[25] also investigated conventional composite laminates with and without additional composite layers subjected to thermal and acoustic loads. He reported that as little as 13% volume fraction of SMA will completely nullify thermal post-buckling over a small temperature range and that embedding SMA wire actuators into hybrid composite laminates is more effective in increasing the fundamental frequencies and reducing the amplitude of dynamic response when compared to stiffening the hybrid composite laminates by adding additional composite layers. He established that an enormous reduction in dynamic response can be achieved by embedding SMA actuators into composite laminates.

Gordaninejad et al.[26] investigated the transient response of a thick polycarbonate composite cantilever beam which had SMA reinforcements embedded along its neutral axis. Under the influence of a harmonic force excitation exerted as a point load at its free end, they reported that the vibration amplitude of the composite cantilever beam depends on temperature, activation voltage, SMA layer thickness, beam length and the martensitic residual strain. They established that the thicker the SMA layers are, the greater the reduction of vibration amplitude. Their results confirmed that embedding thin SMA layers in such a beam was an effective way to actively control beam vibration.

Mei et al.[27] studied the vibration of rectangular graphite–epoxy laminated composite plates with and without embedded NiTi SMA fibres at elevated temperatures. They found that an increase in the volume fraction and pre-strain of the NiTi SMA results in a stiffer plate. They also found that at temperatures lower than the critical buckling temperature, the recovery stress generated by the SMA overwhelms the stress caused by thermal expansion. They reported that the large recovery stress generated by the NiTi SMA increases the stiffness, the critical buckling temperature and the natural frequency of the SMA embedded composite plate. They established the effectiveness of embedding SMA for frequency tuning and vibration control at elevated temperatures.

Stiffness and impact damage controls

Tsai and Chen[28] studied the dynamic stability of a NiTi SMA fibres reinforced composite beam subjected to an axial periodic dynamic force. They confirmed that the dynamic stability is a function of temperature, the volume fraction of the NiTi SMA fibres and the pre-straining of the wires. The higher the temperature, the more stable was the composite beam. They reported that an increase in the number of the NiTi SMA fibres increases the stiffness of the composite beam and hence increases the buckling strength; the presence of the NiTi SMA fibres increases the stiffness of the composite beam and thus enables a more dynamically stable composite beam.

Meo et al.[29] investigated the impact damage behaviour of carbon fibre–epoxy composite plates embedded with NiTi SMAs. They found that because of the superelastic and hysteric behaviours of SMA wires, their implementation improves the strain energy absorption capability of the composite plate, thus increasing its overall bending and shear elasticity, and hence reducing ply failures. They also found that the closer the SMA wires are to the impact location, the greater the effect of the SMA wires on the absorption of impact energy, particularly on the contact deformation, the global bending deformation and the transverse shear deformation.

They confirmed that increasing the density of SMA wires significantly reduces ply failures of the composite plate. They established that for low-velocity impacts, embedding SMA wires can be an effective way to increase the impact damage resistance of hybrid composite structures when compared to conventional composite structures.

Armstrong and Lilholt[30] investigated the time-dependent, super-viscoelastic behaviour of low-density polyethylene matrix material embedded with NiTi fibre reinforcements when subjected to an isothermal tensile cycle composed of a constant strain rate tensile loading followed by a constant stress rate tensile unloading. They reported that the qualitative behaviour of the SMA fibre reinforced composite was primarily dependent on the fibre mechanical response. This finding is as a result of the SMA fibres possessing higher strength and stiffness than the polymeric host. They established that the NiTi fibre actuated viscoelastic low-density polyethylene matrix composite exhibited large increases in strength, stiffness and shape recovery energy in comparison to the homogeneous polymer matrix.

Zhao and Zhang[31] investigated the thermomechanical properties of a composite asymmetrically embedded with an SMA layer. They found that the beam deflection depends on the thickness of the SMA layer and the moment generated by the SMA. They also found that, whereas an asymmetric SMA layer results in moment generation in the beam, SMA embedded symmetrically produces no moment. They confirmed that the more asymmetric the SMA layer, the greater the bending. They established that the thicker the SMA layer, the stiffer the composite beam and hence the smaller the composite beam deflection as a result of mechanical load.

Kim and Roh[32] studied the adaptability of a hybrid smart composite plate under low-velocity impact. SMA fibres were embedded within the graphite–epoxy composite plate and piezoelectric sensors were mounted on the opposite side of the impact. They found that at an elevated temperature, the elastic modulus of the SMAs increases in its austenite phase and results in a stiffness increase in the composite, which reduces the deflection. An increase in the SMA fibre volume fraction decreases the dynamic impact induced deflection. They ascertained that SMA fibres embedded within the layers of a composite beam can significantly enhance the global resistance of the beam to low-velocity impact.

Shape and position control

Lee and Choi[33] studied the shape control of a composite beam with embedded SMA wire actuators. The SMA wire actuators were eccentrically embedded. The flexible composite beam was investigated under the action of axial compressive loadings. They found that the shape control of these composite beams did not depend on thermal moment but on initial geometric imperfection. They also found that the activation force generated by the activated SMA wire actuators results in either an increased buckling load or 'snap-through' of the composite beam. They reported that the dominant and decisive factor which influenced the shape control of the composite beam was the reactive moment generated by the SMA wire actuators recovery force. They verified the shape-control capability of SMA wire actuators when embedded in real composite structures which function in an unanticipated environment.

Gangbing et al.[34] investigated the active position control of a honeycomb structure composite beam with SMA wire embedded in one side. The cantilevered beam was activated by supplying appropriate current (ranging from 1.5 A to 3.0 A) to the SMA wires. They reported that the displacement of the tip of the cantilevered beam showed that the tip moved to the desired position. Their results demonstrated that the tip position of a composite beam can be precisely controlled by SMA actuators.

Conclusions

Composites are used in applications that require lightweight construction. However, there is a need to improve on the performance characteristics of composite materials by engineering them to positively respond to their environment. SMAs possess the unusual characteristics of either SME or pseudoelasticity. These unusual properties, if properly exploited, can result in the generation of large recovery stress. A recovery stress of between 500 MPa and 900 MPa can be generated when the shape recovery of NiTi SMAs is constrained.

Integrating SMAs into composite materials has the potential to create hybrid composites with smart capabilities and hence improved performance. A concise review of NiTi SMAs in general, and of the utilisation of these unusual properties for the control of vibration, dynamic response, stiffness, position and shape has been presented. As a result of their excellent biocompatibility characteristic, NiTi SMAs are being employed in surgical instruments, in cardiovascular, orthopaedic and orthodontic devices, and in robotics and satellites. The novel properties of NiTi SMAs can also be successfully exploited for damage repair in composite structures.

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Authors' contributions

K.O.S. wrote the manuscript; O.L.A. is a researcher on the project and contributed to the manuscript; M.T.E.K. edited the manuscript; and all authors contributed to revisions of the manuscript.

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An outline of possible pre-course diagnostics for differential calculus

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There is a view that many first-year students lack the basic knowledge and skills expected of them to study at university level. We examined the expected work habits and pre-course diagnostics for students who choose to take a course on differential calculus. We focused on the lecturer pre-course expectations of a student in the context of work habits, knowledge and technical skills. In particular, we formulated outcomes and then sample diagnostic questions to test whether the identified learning outcomes on expected work habits and learning are in place. If students are made aware of the expected learning outcomes and if they take the diagnostic test, they should be able to achieve greater success in their studies. The validity of this assumption will be the subject of a future paper which will report on the implementation of the learning outcomes and diagnostic questions that we formulated for pre-course diagnostics in differential calculus.

Introduction

Informal interviews with students across disciplines from a sample of institutions within South Africa indicated generally that students do not know what the precise outcomes of their courses or modules are. They stated the outcomes very vaguely, if at all. Without knowledge of the outcomes, students do not know what is expected of them. The process of thinking and the questions that lead to proper observations are rarely stated. We attempted to bridge such gaps in the context of the Math130 module (differential calculus) offered at the University of KwaZulu-Natal (UKZN).

Outcomes-based education (OBE) has been implemented at secondary-school level in South Africa.[1] There is a general feeling that OBE at school level has not been successful. We believe that merely stating outcomes is not enough to ensure improvement in student understanding and performance. In the case of OBE the outcomes were mostly known to the teachers, but not the learners. We believe that it is important to document the outcomes for a course or module, and to make these outcomes available to students. In our opinion, students also need support in the form of diagnostics and skills to be acquired over a substantial period of time, which is generally absent. It is unrealistic to assume that students will have a long-term mastery of concepts and skills relevant to differential calculus, when exposed over only a 13-week period, as disuse degrades these skills. We are not disputing that students could attain a significant level of mastery for a limited period. The challenge is for students to be able to recall and use their skills and knowledge over a sustained period of their studies (while at university) and beyond (in their work and social contexts). Based on our experience, as well as from informal discussions with colleagues, a significant number of students are underprepared for university studies in mathematics. Our hope is that by providing clear pre-course diagnostics for expectations on work habits, background knowledge and means for self-assessment of the required background, there will be an improvement in the achievement of course outcomes. In another paper we focus on the course diagnostic component which is to help focus attention on crucial possible gaps in learning that could lead to underachievement by students. In this paper we attempt to answer the following research questions: What are the views of lecturers on pre-course expectations of a Math130 student in the context of work habits, knowledge and technical skills necessary for effective mathematics learning? And how do we test work habits, knowledge and technical skills?

Review of relevant literature

We use the term 'learning outcome' to refer to a clear and detailed statement of what students should be able to do when they have learnt the content of a particular topic. In its discussion of student learning principles, the Council of Regional Accrediting Commissions[2] flagged the importance of learning outcomes. With regard to learning outcomes towards which students are expected to aspire, the Council noted that (1) these should be clear and easily available (made public) and (2) there should be reflection on such outcomes for a commitment to educational improvement. If these points are accepted then it follows that it is important for the learning outcomes of courses and modules offered by a tertiary education institution to be clearly documented, assessed regularly and improved upon if necessary, and to be made available at the outset to students. These learning outcomes should guide the type and level of assessment.

Discussing the characteristics of effective outcomes assessment, Banta[3] noted that (1) there should be a recognition that assessment is essential to learning, (2) assessment should begin when the need is recognised and should allow sufficient time for development, (3) faculty development is required to prepare individuals to implement assessment and use the findings, and (4) an environment which is receptive, supportive and enabling should be available to students continually. The American Association for Higher Education[4] gave the following principles of good practice for assessing student learning: (1) assessment requires attention to outcomes and to the experiences that lead to those outcomes; (2) assessment is most likely to lead to improvement in learning when it is part of a larger set of conditions that promote change; and (3) through assessment, educators meet their responsibilities to students and the public. We agree with all of these points. The challenge we face in developing countries is that an increasing number of underprepared students are admitted for university studies in mathematics. With this in mind we believe that diagnostic testing based on clear pre-course outcomes could help many students achieve success in their studies. Our view is that diagnostic testing should form an integral part of assessment, because

the assessment should also promote student learning. By a diagnostic test, we mean a test that is designed to evaluate the precise strengths and shortcomings of a student with reference to a given context, such as preparedness for a particular course.

We looked at how some institutions addressed the issues of course outcomes and diagnostic testing. Florida International University[5] gives a comprehensive list of learning objectives or outcomes for their calculus module. This list includes the general course objective and desired learning outcomes for their major topics in calculus. The calculus course outline of the University of Manchester[6] stipulates under learning outcomes: 'On successful completion of this module students will have acquired an active knowledge and understanding of some basic concepts and results in calculus.' The required concepts and results were not clearly indicated, but the major topics and sub-topics were listed under the syllabus section.

The Stevens Institute of Technology[7] gives the overall course objective and lists the expected learning outcomes under each of their topics in calculus. The website of the University of New England's[8] calculus course gives a general description of the unit and assessment tasks. Each assessment task relates to stated learning outcomes in the context of the content as well as graduate attributes. We found the latter to be interesting because it gives a new dimension of what could be required of students. The following five graduate attributes were listed: knowledge of a discipline, communication skills, information literacy, problem-solving and team work. The expectation of a student for each of these attributes is clearly indicated. For example, communication skills are unpacked as follows:

> *The student will be encouraged to participate actively in discussion during lectures and tutorials. Written communication skills, particularly with regard to construction and presentation of logical expositions and arguments, will be taught and assessed.*[8 (p.3)]

For each of these five graduate attributes, the intention was for it to be taught, assessed and practised.

The Mathematics Diagnostic Testing Project (MDTP) of California State University[9] provides free online student tests which can be taken more than once. There is a calculus readiness (CR) test which is designed to help individual students review their readiness to study calculus. Students are advised to take the test without the aid of a calculator. The recommended time for taking the test is approximately 1 h, but no time limit is enforced. The online test includes a diagnostic scoring report to help students identify their strengths and weaknesses in different topics. Students are expected to use these tests and reports to identify their weaknesses to study those topics more and overcome the identified weaknesses. Our review of the diagnostic test questions gave us the impression that they were too difficult for the majority of underprepared students who now gain access to universities in developing countries.

The California Mathematics Diagnostic Testing Project[10] tests cover similar topics as those of the MDTP CR test and pre-calculus (PC) diagnostic tests administered by many Californian schools. This web-based test is intended to provide students with feedback on how well prepared they are for any of those tests. The only purpose of this test is to indicate the extent of a student's understanding of and facility for some important concepts and skills. Students are given a total score as well as a score for each of the topics covered by the test. It is stated that these results could help a student focus on additional study to be better prepared for a calculus course. This test is intended to give students an indication of their level of preparedness for the MDTP CR test. The prerequisites to study differential calculus, in terms of technical knowledge and skills, are indicated in the above diagnostic tests.

We have observed that our students often understand the calculus concepts but that their algebra tools fail them when they are solving problems. The University of British Columbia[11] reported that data from their past final examinations showed that 75% of students' mistakes were related to basic high-school knowledge and skills. In order to address such underpreparedness, pre-course diagnostic tests for calculus are used in a number of institutions.[11-14] A study of those diagnostic tests revealed that: (1) in many cases, for example Acadia University[14], diagnostic tests are compulsory for all students taking a differential calculus course, (2) the tests cover high-school mathematics skills that are essential for the passing of a university-level calculus course, (3) the pre-calculus questions for such tests should be developed by using errors actually made by previous students, (4) such tests show a student where his/her basic weaknesses are, and provide him/her with means to improve, and (5) the main purpose of the tests is as an early warning system for those students with a weak mathematical background. Some institutions, for example the University of California[15], use diagnostic tests as a placement tool to help students choose between the various mathematics modules that are offered.

We used the above findings and our experience to develop pre-course diagnostics that we consider to be more appropriate for the students we encounter. We note that most of the institutions referred to above place the responsibility of remedial measures on the student.

Conceptual framework

The literature review and our experience guided the formulation of principles which give an overview of the conceptual framework for this study. These principles are:

1. There is a conceptual hierarchy in the body of mathematics.
2. To study mathematics students should understand and possess good work habits.
3. It is important for the outcomes on prerequisites for the module to be clearly documented.
4. For effective learning, it is not enough for only the instructor (teacher, lecturer, tutor) to be aware of the prerequisite work habits and technical knowledge outcomes of a course or module.
5. Students should know explicitly at the outset what the expected outcomes for these prerequisites are.
6. Instructors should use the documented prerequisite outcomes to formulate suitable diagnostic questions for students.
7. When students attempt the diagnostic questions there should be provisions for remedial activity, in order to overcome their identified shortcomings.

Methodology

We first looked at the aim and the content for the Math130 module as indicated in the handbook of the UKZN's Faculty of Science and Agriculture,[16] which is in the public domain. The aim is given as: 'To introduce and develop differential calculus as well as the fundamentals of proof technique and rudimentary logic.' The content includes: 'Fundamental Concepts – Elementary logic, proof techniques. Differential Calculus – Functions, graphs and inverse functions, limits and continuity, the derivative, techniques of differentiation, applications of derivatives, antiderivatives.'

Based on our experience with respect to teaching at secondary and tertiary education institutions, we documented outcomes and diagnostics on:

1. Expected student work habits. Students should be aware of the work habits that their instructors (lecturers, tutors) expect of them. We documented such outcomes that in our opinion give the characteristics of the work habits of successful students.
2. Pre-course (prerequisite) outcomes. We formulated these outcomes based on the conceptual hierarchy of mathematics and common errors of past students.
3. In-course outcomes. We formulated such outcomes for the Math130 module by studying the aim and the content, as indicated above.

4. Work habits. Firstly, work habits were classified into different areas, for example, be responsible for your own learning, be critical of your thinking, and be able to work constructively in group situations. We also formulated questions to focus students' attention on these aspects. Our thinking here was that we should help students improve their work habits to the level of that expected of them.
5. Pre-course diagnostics. Based on the outcomes identified, we formulated sample diagnostic questions on compulsory background and essential mathematical vocabulary. The compulsory background check focused on basic arithmetic and algebra, while the vocabulary check focused on mathematical syntax and precise knowledge of elementary mathematical terms. These diagnostic questions were discussed at meetings of interested role players (relevant lecturers, experienced members of staff and certain students). Feedback was encouraged with regard to the suitability of the diagnostic questions, their framing and the answers. A three-member editing team then looked at the feedback, considered the suggestions and revised the questions accordingly.
6. In-course diagnostics. We used the outcomes identified to formulate questions on course content for logic, functions, limit of a function, continuity of a function, derivative of a function, antiderivative and integral of a function, and specifically on creative thinking (for example, application to cooking).

Findings and discussion

We present the findings in four sub-sections: (1) outcomes for the expected work habits and questions to focus the students' attention on these, (2) compulsory background check, (3) essential mathematical vocabulary check and (4) exposure of students to outcomes, ways of diagnostic testing and remedial measures.

Outcomes for expected work habits and diagnostic questions

We expect students to acquire the following work habits:

1. Be able to take responsibility for your own learning
    - Read in advance and make a note of concepts that are not clear
    - Participate actively in classroom discussions
    - Attempt the homework problems seriously
    - Recall basic knowledge quickly and correctly and also practise basic skills regularly
    - Be self-motivated to work
    - Seek help when required
2. Be able to unpack what is required to answer a question
3. Be able to identify gaps in your knowledge or skill set that hinder question solving
4. Be able to take appropriate measures to overcome the identified gaps
5. Be able to ask appropriate questions in class to improve understanding
6. Be able to learn what constitutes understanding
7. Be able to recall correctly the relevant knowledge and skills for a section
8. Be able to see connections within and across sections
9. Be able to formulate questions and then explore these in a manner that will promote your understanding
10. Be able to write down solutions to problems in a manner that enables others to follow the solution. Includes appropriate use of connectives, reasons and explanations
11. Be critical of your thinking
    - Look for invalid assumptions
    - Think of alternative strategies
    - Check the flow of the logic, in particular for unnecessary sidetracks
12. Be able to critically examine solutions to problems
    - Look for invalid assumptions
    - Detect errors in your written solutions
    - Check the flow of the logic, in particular for unnecessary sidetracks
    - Check your written attempts to problems against given answers and do the necessary corrections from the point of breakdown
    - Think of alternative solutions
13. Be able to take appropriate notes, including making notes during lectures, from appropriate material and from critical examination of your own work
    - For a lecture and reading of appropriate materials this refers to a framework that enables one to reconstruct (within an appropriate time) the essentials that include definitions, statements of theorems, illustrative examples or counter-examples, observations and remarks
    - For critical examination of your work, this outcome refers to observations, strategies, alternative strategies, misconceptions and common errors
14. Be able to constructively work in group situations
    - Prepare for group sessions
        - Read and work through the identified required materials
        - Formulate questions and observations
        - Identify points that you feel need further elaboration
    - Participate actively
    - Allow others to participate actively
    - Make relevant notes or recordings
    - Learn from others and allow others to learn from you
    - Plan for everyone to have a share of the collective time
    - Be polite
15. Be able to plan for your work
16. Be able to implement the work plan effectively
17. Be able to handle stress, including stress from examinations, tests, assignments and interviews
18. Be able to analyse a definition or statement of a theorem or relevant principles and use them appropriately in a given context
    - Detect the conditions under which the definition or statement of the theorem applies
    - Check that the conditions of the definition or of the statement of the theorem are satisfied in the given context.

The reference to homework in Point 1 refers to what is normally referred to as tutorial problems at university. We used the concept 'homework' because first-year students may be more familiar with this concept than the concept 'tutorial'. Our interactions with mathematics students have indicated that the above work habits lead them to take responsibility for their own learning, to develop a deep understanding for the subject matter and to be critical of their own thinking and the work of others. In formulation of the above outcomes on expected student work habits we tried to unpack for our context some of the graduate attributes focused on by the University of New England[8]. To make students aware of these attributes we formulated two diagnostic questions on

work habits: (1) What do you need to do to take responsibility for your own learning? and (2) What is required of you to work constructively in group situations?

Question 1: What do you need to do to take responsibility for your own learning?

In our opinion, students are taking responsibility for their own learning if they comply with Points 1–13 and Points 15–17 above.

Question 2: What is required to work constructively in group situations?

In our opinion, students are able to constructively work in group situations (e.g. during tutorial sessions) if they comply with Point 14 above.

We believe it is important to expose students to these questions as a catalyst for them to reflect on pertinent points regarding responsibility for their own learning and working in group situations. Often new students coming to university do not know what is expected of them. Our experience in mentoring students who repeat modules suggests that these students could have succeeded in their first attempt. For example, when mentoring such a student on the work habits expected of students at a university, the student remarked, 'If only I knew this last year … I would have passed!' Another such student asked 'Why was I not made aware of this last year?' Such responses indicate to us the need to expose students to diagnostic questions on work habits.

Compulsory background check

The background check consists of operations on numerical fractions, operations on algebraic functions, laws of exponents and laws of logarithms. Sample questions and answers for this part are given in Table 1. In our opinion a time limit of 40 min should be given to answer the sample questions in Table 1.

In our opinion, every first-year student who wants to study first-year mathematics should be given such a test. This assertion is supported by the literature review.[10,14] Tests should be re-administered weekly for students who perform poorly (below 80%) and there should be increasingly less time for completion with each test. Candidates should know in advance that this process will be followed. One can formulate similar tests for each week until the student is able to score full marks. Note that the computations should be simple.

Essential mathematical vocabulary check

The background check tests familiarity with synonyms for commonly used mathematical syntax and precise knowledge of elementary mathematical terms. We present our sample questions and answers for arithmetic, algebra and mathematical syntax in Tables 2, 3 and 4, respectively.

Note that all of the above categories are pre-course diagnostics. Many of our students have English as their second language. It is for this reason that we included simple translations from English phrases to mathematical symbolism (see Table 3). Because mathematics has its own language we felt that it was important to expose students to the subtleties of mathematical syntax (see Table 4) and to check on their preparedness for this.

One could argue that the outcomes of expected work habits, compulsory background check and essential mathematical vocabulary check are general mathematics expectations. However, it is important for students to know exactly what work habits their lecturers expect of them so that if required a student could rectify their work habits timeously. Our experience is that first-year students who find it difficult to cope with their studies on differential calculus lack what could be termed good work habits. Often the case is that students know the work taught at university for differential calculus but find it difficult to solve problems based on differential calculus correctly because of a lack of the basic knowledge and technical skills necessary for success. This premise was the rationale for formulating the outcomes and then the sample diagnostic questions for the compulsory background and essential vocabulary checks.

Table 1: Sample questions and answers for the compulsory mathematical background check

Complete the following in the simplest possible form:	Answer
$\frac{1}{2}+\frac{1}{3}=$	$\frac{5}{6}$
$\frac{1}{2}-\frac{1}{3}=$	$\frac{1}{6}$
$\frac{1}{2}\times\frac{1}{3}=$	$\frac{1}{6}$
$\frac{1}{2}\div\frac{1}{3}=$	$\frac{3}{2}$
$\frac{1}{2}\times\frac{1}{2}=$	$\frac{1}{4}$
$\frac{1}{x}\times\frac{1}{x^2}=$	$\frac{x+1}{x^2}$
$\frac{1}{x}-\frac{1}{x^2}=$	$\frac{x-1}{x^2}$
$\frac{1}{x}\times\frac{1}{x^2}=$	$\frac{1}{x^3}$
$\frac{1}{x}\div\frac{1}{x^2}=$	x
$\frac{1}{x}\times\frac{1}{x}=$	$\frac{1}{x^2}$
For what value of x is $\frac{1}{x+1}$ undefined?	–1
$2x^3.3x^5=$	$6x^8$
$2x^3+3x^3=$	$5x^3$
$2x^3-3x^3=$	$-1x^3$ or $-x^3$
$2x^3\div(3x^5)$	$\frac{2}{3x^2}$
$(2x^3)^2=$	$4x^6$
$(2^{x+1})^3=$	2^{3x+3}
$\log_{\sqrt{2}}2=$	2
$\log_a 2+\log_a 5=\log_a$ __	10
$\log_a 2-\log_a 5=\log_a$ __	$\frac{2}{5}$
$7\log_2 a=$	$\log_2 a^7$
$\log 2+\log 5=$	1
$\frac{\log 16}{\log 8}=$	$\frac{4}{3}$
If $2x+5=a$ then $x=$	$\frac{a-5}{2}$
If $2x+5\geq 3$ then $x\geq$ __	-1
If $-2x+5\geq 3$ then x is in the domain __	$(-\infty, 1]$
The solution set of $x^2=1$ is __	{-1, 1}
If $x^2-1\geq 0$ then x should take values in the domain __	$(-\infty,-1]\cup[1,\infty)$
Interpret the statement: 'n is not a composite number'	n is either 1 or a prime number

Table 2: Sample questions and answers for arithmetic

Question	Answer
'*a*' is a factor of '*b*' means	'*a*' divides '*b*' or $b = ka$ for some integer k
A number is prime means it has only __ divisors	two
A number is composite means it has __ divisors	more than two
Multiplicative identity is the number __	1, because for any real number x, $x.1 = x$
Additive identity is the number __	0, because $a + 0 = a$ for any real number a
3 x 4 is a factorisation for the number __	12
The prime factorisation for the number 12 is __	$2\times2\times3$; $2^2\times3$; $3\times2\times2$; $2\times3\times2$; 3×2^2
For the numbers 3 and 6, __ is a multiple of __	6, 3
For the numbers 3 and 6, __ is a divisor of __	3, 6
The LCM of 6 and 9 is ___	18
The GCD of 6 and 9 is ___	3
-7 is an integer. True or false?	True
Consecutive integers differ by ___	1
The usual denominator for the integer -2 is ___	If -2 is written as $\frac{-2}{1}$ then 1.
If $\frac{a}{b}$ is a rational number written in its simplest form then a is __ and b is __	an integer, a non-zero integer
The cube root of -8 is ___	-2
The 7th root of '2 raised to 7' is ___	2
$\sqrt{16-9}$ is an irrational number. True or false?	True
Which two sets of numbers cover all real numbers?	Rational, irrational
The common decimal expansion for $\frac{1}{4}$ is __	0.25

Table 3: Sample questions and answers for algebra

Question	Answer
Of the three real numbers 3, π and a, which are the constants?	3, π
Of the three real numbers 3, π and a, which are the variables?	a
Of x, y and x^2, how many are different?	All three
Write down three consecutive integers if x is the middle integer	$x-1, x, x+1$
Three times a number x is represented as __	$3x$
The number x increased by three is represented as __	$x + 3$
The cube of the number x reduced by one is represented as __	$x^3 - 1$
The cube of the number, x reduced by one, is represented as __	$(x-1)^3$
The square of the number 'y reduced by two' is represented as __	$(y-2)^2$
The square root of the number, x increased by two, is represented as __	$\sqrt{x+2}$
The term infinitesimal means __	a variable whose values are generally chosen to be close enough (as close as we desire) to zero

Table 4: Sample questions and answers for mathematical syntax

Question	Answer
x is not greater than 4 is represented as ___ or ___	$x \leq 4, x \geq 4$
x is not less than 4 is represented as ___ or ___	$x \geq 4, 4 \leq x$
y is at most 5 is represented as ___ or ___	$y \leq 5, 5 \geq y$
y is at least 7 is represented as ___ or ___	$y \geq 7, 7 \leq y$
x is more than 9 is represented as ___ or ___	$x > 9, 9 < x$
x is less than 9 is represented as ___ or ___	$x < 9, 9 > x$
Real number z is between a and b is represented as ___ or ___	$a < z < b, z \in (a, b)$
Real number z is between a and b, and includes b, is represented as ___ or ___	$a < z \leq b, z \in (a, b]$
Real number u is from a to b is represented as ___ or ___	$a \leq u \leq b, u \in [a, b]$
Real number u is from a towards b but excludes b, is represented as ___ or ___	$a \leq u < b, u \in [a, b)$
The commonly used synonyms for 'therefore' are ___ or ___ or ___	hence, thus, implies
The commonly used synonyms for 'because' are ___ or ___	as, since
The commonly used synonyms for 'if' are ___ or ___	given, given that
The commonly used synonym phrases for 'arbitrary' are ___ or ___ or ___	for any, for some, for random
The commonly used synonym phrases for 'for all' are ___ or ___ or ___	for every, for any, without exception
The commonly used synonym phrases for 'there exists' are ___ or ___	there is, for some
y is bounded above by 7 is represented as ___ or ___	$y \leq 7, y \in (-\infty, 7]$
y is bounded below by 7 is represented as ___ or ___	$y \geq 7, y \in [7, \infty)$
The value of y is from a to b, is represented as ___ or ___	$a \leq y \leq b, y \in [a, b]$

Exposure of students to outcomes, diagnostic testing and remedial measures

In this section we focus on ways to expose students to the pre-course outcomes, the diagnostic testing of these outcomes and the remedial measures thereof.

Exposure to pre-course outcomes

Outcomes could be given to students as part of the welcome kit for the course, if costs permit. They could also be made available on the website of the course. Regardless of how they are made available, it is important that students have access to the pre-course outcomes at the outset of the course.

Ways of diagnostic testing

The diagnostic questions on work habits and those for the compulsory background and essential vocabulary checks could be administered as formal pre-course tests. We suggest that as much as is possible be done during the orientation programme for students. Tests could be completed by students either in hard copy or online. The tutors of the groups to which the students belong should look at their students' responses and prepare suitable feedback for the students.

Remedial measures

It is important that students be given qualitative feedback with regard to areas in which they have difficulties. Suitable feedback by tutors to students could also be one of the remedial measures. Similar diagnostic tests should be planned and administered on a regular basis to students who perform poorly. A student could also approach his or her tutor to discuss relevant difficulties. Students could also form self-help groups with the intention of overcoming identified shortcomings. The course coordinator or lecturer could also upload to the website additional notes with examples to address common shortcomings.

Conclusions

We were able to detect and document the views of lecturers on pre-course expectations of a Math130 (differential calculus) student in the context of relevant work habits, knowledge and technical skills necessary for effective mathematics learning. Our formulations of outcomes relating to the above context and sample diagnostic questions were an eye-opener for us. The outcomes and sample diagnostic questions indicated to us that there was much that we as lecturers at academic institutions assumed, often incorrectly. We detect an urgent need for addressing this issue across disciplines, particularly in the context of developing nations for which, in general, continuously falling educational standards are a major concern. Depending on the availability of resources, the implementation of diagnostic tests could be hard copy or electronic form. In another study we will look at the correlation of the pre-course results of the diagnostic tests with that of student performance in their differential calculus course at UKZN. Those results will inform the evaluation of the pre-course outcomes and diagnostic material that we have formulated and developed.

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Authors' contributions

V.W. came up with the idea of including expected work habits of students who want to study at university. The learning outcomes and the pre-course diagnostics were jointly formulated by both authors. All sections of the paper were jointly written by both authors. A.M. typed the manuscript and did most of the proofreading.

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Opening dialogue and fostering collaboration: Different ways of knowing in fisheries research

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We set out to explore some of the impediments which hinder effective communication among fishers, fisheries researchers and managers using detailed ethnographic research amongst commercial handline fishers from two sites– one on the southern Cape coast and the other on the west coast of South Africa. Rather than assuming that the knowledge of fishers and scientists is inherently divergent and incompatible, we discuss an emerging relational approach to working with multiple ways of knowing and suggest that this approach might benefit future collaborative endeavours. Three major themes arising from the ethnographic fieldwork findings are explored: different classifications of species and things; bringing enumerative approaches into dialogue with relational approaches; and the challenge of articulating embodied ways of relating to fish and the sea. Although disconcertments arise when apparently incommensurable approaches are brought into dialogue, we suggest that working with multiple ways of knowing is both productive and indeed necessary in the current South African fisheries research and management contexts. The research findings and discussion on opening dialogue offered in this work suggest a need to rethink contemporary approaches to fisheries research in order to mobilise otherwise stagnant conversations, bringing different ways of knowing into productive conversation.

Introduction

In 2000, with a stock crisis in the country's commercial line fisheries looming, South Africa's government took steps to mitigate against widespread collapse by adopting a policy of reduced access rights for commercial fishers. What transpired was a dramatic curtailing of effort in the inshore fisheries, concomitant with the introduction of the *Marine Living Resources Act of 1998* (MLRA), which left many fishers without legal rights to carry out their trade on a commercial level. This disenfranchisement lead to widespread dissatisfaction and often contempt for the authorities and MLRA amongst many fishers and fishing communities, resulting in both political action and poaching in a number of instances.[1,2]

Today, South Africa's fisheries continue to face a number of severe and pressing challenges which must be addressed if progress is to be made in safeguarding marine ecosystems and the livelihoods of those who depend upon these in various ways. Instead of looking solely at how fishers know, which reiterates their apparent difference from science, the more productive approach is to try to understand where and how the dialogue runs into difficulty. We by no means make any claim to resolving all the difficulties that attend collaborative work among managers, fishers and researchers. Rather we explore some of the instances in which difficulties arise and present some possibilities with which to begin to move forward conversations which have in many cases become stagnant. As such, our intention in this paper is to introduce a theoretical foundation which poses significant practical applications, whilst highlighting its relevance through ethnographic examples. The conceptual framework and associated tools which we employ begin with the idea that the ways in which people engage the world are based on interactive relationships with humans and non-humans alike. The strength of this approach lies in being open to working with multiple ways of knowing without assuming that one represents complete truth while another is complete falsehood.

It is our contention that what is required is a shift in focus away from traditional 'top-down' management structures, in which local perspectives are generally not taken into account, towards an understanding of the extent to which social and ecological changes are mutually contingent.[3,4] In their 2007 work, the Canadian Coasts Under Stress (CUS) team recognised that 'the fundamental problem is an inadequate understanding of the highly complex links between social and environmental restructuring and how they interact with the health of people and places'[3]. Sutton Lutz and Neis[4] suggested that 'disciplinary boundaries (between social, natural, humanist and health researchers) have tended to mask interactions between these realms…' often with unfortunate and unforeseeable consequences. In answer to this dilemma, following Sutton Lutz and Neis, 'a key point of departure for CUS research…is the assumption that exploring these interactions requires cutting across traditional disciplinary boundaries'[4].

The social-ecological approach adopted by CUS suggests that it was necessary to create a third space in which different knowledge positions might be brought into conversation and worked with productively. In a bid to facilitate the creation of this third space, the CUS team perceived different ways of knowing and disciplines as bounded but simultaneously called for the recognition of heterogeneity and overlap as a means of bringing different ways of knowing into conversation.[4] The upshot of this outlook was the call for researchers to work across categories of knowledge. However, whilst such an approach began to open up the possibilities for collaborative research, it still implicitly relied upon and thus maintained categorical distinctions between knowledge groups such as scientists and fishers.[4-8] The contribution offered by our approach, by contrast, is an effort to move to recognise and work symmetrically with multiple ways of knowing the world, seeking the convergences and overlaps but also finding means of acknowledging and working with difference and divergence in productive ways.[9-12] As a point of departure, we begin with the assumption that knowledge boundaries are arbitrarily maintained and can be dissolved. We argue that different knowledges exist but these different ways of coming to know are not necessarily tied to, nor emerge from, specific disciplines or identities and rather are patterned on interactions between beings. Our

work, therefore, attempts to move beyond the restrictions of disciplinary and epistemological categories by working with individual knowledges rather than notions of bounded bodies of knowledge. Note that the term 'knowledges' is used to suggest that there is not a singular and universal way of producing knowledge about the world, but that there are ways of knowing the world which lie outside of the formal disciplines which people use and find effective. These may include practical and embodied knowledges, as well as different ways of thinking about the major ontological structures that frame modernist knowledge.[9,13] The focus of this kind of work is on the convergences and overlaps which exist. Where divergences do arise, these too may also be worked with productively, as discussed later in the text.

Building on the CUS approach, we take the view that productive dialogue with the knowledges of fishers is both possible and necessary.[3,4,14,15] There are several reasons for this view. The work of Van Zyl[1] and Schultz[2] on South Africa's east and west coasts, respectively, has illustrated that people excluded from conservation and management decisions resort to poaching, not only out of necessity but also as an act of demonstrating disagreement with management. Target-resource oriented management and traditional 'top-down' approaches to management have to date not been especially effective in ameliorating fisheries crises.[16-18] Additionally, with the mandated implementation of an ecosystems approach to fisheries (EAF) in South Africa in terms of international agreements, there is pressure on government to implement a more inclusive means of managing our fisheries and to allow for debate around knowledge.[19-21] There is also a need to rethink the state-science-public nexus in terms of which conservation policy in South Africa is increasingly implemented via control rather than cooperation.[1,2,11] The lack of effective dialogue between fishers and scientists – even though many scientists themselves are fishers and make the effort to communicate their work to fishers – is often framed as a problem of 'indigenous knowledge'. We believe that such an approach severely limits dialogue,[11,12] as making knowledge debates contingent upon socio-cultural identity renders them unavailable to critique or rethinking, with the consequence that they come to occupy seemingly intractable positions.[9] The work presented here is part of a larger project that reframes the possibilities for scholarly dialogue across different ways of knowing the sea and its creatures, and takes as its focus the ways in which people come to know the world. As such, we argue that the shift to research on dialogue creation between fishers and the sciences, is vital both in implementing an EAF in South Africa and in beginning to address the problems which face the country's fisheries.

Project background

We draw on initial findings and fieldwork from an extensive interdisciplinary research project which has been running for the past 4 years. A collaborative undertaking between the University of Cape Town's (UCT) Marine Research Institute (Ma-Re) and Anthropology, the project seeks to rethink the complexity and interface of multiple knowledges and ways of knowing in selected fisheries on the west and southern Cape coasts of South Africa as well as in Namibia's hake fisheries.

Over the past two decades, growing evidence of stock collapses and associated failures of centralised, quantitatively managed fisheries in many parts of the world have led to a number of calls for alternative approaches to fisheries management which address the concerns of biophysical ecosystems as well as human well-being.[3,22-25] Recently, a growing body of research has begun to suggest that working with the knowledge of fishers within the fisheries management context offers the possibility of augmenting scientific knowledge by contributing locally grounded, experiential understandings and strategies for dealing with the variability of fish and climate.[3,24-29] In 1992, the Convention on Biological Diversity (CBD) was formulated to address growing concerns surrounding the preservation and safeguarding of the earth's natural resources. Central to the CBD was a commitment that contracting states 'respect, preserve and maintain the knowledge, innovations and practices of indigenous and local communities'[30]. In terms of fisheries management, the guidelines outlined in the CBD laid the foundations for a significant shift away from established 'top-down' management paradigms, which ignored local people and their concerns, towards more inclusive approaches which worked with local people and ecologies.[20,30,31] One of the more prominent approaches to fisheries management which emerged from the guidelines of the CBD was the EAF.[21,32] A somewhat radical departure from established norms of fisheries management, an EAF adheres to a number of core premises which directly challenge conventional top-down management structures. One of its guiding principles is a focus on working with complex interlinked social-ecological systems. In 2002, at the Johannesburg World Summit for Sustainable Development, South Africa committed to the implementation of an EAF by 2010, which compels fisheries management to work in dialogue with fishers. However, this EAF has been slow in coming.[33]

In 2010, amid growing concerns surrounding climate change and variability; the 2002 Johannesburg World Summit mandate; perceived shortcomings in the MLRA; and the failure of top-down stock assessment-based management protocols to adequately work with people and marine resources, Ma-Re (UCT) initiated the 'Marine Research in the Benguela and Agulhas Systems for supporting Interdisciplinary Climate-Change Science'(BASICS) project. The project is interdisciplinary in nature and receives considerable support through the South African Research Chair in Marine Ecology and Fisheries. BASICS seeks to challenge the conventional management approach by explicitly investigating an EAF through social-ecological research and collaboration with fishers. The BASICS project incorporates perspectives from industry, government, fisheries management and academia as well as physical and ecological modelling across a range of scales and case studies working with fishers from within the Benguela ecosystem.[34] The objective of this multi-sited, multi-scalar, interdisciplinary project is to provide understanding of the impacts of climate variability as well as to predict future outcomes at various levels including marine ecosystems, individual species and human coastal communities.[34]

The Fishers' Knowledge Project (2010–2012) is a collaborative interdisciplinary and multi-sited research project conceptualised across a range of research partnerships, including the SeaChange programme of the South African National Research Foundation, UCT Sawyer Seminar's Contested Ecologies Project and UCT's Africa Knowledges Project as part of the larger Programme for the Enhancement of Research Capacity. Seeking to bring the objectives of Ma-Re BASICS, the Fishers' Knowledge Project and the Contested Ecologies Project together, Astrid Jarre (Ma-Re) and Lesley Green (Anthropology) co-supervised several Anthropology dissertations which focus on fishers' knowledge in a range of fisheries along the Benguela current ecosystem coastline of South Africa.

Methodology

Drawing on ethnographic participant observation methodology, the research presented here took place in two separate field sites over extended periods.[11,12,35] All research was conducted after receiving appropriate ethical clearance. Participant observation entailed researchers spending prolonged periods of time in the given field site and at sea with local fishers, with a focus on the collection of empirical data. Placing emphasis on extended fieldwork and engaging with local people while they went about their daily activities enabled the development of rapport and the building of relationships of trust, providing insight into the local context and people's ways of understanding and being in the world. The ethnographic examples presented in this paper refer to the work of Rogerson[11] and Duggan[12]. Duggan's[12] field research was conducted in the small commercial handline fishery in the southern Cape town of Stilbaai over a 7-month period; Duggan conducted participant observation, that is, spending time with fishers at work, both at sea and on land. The research revealed a complex set of interactions between fishers and fish in which fishers knew fish as intelligent, reactive beings and sought to balance a range of objectives including ecological, economic and ethical concerns via a suite of strategies aimed to cope with variability in the fishery at all levels. Over a 3-month period, also drawing on participant observation methodology, Rogerson's[11] work in Lamberts Bay focused on the embodied ways in which fishers come to know the sea. In her work, Rogerson suggested that the conservation

science which informs state-regulated fisheries policies such as the MLRA has served to exclude fishers from debates about the management of the marine environments they have fished for generations. Rogerson's study found that the fishers with whom she worked interacted with and related to fish and seals as knowing subjects rather than simple objects for capture.

In analysing the ethnographic data, our approach was grounded in that described by Lien and Law[36] as a relational ontology.[37] Whereas a cultural ontology rests upon the notion that different views of the world arise from social identity (such as ethnicity, race or region), a relational ontology concerns itself with the ways in which knowledge producers attend to specific objects and relationships in the world, and, in foregrounding them, bring them into being as matters worth attending to in scholarship and in political life.[36-38] The fishers with whom we worked were of varying ages and levels of experience. Stilbaai fishers *Oom* ('uncle', used as a form of respect) Louis and *Oom* Koos, for example, had between them nearly 65 years of experience on the sea in commercial fishing. Many of their peers had spent over 40 years as commercial fishermen working in a range of fisheries (commercial handline, commercial trawl and west coast rock lobster) in the Benguela and Agulhas ecosystems. A commonality shared by all of the people in the ethnographic conversations which follow is a self-identification as commercial fishers.

Research findings

The identification and classification of species and sub-species, the process of enumerating fish, and different ways of relating to fish and the sea are prominent themes which recur in both Rogerson's[11] and Duggan's[12] research. These themes represent nodes or moments around which convergence and divergence often take place in fisheries research and management and, as such, the interactions through which they come about warrant further exploration.

Species, classifications and 'artful deletions'

During any process of research, data are collected and recorded. The collection of data happens through equipment and different processes along the way. Streamlining, evaluating and interpreting data culminates in a written report. Through this process, certain elements of the original data set are emphasised whilst others are eliminated or underplayed in the final version. In what follows, we refer to these processes of streamlining as 'artful deletion' and suggest, following Law[38], that it is a practice which takes place in the formation and representation of all knowledge. 'Artful deletions' are achieved through the use of 'inscription devices' which include 'any item or apparatus or particular configuration of such items which can transform a material substance into a figure or a diagram which is directly useable'[38]. The value of inscription devices lies in their ability to direct focus onto the final, smoothed and simplified product, away from the complex interactions, material processes and practices which go into creating it. We begin by exploring this point via a discussion of the ways in which different worldviews result in different classifications of the same fish: kob (*Argyrosomus inodorus)* – known locally as the Silver kob or kabeljou, a highly prized commercially targeted species upon which the inshore handline fisheries of the southern Cape are deeply dependent.

In a weighty tome released in 2001 by the Department of Environmental Affairs and Tourism entitled the *Coastcare Factsheet Series*,[39] a group of government scientists and marine specialists set out to document, for public dissemination, elements of South Africa's marine ecosystems and coastline which were considered important. Included in the factsheet is an introduction to various common species, including a number of fish. In the third section, entitled 'Coastal and Marine Life – Animals: Vertebrates – Fishes', is a subsection dedicated over two pages to 'kob'. A single colour picture of a Snapper kob is shown at the bottom of the page. The description starts with an account of how many species of kob are found on the South African coastline ('about nine') and continues with a description of what kob *is*: under different headings such as 'Breeding Habits', 'Feeding Habits', 'Life Cycle' and 'Commercial Importance', the reader is presented with a neat, uniform version of kob – what can be expected of it, where to find it and how it operates in its environment. The account describes *all* kob as having 'a coppery sheen…fairly robust with an elongated body and a rounded tail fin' and that 'various kob species are superficially very similar, making it difficult for non-scientists to distinguish between them'.

We turn now to an ethnographic account concerning kob, taken from Duggan's[12] work amongst commercial handline fishers in Stilbaai:

> *Various boats, motors, trailers, tow-vehicles and a small freezer truck stood parked around the front and back of the house in various states of repair. The lounge served as an entrance to the home and I knocked on the door announcing my arrival.* Oom *Koos turned round in his seated position at his desk, and, beaming at me over his glasses extended a massive calloused hand to envelope mine in a firm, friendly handshake. As he gestured to a couch and told me to sit,* Oom *Koos informed me that he had invited his friend and fellow skipper* Oom *Louis to join our conversation. I was here to talk about the kob and both* Oom *Koos and* Oom *Louis were happy to do so. The discussion below picks up approximately twenty minutes into our conversation:*
>
> *Greg Duggan [GD]: How many types of kob are there?*
>
> *Oom Koos [OK]: There's about three, four…five!*
>
> *GD: That you catch here?*
>
> *OK:* Ja [yes]*, that you catch here, that is different from each other.*
>
> *Oom Louis [OL]: There's seven different species of kob. The only one that you don't get here definitely is the Snapper salmon that you get in Durban.*
>
> *OK: But we catch the square-tail also here!*
>
> *GD: The main ones I know of are the Dusky, the mini-kob, the Square tail and the Silver…*
>
> *OK:* Ja*, but the Silver kob, neh, the Silver kob – there's more subspecies of Silver kob – there's not only one. There's one with the long tail, the one with the funny fins – I showed the researchers the other day – what the difference is – there's a seven kilo fish, his tail is like that (broad), there's the other seven kilo fish and his tail is like that (thin, flat) – there's a hell of a difference between the fins – it's a different species... And then there's one of the fish where his head is small, and his body is fat –*
>
> *OL: – and then the other one with that rounded nose –*
>
> *OK: –* ja*, his top of his mouth is shorter than the bottom of his mouth.*
>
> *OL: Now they, if you look when the one's got a thick tail and the other a thinner tail, for the same size fish, they will, for the fun of it – not the fun, to get the knowledge – they will open both, see whether it's male, whether it's female – and you do get females with different bodies, males with different bodies. So it's definitely different species.*

GD: But are you catching them all together?

OK & OL: Together ja*, together!*

OK: But some times of the year, that short fish –

OL: – the thick one –

OK: – the thick one, yes, is at a certain time of the year, I think it's September, October, we catch plenty, plenty, plenty of it.

OL: You know where you get that is in Namibia as well.

OK: Really?

OL: It's different!

OK: Scientists don't class it differently but it's different.

OL: Ja *but to me it's still a kob and a kob is a kob* ou broer ['old brother'].

OK: [laughing] But we as fishermen see that as another species – we know it's another species and it's fighting more than the other species of kob when it's on the line. That shorter fish is much stronger, much, much stronger than the other kobs. Much, much, much, much stronger! And I show that to Lloyd the other day, I said 'look here, can you see the difference?' and he said yes, he can see the difference…but when you get to the harbour, neh, the inspector doesn't want to know it and the factory guy, he doesn't care either. You have a kob and for them it is a Silver kob and that is so.

OL: Ja*, he doesn't care because he gets his same price. Look if he turned around and said it was something else –*

OK: – or if we said it was something else –

OL: – ja*, if we said it was something else, we and him would get a different price. And probably not a better one, you understand? So we must look and speak about it to each other and leave it at that.*

OK: But that factory guy, he knows it's different, he sees it every day – a different shaped fish that's not a Dusky but that he sells as a Silver but clearly isn't a Silver.

What emerges from these two accounts are two knowledge claims about kob, which at times contradict one another. Two networks of actors[40] narrate their knowledge and research in the same environment featuring the same actor – kob. Yet their descriptions clearly reference two different versions of kob and ways of identifying and knowing the fish. In the knowledge claims of official state science, kob is a clearly defined, universalised fact which, whilst knowable to scientists, is 'difficult for non-scientists to distinguish'[39]. The narrative of the factsheet suggests that the version of kob presented therein is universally true for all kob, and is the only possible way of identifying and knowing kob. In *Oom* Koos' and *Oom* Louis' version of the fish, the definition is not as clear. While the two fishers identify officially recognised and classified species such as 'Silver kob', and 'Snapper salmon', they also talk about the existence of 'another species' or subspecies. Their descriptions, rather than being about a singular, authorised version of kob, speak of heterogeneity, complexity and multiplicity. Rather than being universalised and removed from context, their narrative speaks of identifying the fish through interaction when they are fighting the line. In other words, the fishers' way of knowing kob is mediated through interactions which change with context and time.

The process of enumeration

In the same way that fish are classified via the Linnaean system into a hierarchy of kingdoms, classes, orders, genera and species in descending order of specificity, a similar effect results from the process of enumeration in which relations and beings are represented as numbers for various purposes.[36-42] In the ethnography below, taken from Duggan's[12] fieldwork, an 'artful deletion' results:

> *Returning to the harbour with* Oom *Koos, we have made a good haul of kob, slightly over 800 kilograms by his estimate. Arriving at the quayside, we winch the boat up onto the trailer and tow her over to the Viking Fishing factory where the buyer, Willie, is waiting next to the scales. As the crew begin offloading the* bakke [large, hard plastic bins used to store the fish at sea and transport them on the quayside] *of fish, the process begins: at sea,* Oom *Koos had shown me some of the characteristics of different subspecies of Silver kob – the different fin, tail, head and body types. Opening some of them up, he showed me that these were both males and females and that there were indeed distinct differences between the subspecies, even though they swam together. Now, however, as Willie draws closer and the fish come to the scale, the different species of kob we had identified at sea quickly and seamlessly became one – Silver kob. It is a game, a performance for one another by fisher and buyer. As every fish is taken from the boat a length and weight measure are taken. Nothing else seems to matter. Individual characteristics are unimportant – in fact I get the sense that* Oom *Koos would rather not discuss these while Willie is around. The different individuals are thus transformed in a moment, becoming numbers. Then, once all of their number had been tallied, they became a single whole – the catch for the day, represented in kilograms and currency and later to be filled in on the log sheet which* Oom *Koos will submit to MCM/DAFF* [Marine and Coastal Management/ Department of Agriculture, Forestry and Fisheries] *at year end.*

Upon arriving at the quayside and pulling the boat out of the water, *Oom* Koos now related to kob differently, seeing them no longer as interesting individuals but as numbers. It was a relationship into which *Oom* Koos entered tacitly with Willie in which both agreed to a description of Silver kob in line with a Linnaean classification of what kob is. On the boat, *Oom* Koos had been quick to point out differences in subspecies of kob but outside the factory an altogether different account of nature again took place in *Oom* Koos's interaction with Willie. Now, *Oom* Koos's enactment and knowledge claim about the fish shifted: in order to sell the fish to the factory the multiple subspecies of kob were referred to by one name –Silver kob – thus becoming and becoming recognised as a unified entity. This shift was characterised by a seeming detachment from the fish, which were being thrown from the boat into waiting plastic *bakke*. The individual characteristics that had mattered at sea were no longer important in the relationship. Willie's compliance with this enactment of Silver kob was also important in securing a price for the catch and together the fisher and the buyer engaged in a process of transforming fish into figures. In so doing, the complexities observed at sea – the individual subjective characteristics such as nose, tail and body shape – were now of no importance, smoothed over and translated into object via number, an artful deletion of characteristics

which transformed the fish. Later that evening while writing up the day's experience Duggan[12] noted:

> *Perhaps it was just my perception of them or the sun and water reflecting off of their skin, but when we were at sea the kob, although dead, had still seemed lively. Now they appeared grey and waxen, bereft of their individual characteristics, flung unceremoniously as objects through the air. Suddenly they were lifeless numbers…one… two…thirty…forty five. I could almost see the fish being transformed from subjects as they were tossed off the boat and landed with a dull wet thud as an object in the* bakke.

In effect, the process of creating a number from fish represented a change in the relationship between fisher and fish and the latter's transition, entering into new relationships with other sets of actors. In this way, the end of the fish's interactions with fishers and their translation into numbers marks an entry into new networks in which they are further enacted. The numbers generated in the fishery enter into networks of resale, consumption, research and management, moving through processes which work with and shape them into accounts of reality. Lien and Law[36] argue that 'the inscription of a number in a notebook serves as a first point of making them real'. In other words, where management, research or the sale of fish are concerned, the creation of a number is a means of quantifying the existence of a thing. The day's total catch weight would be added to the month total for kob which in turn would be written down by *Oom* Koos on his catch log sheet and submitted to DAFF at the end of the year. At this point it would serve a range of purposes within DAFF research and management as well as informing future regulation of the country's commercial fisheries. The individuality and conditions of each fish and its capture are omitted at this stage. There is no space available to talk about different species or subspecies, water conditions, location, wind, currents, bait or fish behaviour. The log sheet simplifies and expedites data capture, severing ties between fishers and fish and the time–space in which they interacted. Only the month's total catch of the fish type is entered in each corresponding column and row. In this way, the messiness of the story of the catch is transformed, and the fish become universalised, represented by a series of digits. The complex, multiple, dynamic, unpredictable, sought after are, through this simple process of enumeration, rendered knowable, quantified, simple, predictable, singular, ready for entry into a stock assessment model or levy accounting sheet for next season's licensing purposes. It is in the moment of translation that the object of attention, although ostensibly the same being (a physical biological organism), can be very different and known as different 'things' dependent upon the perspective of the knower. Multiple versions of itself are simultaneously brought about, depending on who is interacting with it and the context in which these interactions take place.

Relational interactions among fishers, fish and sea

After a brief examination of the ways in which living beings are rendered as numbers through networks and processes of inscription and enumeration, we turn now to the ways in which particular relationships and ways of knowing fish and the sea make certain versions of reality possible. The question of embodied knowledge and relational engagements with the sea and sea creatures is an important one in the context of fisheries research and management, particularly where collaborative efforts are concerned. In the South African context, the objectives of conservation science are often perceived by fishers as not readily compatible with their own needs.[1] As such, many fishers reject conservation arguments and policies on grounds of knowing the sea and fish very differently from what is presented to them in official science and management.[1] To this end, the ethnography below, taken from Rogerson's[11] thesis, provides insight into some fishers' ways of understanding the sea and sea creatures, and highlights what we refer to as a relational way of knowing.

For many of the people working in Lamberts Bay, while they did not see the sea or the fish there as persons, they seemed to share a relationship with them that was more than one of fisher and catch. Willem, a local handline and west coast rock lobster fisher, spoke of how they needed to go out to sea with positive attitudes and with a smile on their faces or else fishing would not be successful because, according to Willem, the sea, fish and lobster could sense moods and act accordingly. In particular, the sea was understood by the fisher as a living being: a source of life and nurture as well as dread and harm. It became confusing at times because one person would be talking about how the sea gave him so much trouble and a minute later another would be talking of how much she loved the sea and how she felt free there. After some months, no longer a complete outsider, these apparent contradictions began to appear complementary to me. As Willem put it, 'sometimes the sea will give you so you can save, on other days nothing, so you can come back on those days that you have saved for'.

The sea in this example was a provider to Willem, generous on some days, miserly on others. The sea was bountiful but it did not allow fishers to have excess fish, meaning planning ahead and saving money were always necessary strategies. Often when we spoke, Willem's face became animated and excited when he spoke of the sea and how it works with him. Willem and Hennie spoke of their relationship with the sea:

> *Willem [W]: It's like the sea is in love with us because before he will take you he will warn you and then if you are reckless, careless then something will happen to you, but at least he has warned you.*
>
> *Jennifer Rogerson [JR]: The sea almost gives you a chance.*
>
> *W: Yeah.*
>
> *Hennie [H]: I'll share a personal experience of where the sea, he warned me. One day we were working close to Muisbosskerm, south of Lamberts Bay. There are lots of reefs and we work, putting a set of nets there. There is a wave coming but it's not breaking, it's coming and we could see. I told my* bakkie [a small wooden rowing boat typical of the West Coast traditional handline fisheries] *mate that we have to leave and we leave. At that time another* bakkie *came and that morning they smoked something, you could see. I went to them and I warned them, I said guys we've just been out there and we see the sea is standing up so I warned them and they ignored me, went in there and I warned my* bakkie *mate, I said 'you don't go after them, we wait outside'. They went a little bit deeper but we could still see them, they put their nets in the water. Then suddenly, the waves start to break and it turned them upside down. Capsized the whole boat, but from the head down, right over and we had to rush back to save them. The point is the sea warns you and you have to listen to that.*
>
> *W: I wouldn't say the sea is like a person but the sea it will tell you 'it's my area, I'm in control of it' and we have to listen to that. There are so many chances that the sea will show you.*
>
> *JR: It communicates with you in a way.*
>
> *W: Yes.*

Further to this, in the conversation below, one sees how Jacques and Ernest accord seals living in the bay with an intellect which goes beyond merely collecting food. The seals in this example actually learn the best

ways to get fish from fishermen. The seals directly affect fishers' catch efforts as well as the safety of their hands.

> *Jacques: The seals are really clever, the one seal, we don't know where he got his education but you can put your net in the water and then you put down your bait and without destroying your net he will take out the bait.*
>
> *Ernest: The seals aren't stupid, in the past I've caught mullets and you catch mullets with a net so when they come into the net their heads get stuck and they can't go back so you can't pull them, you have to push them through the nets. So the seals catch mullets from the nets, they pull them out and they are well educated. If you fight with a seal, hit him with rocks, disturb him, then he will cause trouble for you and destroy your net. But if you leave him he will just take your bait.*
>
> *Jacques: If the boats come in with catches of snoek then you can come and see what the seals are doing in the harbour. We have a way that we wash the fish, we take it and hit the water with it. Now the seals are clever, they won't come for the head or the middle part of the snoek, they will come for your hand so that you have to let go. And twice now, recently, there were seals who bit fishers.*

Rather than maintaining a conceptual separation of culture and nature, or human and non-human in the accounts above, Ernest and Jacques did not separate themselves from 'nature' around them. Rather they spoke of the sea and seals as knowing beings with which they interacted on an almost equal level. Through their interactions and accounts, the fishers produced particular versions of nature. In these versions, seals learned from people by observing them carefully. For Willem, the sea worked with him if he worked with it. Through their particular ways of knowing and the interactions which resulted from these, the fishers' ascribed attributes of social intelligence beyond themselves and into the natural world. In the context of an EAF and social-ecological research, such ways of engaging and thinking provide potentially powerful means of resolving theoretical and conceptual distinctions between the realms of humans and non-humans. By acknowledging that fishers, seals and the sea are engaged in relationships of mutual influence, a space is made available in which it is possible to view members of social-ecological systems as engaged in symmetrical relationships rather than hierarchies of power.

Discussion

In the ethnographic examples provided in this paper, the fishers provide conceptual interactive tools through which it is possible to rethink conventionally accepted approaches to research and management which rely on binary separations of humans from nature. Fishers hold valuable insights which are particularly pertinent in an EAF-type approach and can be valuable additions when brought into conversation with research and management. Social research on South African fisheries suggests that an approach that criminalises and disenfranchises those who fish for a living (particularly small-scale commercial handline fishers) is ineffective in the management of fisheries because communication is foreclosed, with a resultant increase in poaching and related criminal activity.[1,2,11,43,44]

We have argued that different ways of relating to others (be they human or non-human) inform multiple ways of knowing the world. In turn, these apparently different ways of knowing display moments of convergence as well as divergence. All knowledge positions undertake deletions and translations in order to tell their way of knowing the world. It is precisely because of the deletions and translations that people must make in order to be heard by their peers or other groups, that certain conversations are often rendered difficult and daunting, and become completely untenable. Within the existing fisheries paradigm, public consultations often become battlegrounds.[1] The reasons for this are many and vary with context, but at least part of the reason is that people come to them as stakeholders of particular positions and viewpoints that are pre-defined and as such feel compelled to carry their roles through in public for fear of losing what influence, authority, legitimacy or respect these might have.[1,44,45] In the experience of this project, representing a combined 13 months of field research, ethnographic methods offer a quieter conversational space. This space allows for a mediation of both views that differ from one another as well as those that go against mainstream research, established positions or management objectives. Such a space moves beyond treatments of knowledges as separate entities and acknowledges both convergences and divergences between different ways of knowing. In so doing, it is possible to pose questions and think about unexpected connections across 'the great divide', set up when one contrasts the knowledge of fishers with that of science. In the context of an impending EAF in South Africa, where opening up dialogue is essential to conduct effective research and management, how might fisheries researchers involved in the humanities and social sciences facilitate this? After all, fishers, fisheries managers and fisheries scientists (government and academic alike) undertake 'artful deletions' whenever they speak to one another. One possible avenue, we suggest, is evidenced in the earlier discussion on subspecies of kob. It is important to note here that we are not making a claim either way about the existence of a genetic kob subspecies population in Stilbaai. However, we seek to explore the possibility of collaboration further in line with Verran's[10] work in suggesting the use of alternative frameworks and exploring the situations in which these may be more effective than classical scientific categories in dealing with specific contextual issues. The question of kob genetics and morphology, as discussed previously by *Oom* Koos and *Oom* Louis, points to a possible research project in which fishers and scientists might work with different identification systems in relation to studies of population genetics.

Further to this, recent work has begun to tackle the thorny issue of actually facilitating dialogue between different ways of knowing and systems of classification.[10] Describing an interaction between an Australian Yolngu Aboriginal elder and an environmental scientist, in which the two discussed their alternative strategies for bush firing in the Australian outback, Verran[10] describes what she calls a moment of 'epistemic disconcertment', an interaction which results in discord and unease where the knowledge claims of experts come into contact in what both feel is their 'home turf', revealing divergent ways of perceiving, receiving and being in the world. In the example, collecting two sticks from what are classified in the Linnaean system as two different tree species, a senior Yolngu man suggests to the scientist that the two are in fact the same thing, being in a relationship of grandparent and grandchild rather than separate families. A moment of disconcertment arises as the scientist, drawing on his knowledge of Linnaean taxonomy and plant botany, tries to demonstrate that the two plants are in fact not related.

Eventually, the awkwardness of the situation is eased when the scientist provides an allegory to explain away the disconcertment. However, warns Verran[10], the use of allegory as a 'soothing balm' risks cutting off the possibility of what she refers to as 'generative tensions'– the ability of a situation of disconcertment to force invested parties to invent new ways of working with each other and their knowledge. In this instance, translation of one way of relating to and thinking about the ecology of an area into another weakened the original efficacy. Instead what was necessary was not translation but a means of working through these knowledge positions and moments of disconcertment rather than explaining each other away. The use of allegory explains away the position of others in familiar terms – enacting a translation on their worldview without actually resolving difference, thereby leaving imbalances in knowledge positions unchanged.[10] In Verran's[10] proposition, the tensions which arise from moments of disconcertment are positive because they challenge people to come to new understandings of one another's knowledge. Where allegory is used to explain away differences in perspective, it prevents the different perspectives from finding a possible common ground from

whence to open a productive dialogue. Verran's[10] suggestion is to foster unease with a series of epistemic questions which in turn could enable participants to confront their differences as well as to come to a greater understanding of their own positions. In the context of an EAF, in which a multitude of disciplines, objectives and knowledges are brought together in close working contact, Verran's suggestions are of great significance. If participants are to work meaningfully and respectfully with knowledge and the often divergent perspectives that attend these, it is important to work with difference generatively or else risk marginalising certain positions by claiming them to be merely allegorical.

In the ethnographic interview presented at the start of this paper, *Oom* Louis and *Oom* Koos speak of subspecies of Silver kob not recognised by DAFF scientists or the Linnaean system. In the conversation, these fishers initially speak in terms of common names recognised by the Linnaean system. However, the picture begins to change quickly as the conventional terminology and classifications reach their limits: speaking initially in terms which resonate with an official scientific version of kob, the fishers then speak from their own experiences in which they have come to recognise a range of 'different species' or subspecies not recognised by marine biologists. The means by which they recognise and categorise these subspecies are markedly different from the means scholarly taxonomists would employ within a Linnaean classification. The subspecies are identified by a range of characteristics including long tail and 'funny' fins; broad tail; thin, flat tail; small head and fat body; rounded nose and protruding lower jaw, with the fishers agreeing on the naturalness of these classifications to the extent that they are able to finish each other's descriptions.

Murray et al.[14], writing on the migration and stock structure of cod in the Northern Gulf of St. Lawrence (working with local fishers in conjunction with scientists), found that a more nuanced map of cod population structure and their movements was produced, yet neither group was found to have a complete understanding of these prior to the exercise. Conducting research with local fishers, Murray et al.[14] argue, presents the potential to augment scientific data with higher local resolution, suggesting the prospect of identifying local fish populations. In Gilbert Bay, Southern Labrador, Wroblewski[46] explains how scientists, working with data supplied by local fishers, were able to conduct a taxonomic study which revealed a genetically distinct population of cod which warranted separate management. In light of Murray et al.'s and Wroblewski's findings, the Stilbaai example points not only to a possible collaborative project but also to the existence of a potentially valuable additional system of classification. Even if subspecies in the Linnaean sense may not be identified (i.e. in contrast to the Gilbert Bay example), a further worthwhile collaboration might explore the circumstances in which it may be of advantage to use the fisher's relationality and classificatory system rather than the Linnaean one without carrying out translations (i.e. using allegory) between these two relational 'taxonomies'. This suggestion is in line with Verran's example in which the Yolngu classification of species and associated bush firing practices resulted in a higher plant species diversity than was achieved through conventional scientific firing practices.

Conclusion

In this paper, we have suggested that knowledge is always in a constant state of mediation and translation. All people engage in 'artful deletions' for a number of reasons. On the one hand, the complexity and messiness of knowledge is most often smoothed in the final description of a thing in order to render the subject knowable and more accessible, whether it be to fishers, researchers or managers. On the other hand, fishers, for example, feel compelled to undertake a series of artful deletions when dealing with researchers, managers and factory buyers in order to be heard. Likewise, those interacting with fishers might feel compelled to enact their own artful deletions in order to more effectively communicate their intended message. In the retelling of knowledge, the interactions and relationships (as seen in the kob multiple and 'sea as actor' examples) are, out of necessity, filtered. The shift we have proposed in our work is one which seeks to move beyond an identity politics of knowledge, towards an approach in which knowledge is an open and continual process of evaluating what is known.

One of the guiding principles of conflict mediation is to focus on underlying interests rather than established positions. Fishers and scientists have a shared interest in knowing and understanding the ecologies they work in. Taking this view, how people know something becomes as important as what is known. Understanding the former empowers researchers, managers and fishers alike to enter into dialogue and collaboration on a more equal footing. It is certainly a difficult and lengthy process and there are many biases, assumptions and hierarchies which must be challenged in order to take the work forward. Nevertheless, the relational approach outlined in this paper is an essential first step if researchers are to work realistically with social-ecological systems. The intention is that work such as this engage fishers, scientists and managers in collaborative dialogue. Before embarking on a new path it is necessary to slow down and carefully unpack new concepts, allowing them to take shape through feedback with all concerned and through careful testing. The aim of this paper has not been to present a 'new way forward', but rather to unpack an emerging approach to working with multiple ways of knowing which might benefit future collaborative endeavours. There is certainly a pressing need to address urgent concerns in South Africa's fisheries. However, it is our belief that taking the time to understand the context and the continually evolving knowledges will provide deeper understanding of positions and yield more appropriate and implementable strategies.

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Authors' contributions

All ethnography presented in the work emerges from the master's research by G.L.D. and J.J.M.R. A.J. and L.J.F.G. co-supervised both degrees and provided funding for the research from their respective grants.

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Relationships between ecological infrastructure and the economy: The case of a fishery

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The Millennium Ecosystem Assessment identified the regulating services as amongst the least understood but potentially most valuable services offered by ecosystems. This lack of understanding of regulating services has been a major reason for the overexploitation and degradation of ecosystems. The value of regulating services is best determined through an economic production function approach, which derives the value of regulating services as intermediate inputs into other economic goods and services. We used existing scientific knowledge and data sourced from existing scientific databases and studies to develop and demonstrate empirical production functions that measure relationships between ecological infrastructure and the economy in fisheries in KwaZulu-Natal, along the east coast of South Africa. We applied econometric analyses – a technique that allows for evidence-based analysis of observed data, based on existing scientific knowledge. Our work demonstrates that existing scientific databases may contain useful evidence of relationships between ecological infrastructure and the economy, and that decisions need not always wait for the results of controlled experiments.

Introduction

The Millennium Ecosystem Assessment (MEA) identified the regulating services as amongst the least understood but potentially most valuable services offered by ecosystems.[1,2] These services enable ecosystems to continue to produce other direct benefits to humans, over a range of stresses or shocks, often of anthropogenic origin. Such services may also be interpreted as providing 'insurance' value, as they allow the system to continue to function over a range of conditions.[2,3]

The lack of understanding of regulating services has been the major reason for overexploitation and degradation of ecosystem assets and the ecosystem services they provide to humans.[1,4-7] Dasgupta[8] attributed this exclusion to a historical propensity by mainstream development economists to judge ecosystems as luxury goods which would improve as wealth improves, as well as to the low visibility of continuous ecosystem degradation. In addition, Perrings[9] described several typical weaknesses in environmental economic study approaches. One of the most significant weaknesses was that most of these studies focused primarily on the direct use values of the environment, and put comparatively little effort into understanding the indirect linkages among ecological functioning, ecosystem services and the production and consumption of other economic goods and services.

In order to address these problems, the MEA[1,5] and The Economics of Ecosystems and Biodiversity[6] (TEEB) initiative introduced a new way of thinking about the value of biodiversity as a life-supporting system underlying the benefits provided by ecosystem services to human society. Central to this approach is the definition of the concept of ecosystem services. TEEB defines ecosystem services as the direct and indirect contributions of ecosystems to human well-being. TEEB distinguishes among four types of ecosystem services: provisioning, cultural, regulating and supporting services. Provisioning services describe the material or energy outputs from ecosystems. Cultural services include the non-material benefits people obtain from contact with ecosystems. Regulating services are the services that ecosystems provide by acting as regulators. Supporting services underpin almost all other services through their function of providing living spaces for humans, plants and animals. Regulating services play an indirect role in the economy and mitigate environmental risk.

There is consensus amongst the professional community of resource economists that an economic production function approach is best suited as a valuation method for intermediate ecosystem services. These production functions quantify values for ecosystem services that contribute at least part of the value of those resources. They would apply knowledge of ecosystem functioning and processes to derive the value of supporting and regulating ecosystem services. They do this through deriving the value of ecosystems and the services they provide as intermediate inputs into goods and services that are produced and consumed by economic agents.[9-14] An ecological production function considers an ecosystem service as a dependent variable (or response variable), and one or more ecosystem component and/or process indicators as independent variables (or influencing factors/determining variables).

Ecological production functions require an understanding of the concepts of ecological infrastructure and biodiversity. The South African National Biodiversity Institute describes ecological infrastructure as a network of natural assets 'that conserve ecosystem values and functions and provide associated benefits to society'. Another useful characterisation is provided by Noss[15] who describes biodiversity as the composition, structure and function of an ecosystem:

> ...[C]*omposition has to do with the identity and variety of elements in a collection, and includes species lists and measures of species diversity and genetic diversity. Structure is the physical organization or pattern of a system, from habitat complexity as measured within communities to the pattern of patches and other elements at a landscape scale. Function involves ecological and evolutionary processes, including gene flow, disturbances, and nutrient cycling.*

In this study, we applied the ecosystem services framework and used the concepts of composition, structure and function of an ecosystem to formulate and demonstrate production functions to link ecological infrastructure and biodiversity to the economy, in the form of a case study. The practical challenge in so doing lies in the application of an economic technique known as econometric analysis. This technique allows for evidence-based analysis of multiple variables. Econometrics requires the application of time-series or cross-sectional, observed data for assessing economic theories, in this case resource economic theories, based on existing scientific knowledge. Econometrics most often employs regression analysis, as the data available are most often not sourced from controlled experiments. The advantage of this type of analysis is that it provides information on the extent to which society indirectly depends on components of ecosystems and the degree of risk that society is exposed to when ecosystems degrade.

Thus, using existing scientific knowledge and data sourced from existing databases and studies, we developed and demonstrate empirical production functions to measure such relationships in KwaZulu-Natal (KZN) fisheries along the east coast of South Africa as a case study. Marine and estuarine systems are demonstrated separately.

KwaZulu-Natal fisheries

The province of KZN on the east coast of South Africa supports a significant shore and boat recreational fishing industry, a small commercial linefishing industry and various subsistence fisheries.[16] The KZN fish fauna include resident species that spawn locally and have local nurseries (some of which are estuaries), pelagic summer migrants from tropical Indian Ocean waters that spawn in the tropics and have distant nurseries, and winter migrants from Cape waters, which move into KZN waters to spawn, before returning south in early summer.[17-19]

Various studies have quantified the economic size of these fisheries, both in estuarine and marine ecosystems.[20-23] These studies report various economic indicators, for a variety of years, and use different valuation techniques. A combined analysis of the work done in these studies indicates that the size of the total fisheries industry may vary between R900 million and R1400 million per year, measured in terms of the industry's contribution to the gross domestic product (GDP). The variation results from changes in catch and in input and output prices, which vary from year to year. Interestingly, the largest component of this industry is recreational shore and boat fishing (in estuarine and marine systems), for which the expenditure on fishing tackle and the associated travel cost contribute significantly. Another very significant contributor is subsistence fisheries, whose contribution to GDP is a form of economic externality as the activity takes place in the informal economy.

South Africa has an excellent body of marine and estuarine science that explains the dependence of this important and large economic sector on ecosystems. It is well known that the more productive fishery zones around the southern African coast are driven primarily by oceanic nutrient upwelling. In contrast, the KZN coast of southern Africa is located in a highly nutrient-depleted section of the Indian Ocean and is thus believed to rely heavily on nutrient influx from terrestrial run-off.[24] Thus nutrient influx into the system is sporadic, and tied closely to annual variations in climate, rainfall and, ultimately, run-off. In addition, terrestrial plant material is washed down rivers and, together with decaying seaweed, is macerated by wave action, providing a major input of detritus to filter feeders such as mussels, oysters and ascidians.[17]

Rivers and estuarine canals supply freshwater run-off and nutrients into the estuaries. They often are lined with white mangroves and, together with the tidal flats, support the most productive area in the KZN coast in terms of crustacean abundance and diversity.[18,25] The main body of mangroves in the KZN estuarine meta-system comprises white mangrove (*Avicennia marina*) occurring on the fringes of some estuaries, the largest of which (about 1200 ha) is found in the Mhlathuze Estuary. Tidal flats, both intertidal and sub-tidal, comprise the most extensive habitat in the meta-system. These tidal flats, together with the upper estuary areas, bear productive benthic faunas and are the important nursery habitats of juvenile estuary-dependent fish, crustacea and other marine animals, and also of waterbirds and fish that feed on them.[18]

Such scientific knowledge creates an important starting point for the development of ecological production functions.

Measuring relationships between biodiversity and fish production

In this study, we adapted the MEA and TEEB frameworks of ecosystem services, both of which broadly define two sets of services – those that are directly consumed as final products in the economy (direct benefits provided by provisioning and cultural services) and those that are used as inputs in generating products for final consumption (intermediate benefits provided by regulating and supporting services).

Fisheries supply both provisioning and cultural services: fish caught by commercial and subsistence fishers provide food and fishing serves a recreational purpose. Clearly, both of these services provide valuable benefits to various social and economic sectors and to the people off the KZN coast. Market valuation techniques for provisioning services of fisheries are well developed. Cost functions for both commercial and recreational fishing typically take the form of multiple regression functions in which the catch (H) in a period (t) is a function (f) of the fish biological production, e.g. biomass (S_t) and fishing effort (E_t)[12,13]:

$$H_t = f(S_t, E_t) \qquad \text{Equation 1}$$

By comparison, economic valuation techniques for intermediate ecosystem services are less developed. The production function approach has been the most common model for valuing the marginal contribution of intermediate ecosystem services. In the following sections we develop ecological fishery production functions based on the three elements that constitute the concept of biodiversity: function, composition and structure.

Capturing the functional effects of nutrients on fish production

There is ample evidence in the literature that nutrient levels strongly influence fish abundance and biological production. The KZN coastline is characterised as an oligotrophic (or nutrient deficient) marine ecosystem. Thus freshwater run-off from rivers is considered an important source of nutrient loading into estuaries and the marine environment.[16,26,27]

Our specification therefore describes the functionality of the system by the relationship:

$$S_t = f(N_t) \qquad \text{Equation 2}$$

where S_t is an indicator of biological production, and N_t is an indicator of nutrient load in the fish production system.

Capturing effects of ecosystem structure and composition on fisheries

In the case of estuarine-dependent fish species, nutrient levels alone are insufficient to describe the ecological system influencing fish production. The compositional and structural elements of estuarine biodiversity also provide important ecological infrastructure, in particular with respect to hydrodynamics and primary production. Hydrodynamics is important because the ecosystem services yielded by estuaries depend in the first place on the flow of water and the materials carried in the water.[16,28-30] Both tidal flows and freshwater inflows are important. Freshwater inflows, especially during full spate, deliver nutrients in the form of dissolved and suspended solids. Much of the suspended solids settle in the estuaries[31] while the rest pass into the main water body where they precipitate as mud in the benthos, or, if organic, are carried out with the tides or decayed or comminuted, and then consumed by detritus feeders. Primary production in estuaries results from photosynthetic microorganisms, mainly microalgae, in the shallow benthos and from

phytoplankton in the water body and mangroves. The rich benthic filter- and particle-feeding communities of the tidal flats, especially the sub-tidal flats, are key to primary production. They provide energy and nutrition to the fry of sea-breeding and other fish in the shelter of the shallows and thus form the link in the local and regional fisheries chain. The benthic animals and the abundant small fish attract predators, such as larger fish and birds, and form the basis for recreational activities and other services.[24]

Indicators of the ecological infrastructure of an estuary include variables describing the type of habitat services provided, areas of tidal flats and mangroves, and measures of the degree of openness, reflecting retention time and accessibility to juvenile fish. Estuaries are also prone to degradation caused by various forms of human activity, relating to various forms of water pollution, physical destruction and other disturbances. As a result, various estuarine ecology studies have developed indicators of human disturbance through rating the condition of estuaries.[32-34]

Thus, our specification describes the functionality of the system by the relationship:

$$S_t = f(N_t, TYPE_t, HAB_t, COND_t) \quad \text{Equation 3}$$

where S_t is an indicator of biological production, N_t is an indicator of nutrient load in the estuarine system, $TYPE_t$ is an indicator of the degree of openness of the estuary, HAB_t is a vector of habitat types (shallow sub-tidal sand, mud flats and mangroves) preferred by various fish species and $COND_t$ measures anthropogenic disturbance and its resultant degradation of system quality.

In addition to such key structural characteristics, the compositional elements of an estuarine ecosystem are also crucial for biological production of estuarine-dependent fish. There is strong evidence in the literature that higher ecosystem resilience, and thus productivity, is achieved through higher levels of species diversity.[14] Species-area studies further suggest that species diversity is significantly related to the available area of suitable quality habitat.[35] Equation 3 is thus redefined to reflect these effects in a system of two equations:

$$S_t = f(N_t, SPEC_t, TYPE_t, HAB_t, COND_t) \quad \text{Equation 4}$$

$$SPEC_t = g(TYPE_t, HAB_t, COND_t) \quad \text{Equation 5}$$

where $SPEC_t$ is an indicator of species abundance in the estuarine system.

Data and methods

We employed the above analytical framework to specify an empirical model to measure the relationship between the recreational fishery and the compositional and structural elements of estuarine biodiversity.

Data and variables in the empirical analysis

Although the analytical framework developed above implies that Equations 1 to 4 represent a system of interlinked processes and responses, unavailability of appropriate data necessitated separation of the empirical analysis into two components in empirical specification and implementation.

The first component analyses the functional effects of terrestrial nutrient deposition on the commercial marine linefishing industry. An excellent data source is the fish egg database on the website www.fisheggsandlarvae.com.[24] This time-series data forms part of a 24-year sampling record of spawning patterns of fishes with pelagic eggs, on the inshore shelf within 5 km of the coast, along a short section of the KZN coastline 50 km south of Durban.[19] The data set also includes mean annual run-off (MAR) data suitable for the purposes of analysing the relationship between nutrient influx and fish egg biomass.[25] We thus use time series data on run-off available from a different source coupled with corresponding information on an alternative index of fish biomass (i.e. fish egg abundance) to empirically specify and measure nutrient loading influences of run-off as a separate component.

The second component of the model employs cross-sectional data to capture effects of the other elements of biodiversity – in this case, the compositional estuarine ecosystem elements influencing fish productivity. Two data sets containing cross-sectional data collected independently by two research teams from sub-sets of the east coast sub-tropical estuaries of South Africa are available. One data set was compiled by Dr George Begg and was published in hard copy as *The Estuaries of Natal* volumes 1[32] and 2[33]. These data were based on extensive environmental monitoring carried out on 72 estuaries during the late 1970s and early 1980s. A second data set was compiled by Dr Trevor Harrison for the *State of South African Estuaries* report for the Department of Environmental Affairs in 2000.[36] Harrison evaluated 47 estuaries along the KZN coast.

The combined Begg–Harrison cross-sectional data comprised more than 120 measures of various estuary components and processes. Both Begg and Harrison conducted extensive biological sampling and recorded the abundance (biomass) and number of fish species in the surveyed estuaries. Several other compositional and structural characteristics of KZN estuaries were included in Begg and Harrison's cross-sectional data. Key among these measurements are: (1) estuary depth and shoreline length used as proxies for the extent of tidal flat area; (2) the type of estuary, reflecting the degree of openness of the estuary; and (3) rating of the general condition of the estuary. These variables all have important functions in the production of estuarine ecosystem services. The degree of openness measures the connectivity of an estuary to the marine ecosystem. Highly connected estuaries (i.e. those that are open for 12 months of the year) will be more productive than estuaries that are only temporarily open, and would be expected to have higher species richness. The shoreline length (in kilometres) and area of shallow sub-tidal flats (in hectares) are both measures of habitat area. The condition of the estuary is rated through an index, which measures its general health and levels of human disturbance (e.g. pollution and physical alterations). Begg also provides measures of terrestrial run-off, either directly as river inflow into estuaries or indirectly as catchment areas which, with MAR, can yield run-off values. The Begg–Harrison data also contain a measure of dissolved oxygen (in mg/litre), which is indirectly proportional to nutrient content as higher levels of dissolved oxygen in these estuaries are commonly associated with poorer nutrient load conditions.[37] More dissolved oxygen is primarily a result of larger systems which are open and subject to marine flushing, rather than related to nutrient concentration.

A notable difference between Begg's and Harrison's data sets relates to their fish sampling gear: Begg used a small beam trawl while Harrison used a variety of nets including seine nets and gill nets (Connell A 2013, oral communication, March 06). We therefore used only the Harrison data set for fish species and abundance data, with data standardised to a catch per unit effort.

Empirical models

The first component of the above specified analytical framework describing the relationship between freshwater run-off and fish egg abundance (Equation 2) was estimated using nutrient influx data and counts of fish eggs as an indicator of the condition of those fish species that spawn in the area. These data are available in time series.[19] Whilst we recognise that both the condition of the spawner biomass and seasonal variables will influence spawning intensity, counts of fish eggs are expected to be influenced by MAR in the current year (MAR_t), as nutrient inflow indirectly promotes spawning. Nutrient inflow promotes primary productivity, which increases the biomass of zooplankton grazers benefitting from the algal blooms. The zooplankton and algal mix form a good food source for grazing fish such as anchovy, sardine and other small shoaling species. As these are the key spawners, one would thus expect a lag – of about one year – between high nutrient input (rainfall) and high egg production. One can expect a further lag before the predatory fish that feed on these small shoaling species also contribute to higher spawning levels. We accordingly estimated extended

versions of the model in Equation 2 to account for lagged MAR effects. The following specifications of the relationship were empirically tested:

$$S_t = c_0 + c_1 MAR_t + c_2 MAR_{t-1} + c_3 MAR_{t-2} \quad \text{Equation 6}$$

The second component of the analytical framework describing the relationship between estuaries ecosystem structure and composition was estimated using the Begg–Harrison cross-sectional data set, which allowed specification of the following system of ecological production function equations:

$$BIOMF_i = \alpha_0 + \alpha_1 * SPECS_i + \alpha_2 TYPE_i + \mu_i \quad \text{Equation 7}$$

$$SPECS_i = \beta_0 + \beta_1 * COND_i + \beta_2 * SHRLN_i + \beta_3 * TYPE_i + \beta_4 * NUTRI_i + \varepsilon_i \quad \text{Equation 8}$$

where $BIOMF_i$ measures the total weight of fish caught in grams per sample in estuary i; $SPECS_i$ is the number of fish species in the sample from estuary i, $COND_i$ is an index of the condition of estuary i measured through the Harrison–Whitfield multimetric estuary index[25] and $SHRLN_i$ measures the length of the shoreline of estuary i (in metres). $TYPE_i$ is an index that refers to the classification of estuary i as defined by the Whitfield physical classification of estuaries (see Table 1), $NUTRI_i$ is an index of the nutrient capacity of the estuarine system and was calculated by dividing the catchment area (in km^2) by the volume of the estuary waterbody (in m^3), α_j and β_j are model parameters and μ_i and ε_i are the residual error terms.

Equation 7 specifies the biological production of fish to be a function of the number of species present in the system (diversity composition effect) and the estuary type. In Equation 8, the number of species present in the system (species richness) is modelled to vary with differences in key ecosystem component and process variables: estuarine condition as measured by the Harrison–Whitfield multimetric estuary index is a good indicator of the overall ecosystem health of an estuary.[38] Shoreline length is a proxy for the extent of tidal flat area, which is an indicator of the area of shallow sub-tidal flats, which is important fish feeding habitat. Estuarine type is important because larger estuaries that are permanently open to the sea generally provide more diverse habitat and improved connectivity between marine and estuarine habitats, and thus allow for a greater number of fish species. Nutrient cycling is important because estuaries with larger catchment areas (within the same metasystem) would produce more detritus and are more likely to flush the estuary. The *NUTRI* variable also indirectly captures effects of run-off on nutrient capacity, as a larger catchment area is expected to have a higher MAR and thus higher nutrient input.

Results of the empirical analysis

The empirical relationship between run-off and spawning intensity was estimated using linear and Cobb–Douglas functional forms. The linear form function gave the best statistical performance (Table 2). The results show that nutrient input into the system in the current period t, combined with lagged effects of nutrient input over the preceding 2 years (t-1 and t-2), explains 97% of the variation in S_t (fish egg abundance) (Appendix 1). However, the effect of a one-period lag (M_{t-1}) was not statistically significant and hence estimation results for the statistically significant two-period lag are reported in Table 2. Both coefficients indicate a strong positive correlation between run-off and spawning intensity. The lagged effect is consistent with the life-cycle characteristics of fish, which reach spawning maturity after 12–24 months. It should be noted that the improved condition of the spawning adults in the population, resulting from improved nutrition, contributed to the increased spawning.

The fact that the variable *SPEC* appears on both sides of the system in Equations 7 and 8 implies an endogeneity problem and hence that an ordinary least squares estimation is not appropriate. A two-stage least squares (2SLS) procedure was accordingly employed to estimate the parameters of this system, which, unlike an ordinary least squares approach, yields consistent estimators of system parameters.[39] Two functional form specifications were tested: the linear and Cobb–Douglas (double-log) forms. The linear function gave the best statistical fit. Results of the 2SLS estimation of the linear system are presented in Table 3. Results of the double-log function are reported in Appendix 2.

The influences of all factors in the linear 2SLS model are of high statistical significance and all show the expected sign, i.e. direction of effect. Equation 7 relates the number of species ($SPECS_i$) and the estuarine type ($TYPE_i$) to fish biomass ($BIOMF_i$), and these two variables explained 43% of the variation in fish biomass ($BIOMF_i$).

As expected, catch size of fish biomass in an estuary increases with increasing number of fish species at more than 99.9% confidence limit. This result is very important as it provides strong scientific evidence that biodiversity, as measured by species abundance, is positively correlated with biomass abundance, and thus the productivity of the estuarine system. Similarly, levels of fish biomass in an estuary are higher in larger estuaries with a higher degree of openness, as measured by the Whitfield physical classification index of estuaries ($TYPE_i$ was significant at a 99% confidence limit).

Equation 8 measures the effects of estuary ecosystem component factors on fish species abundance, which explained more than 70% of the variation in fish species. The area of shallow sub-tidal flats (measured by shoreline length ($SHRLN_i$)), estuarine type ($TYPE_i$) and the nutrient capacity ($NUTRI_i$) of the estuary were all highly statistically significant variables. This finding means that larger estuaries with larger shallow sub-tidal flat habitats, higher degrees of openness and larger nutrient capacities will accommodate a richer diversity of fish species.

Table 1: Whitfield's[38] physical classification of estuaries

Type	Index	Tidal prism	Mixing process	Average salinity†
Estuarine bay	5	Large (>10 x 106 m^3)	Tidal	20–35
Permanently open	4	Moderate (1–10 x 106 m^3)	Tidal/riverine	10–>35
River mouth	3	Small (<1 x 106 m^3)	Riverine	<10
Estuarine lake	2	Negligible (<0.1 x 106 m^3)	Wind	1–>35
Temporarily closed	1	Absent	Wind	1–>35

†*Total amount of dissolved solids in water in parts per thousand by weight (seawater = ~35).*

Table 2: Estimation results of mean annual run-off (MAR) influences on fish production on the coast of KwaZulu-Natal

	Coefficient	Standard error	*t*-statistic	Probability
MAR_t	0.414260	0.074884	5.532028	0.0026
MAR_{t-2}	11.28793	3.412231	3.308080	0.0213
C	-2890.046	854.1805	-3.383414	0.0196
R-squared	0.927397	Mean (dependent variable)		594.5500
Adjusted R-squared	0.898356	Standard deviation (dependent variable)		394.4448
Standard error of regression	125.7556	Akaike info criterion		12.78655
Sum squared residual	79072.32	Schwarz criterion		12.81634
Log likelihood	-48.14621	Hannan–Quinn criterion		12.58563
F-statistic	31.93388	Durbin-Watson statistic		1.375046
Probability (F-statistic)	0.001420			

Table 3: Two-stage least squares estimates of parameters of the system of Equations 7 and 8 for the linear model

	Coefficient	Standard error	*t*-statistic	Probability
α_0	17708.25	6209.448	2.851823	0.0055
α_1	661.6210	139.7012	4.735973	0.0000
α_2	5963.664	2301.972	2.590676	0.0113
β_0	26.53224	2.924246	9.073188	0.0000
β_1	0.312958	0.079973	3.913315	0.0002
β_2	0.000414	4.53E-05	9.150209	0.0000
β_3	8.317157	1.425839	5.833169	0.0000
β_4	0.017685	0.007858	2.250593	0.0270
Determinant residual covariance 2.59E+09				
Equation 7: $BIOMF_i = \alpha_0 + \alpha_1 * SPECS_i + \alpha_2 * TYPE_i$				
Adjusted R-squared	0.4298			
Equation 8: $SPECS_i = \beta_{0+} \beta_1 * COND_i + \beta_2 * SHRLN_i + \beta_3 * TYPE_i + \beta_4 * NUTRI_i$				
Adjusted R-squared	0.7332			

Estuarine condition ($COND_i$) as measured by the Harrison–Whitfield multimetric estuary index, which uses a multiple of indicators, showed a strong positive correlation with species diversity and was significant at the 99.9% confidence limit.

To derive marginal effects of estuarine ecosystem services on fish catches, one should bear in mind the direct and intermediate effects specified in Equations 7 and 8. These are calculated in Table 4, based on parameter estimates given in Table 3. It is clear that the degree of openness and species diversity contribute the most to fish productivity. These estimates can be used to derive shadow values (accounting prices) of the estuary intermediate and regulating ecosystem services at fish catch prices. However, they overestimate the value of the marginal contribution of these services as our model – because of a lack of appropriate corresponding data – does not account for the effect of economic efforts (inputs) on harvest; but these estimates can be used as upper bound estimates.

Table 4: Marginal impacts of estuary ecological structure on fish catches (in grams) in KwaZulu-Natal

Ecosystem attribute	Direct effect	Intermediate effect	Total effect
Species diversity (SPEC)	661.62 (α_1)		661.62 (α_1)
Openness (TYPE)	5963.66 (α_2)	8.317 (β_3)	(α_2) + (α_1)*(β_3)
Condition (COND)		0.313 (β_1)	(α_1)* (β_1)
Shoreline length (SHRLN)		0.0004 (β_2)	(α_1)* (β_2)
Nutritional capacity (NUTRI)		0.0176 (β_4)	(α_1)* (β_4)

Conclusions, implications and limitations

We have demonstrated how the production function approach can be used to measure the relationships between fishery activities and the compositional and functional elements of both estuarine and marine ecosystems, and we have used this approach to demonstrate how shadow values (accounting prices) may be estimated for KZN estuarine and marine ecosystems. We used available time-series and cross-sectional data sets that were independently collected on various compositional and functional components of the estuarine and marine ecosystem asset and fish biomass.

A single equation ecological production function has been empirically specified to measure the functional effects of nutrient inputs on fish production in the marine system. In addition, a two-equation system of ecological production functions has been estimated to measure the effects of estuarine ecosystem composition and structure on fish production in the estuary. Using the SURE (Seemingly Unrelated Regression Equations) regression analysis method, the estimated system showed highly significant statistical performance and parameter effects consistent with scientific knowledge. The results provide compelling evidence, expressed in econometric terms, of the importance of estuarine structure and composition on fish biodiversity and production. Ultimately, such results are of great importance to estuarine management, harbour development and planning, and various other coastal sustainable development strategies and policies.

There were, however, limitations to the study as a result of a lack of appropriate data. It is expected that seasonal effects related to, for instance, fish population size and rainfall events would explain a large component of the variation in fish production. The modelling of such relationships requires time-series data sets, which were not available. We also did not have access to appropriate data to control for the effects of economic efforts (e.g. economic inputs) on fish harvesting. Accordingly, we could be overestimating the marginal effects and accounting prices based on the derived estimates of the effects of estuary ecosystem assets structure and composition attributes in computing shadow values of their services.

The results nevertheless hold several important policy implications. They demonstrate, through empirical evidence, how ecological degradation and changes in estuarine and marine ecosystems may indirectly affect a valuable industry. The results provide statistical evidence of the importance of ecological infrastructure and biodiversity for the fish production systems along the KZN coast. As tension between conservation of biodiversity and economic development is expected to increase in future, the need for evidence-based policy decisions will become greater. The current work demonstrates the benefits that could be derived from continued investment in long-term scientific monitoring programmes. It also demonstrates that existing databases may contain useful evidence of relationships between ecological infrastructure and the economy, and that decisions need not always wait for the results of controlled experiments.

The production functions also demonstrate the importance of responsible coastal development initiatives. River impoundments, water pollution, harbour development and other coastal developments are all factors that influence fish production and thus the economy.[18,40,41] Future developments should mitigate for their effects on ecosystem services.

This knowledge can also greatly assist policymakers in the issuance of fishing permits. Conventional fisheries models use historical catch records and catch effort data to estimate fish stock sizes and also to control fishing permit conditions. This new knowledge introduces the possibility of using environmental variables as additional predictors of fish stocks. We would like to note, however, that the accentuated response to terrestrial-based nutrients applies only to fish stocks that are located in areas with significant terrestrial run-off into otherwise oligotrophic waters.

Furthermore, elevated spawning does not necessarily mean elevated recruitment. A good spawning could be followed by poor survival of larvae, as their food requirements differ from those of adults; a shortage of suitable food items for early larvae could result in poor survival of recruits.

Finally, a strong correlation between spawning intensity and rainfall-based nutrient input is implied, although not empirically proven. However, this work has demonstrated strong linkages between nutrient levels (using MAR as a proxy) and fish egg abundance and thus enables the investigation of run-off and rainfall-related climate change effects on KZN fisheries.

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Authors' contributions

J.C.G. is the primary author and performed the data mining, production function specification and econometric analysis; R.M.H. assisted in writing the manuscript and the econometric analysis.

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Appendix 1: Effect of run-off on fish production estimation results

Dependent variable: S_t				
	Coefficient	**Standard error**	***t*-statistic**	**Probability**
MAR_t	0.215091	0.089188	2.411666	0.0949
MAR_{t-1}	8.150709	4.976418	1.637867	0.2000
MAR_{t-2}	11.40421	4.191028	2.721102	0.0725
C	-4805.102	1206.367	-3.983117	0.0283
R-squared	0.969937	Mean of dependent variable		513.1857
Adjusted R-squared	0.939874	Standard deviation of dependent variable		346.0199
Standard error of regression	84.84651	Akaike info criterion		12.01512
Sum squared residual	21596.79	Schwarz criterion		11.98422
Log likelihood	-38.05293	Hannan–Quinn criterion		11.63310
F-statistic	32.26321	Durbin–Watson statistic		2.179820
Probability (F-statistic)	0.008769			

Appendix 2: Two-stage least squares method estimates of parameters of the system of Equations 7 and 8 for the Cobb–Douglas model

System: BIOM_M_TSLS				
	Coefficient	**Standard error**	***t*-statistic**	**Probability**
α_0	7.281629	0.674133	10.80147	0.0000
α_1	0.929339	0.197365	4.708722	0.0000
α_2	-0.607428	0.326855	-1.858404	0.0667
β_0	0.279958	0.372497	0.751573	0.4544
β_1	0.157397	0.032251	4.880376	0.0000
β_2	0.294073	0.040109	7.331749	0.0000
β_3	-0.483041	0.135289	-3.570434	0.0006
β_4	0.005454	0.021222	0.256995	0.7978
Determinant residual covariance		0.026485		
Equation 7: $\ln(BIOMF_i) = \alpha_0 + \alpha_1*\ln(SPECS_i) + \alpha_2*\ln(TYPE_i)$				
Observations: 46				
R-squared	0.441443	Mean of dependent variable		9.517919
Adjusted R-squared	0.415464	Standard deviation of dependent variable		0.848863
Standard error of regression	0.648998	Sum squared residual		18.11154
Probability (F-statistic)	1.682823			
Equation 8: $\ln(SPECS_i) = \beta_{0+}\beta_1*\ln(COND_i) + \beta_2*\ln(SHRLN_i) + \beta_3*\ln(TYPE_i) + \beta_4*\ln(NUTRI_i)$				
Observations: 45				
R-squared	0.741723	Mean of dependent variable		2.865228
Adjusted R-squared	0.715896	Standard deviation of dependent variable		0.516789
Standard error of regression	0.275456	Sum squared residual		3.035039
Probability (F-statistic)	1.274492			

Observed and modelled trends in rainfall and temperature for South Africa: 1960–2010

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Observed trends in seasonal and annual total rainfall, number of rain days and daily maximum and minimum temperature were calculated for a number of stations in South Africa for the period 1960–2010. Statistically significant decreases in rainfall and the number of rain days are shown over the central and northeastern parts of the country in the autumn months and significant increases in the number of rain days around the southern Drakensberg are evident in spring and summer. Maximum temperatures have increased significantly throughout the country for all seasons and increases in minimum temperatures are shown for most of the country. A notable exception is the central interior, where minimum temperatures have decreased significantly. Regionally aggregated trends for six water management zones covering the entire country are not evident for total rainfall, but there are some significant trends for the number of rain days. Temperature in these zones has increased significantly for most seasons, with the exception of the central interior. Comparison of the observed trends with statistically downscaled global climate model simulations reveals that the models do not represent the observed rainfall changes nor the cooling trend of minimum temperature in the central interior. Although this result does not rule out the possibility of attributing observed local changes in rainfall to anthropogenically forced global change, it does have major implications for attribution studies. It also raises the question of whether an alternative statistical downscaling method or dynamical downscaling through the use of a regional climate model might better represent regional and local climatic processes and their links to global change.

Introduction

Historical trends in climatic variables are of interest in a variety of academic disciplines and economic sectors, such as ecology, agriculture and water resource management. As a consequence, numerous studies[1-16] have investigated climatic trends in South Africa, mostly focusing on station records of temperature and rainfall as well as various indices derived from these quantities. The greatest restriction to such studies of historical climate is the availability of long-term meteorological station observations that have sufficient coverage to give an adequate representation of a region's climate. South Africa has a relatively good network of rainfall and temperature recording stations compared to the rest of Africa and much of the southern hemisphere,[1-3] which makes it possible to investigate trends and variability over multiple decades. However, it is often difficult to detect clear signals of long-term change given large variability across a range of spatial and temporal scales. This difficulty is particularly relevant for rainfall, which is highly variable in both space and time, thus making any trend calculation sensitive to the specific location and period of the observations. Re-evaluation of trends as new and updated observational data sets become available is therefore necessary and allows for an assessment of how representative a trend over a given record is of underlying long-term climatic changes.

Process-based global climate models (GCMs) are the primary tools used to make projections of future climate under scenarios of anthropogenic greenhouse gas forcing. Although these models generally have skill in replicating large-scale climate features, their coarse spatial resolution does not provide adequate information at local scales. Hence a variety of downscaling procedures, both empirical and dynamical, have been developed in order to represent finer spatial details.[17-19] A question that is relevant in the context of historical trend analysis is whether or not the climate models (or downscaled products derived from these models) are able to replicate local trends in rainfall and temperature. When simulating the climatic effects of anthropogenic emissions, the only persistent temporal forcing applied to a GCM is an increasing concentration of greenhouse gases. If an observed historical trend in a climate variable, for example rainfall, is not replicated by such a GCM simulation, it could imply that the change is not a result of an enhanced greenhouse effect. This subject of detection and attribution of anthropogenic climate change has received considerable attention of late.[20-22] Alternatively, disagreement between observed and modelled trends could be the result of either (1) weaknesses in the models' representation of key processes at the regional or local scale or (2) uncertainties in the observational record. Both possibilities have implications for the interpretation of both past and future climate projections.

In this paper, we present an analysis of climatic trends in rainfall and temperature indices for South Africa for the period 1960–2010 and thus provide an update that will complement previous trend analyses. We first present a review of previous climate trend studies in South Africa to provide a context for our analysis. We then summarise the important modes of variability that are associated with intraseasonal and interannual variations in South Africa's climate and which can have a marked influence on trends calculated over a 50-year period. Finally, we describe the methodology for our trend analysis and present the results. Included in the analysis is a comparison of the observed trends with statistically downscaled climate model simulations.

Review of climate trend studies in South Africa

Because South Africa's mean annual precipitation (MAP) is highly variable from year to year[4,5], few spatially coherent or statistically significant trends in this quantity have been observed[6-8]. However, of more relevance than MAP are the characteristics of how rainfall is distributed throughout the year. These characteristics include the timing of the

onset and end of the rainy season, the typical durations of wet and dry periods and the occurrence of extreme heavy rainfall events. A review by Easterling et al.[2] indicates a tendency for increased extreme precipitation in the southwestern and eastern parts of South Africa during most of the 20th century. In agreement with these observations are results from Groisman et al.[9] who show a significant increase in the annual frequency of very heavy rainfall events over eastern South Africa from 1906 to 1997. Furthermore, Mason et al.[10] demonstrate increases in the intensity of high rainfall events in the 1961–1990 period relative to 1931–1960 over much of South Africa. Kruger[8] shows increases in extreme rainfall indices over the southern Free State and parts of the Eastern Cape from 1910 to 2004. New et al.[6] also show some evidence for increased rainfall extremes over parts of South Africa for the 1961–2000 period. Nel[7] demonstrated a shift in seasonality for stations in the KwaZulu-Natal (KZN) Drakensberg for 1955–2000. Here MAP showed no significant trend, but an increase in summer rainfall, accompanied by decreased autumn and winter rainfall, resulted in a shorter wet season and a more pronounced seasonal cycle. These findings are consistent with results from Thomas et al.[11] for northwest KZN, which show an increase in early-season rainfall along with a decrease in late-season rainfall between 1950 and 2000. Seasonal shifts were also observed in Limpopo for the same period, where there has been a tendency for a later seasonal rainfall onset accompanied by increased dry spells and fewer rain days.[11] A trend toward later onset of rainfall in Limpopo between 1979 and 1997 was also identified by Tadross et al.[12], but they note that this trend is likely part of low-frequency variability rather than long-term change. Increased dry spell duration is also evident for much of the Free State and Eastern Cape, and decreases in wet spell duration have been observed for parts of the Eastern Cape and the northeastern parts of South Africa during 1910–2004.[8]

Long-term trends in temperature-related indices tend to manifest themselves more strongly than changes in rainfall indices. As global mean temperature has been observed to increase over the last century, which is largely attributed to the warming effects of anthropogenic greenhouse gas emissions,[23] so different regions have experienced changes of varying magnitude. In South Africa between 1950 and 1993, Easterling[13] found an increase in annual mean daily maximum temperature (tmax) and widespread increases – although also some decreases – in annual mean daily minimum temperature (tmin). Despite a global tendency for a reduction in the diurnal temperature range (dtr), which is the difference between tmax and tmin, the results of Easterling[13] show much of South Africa experienced an increase in dtr. In contrast, however, Hulme et al.[14] show decreased dtr over South Africa during the 1950s and 1960s. They also show very strong warming in the central interior of southern Africa and in fact a cooling over the coastal regions of South Africa for the 1901–1995 period. It is not clear what the cause of this cooling may be. Kruger and Shongwe[15] examined the period 1960–2003 and found that, with a few exceptions, stations in South Africa have reported increases in annual mean temperatures, with strongest warming having occurred in the interior of the country and during autumn months. The stations showed mixed results with respect to dtr, with no clear regional pattern of change. New et al.[6] also indicate varied results for changes in dtr over a similar period, but they do show a tendency for the cold extremes of tmin to change more strongly than the cold extremes of tmax. They also reveal a general increase in hot extremes over South Africa. The most recent published work on South African temperature trends was done by Kruger and Sekele[16] for the period 1962–2009. They focused on extreme temperature indices for 28 stations and found significant changes in the exceedances of the extreme percentile values for tmin and tmax at many of the stations. More specifically, increases in daily measurements in excess of the 90th percentile of tmax and tmin have occurred along with decreases in exceedances of the 10th percentile of tmin and tmax. These occurrences are indicative of an overall increase in hot extremes and decrease in cold extremes, with the strongest changes tending to occur in the western and northern interior of the country. There is also a general tendency for stronger increases in the tmax indices than for those related to tmin.[16]

Although some general tendencies are apparent for trends in both rainfall and temperature indices, there is some disagreement between studies. This discord can to a large extent be attributed to two factors: the period over which the data were analysed and the locations of the stations from which data were obtained. Large, naturally occurring variations in climate at yearly and decadal timescales can greatly affect the calculation of trends, so it is important to consider the length of record when evaluating any trend analysis. Regional inferences based on individual stations are reliant on how representative a station or group of stations is of that area and should also be treated with caution. Some studies also rely on gridded products where station records have been interpolated in space onto a continuous surface. Such products should closely match the raw station data in places where the observational record is good, but in data-sparse regions this information is less reliable, especially where strong environmental gradients exist. Details of the methods used to calculate trends also differ between studies, but these should rarely result in substantially different results. Further factors that can influence results are data quality and quality-control measures.

Timescales of climate variability and teleconnections

Climate exhibits numerous modes of variability in global and hemispheric circulation patterns at intraseasonal (of the order of 1 or 2 months) and interannual (year-to-year) timescales. The El Niño-Southern Oscillation (ENSO) is recognised as the leading mode of interannual variability in the tropics and is driven by variations in sea-surface temperatures (SSTs) in the equatorial Pacific Ocean. Links between ENSO and southern Africa's rainfall have been established, such that warm ENSO events (El Niño) are commonly associated with below-average summer rainfall over much of South Africa and cold events (La Niña) are typified by above-average rainfall in this region. It has indeed been shown that severe summer drought in South Africa tends to occur under El Niño conditions[24,25] – a relationship which seems to have strengthened since the 1970s[26]. Furthermore, seasonal prediction of summer rainfall in South Africa shows more skill during strong ENSO phases.[27] However, the relationship between ENSO and South Africa's rainfall is far more complex than a simple linear association and there are many more factors that influence the region's climate. For example, the frequency of synoptic-scale patterns of convection over South Africa are modulated by ENSO events, but different synoptic regimes under the same ENSO phase can result in substantially different rainfall responses.[28]

Complexities are also introduced through the influence of other climatic modes, and interactions between these modes. The second prominent interannual mode relevant for southern Africa is a dipole pattern in SST anomalies between the southwestern and southeastern Indian Ocean. A positive phase of this subtropical Indian Ocean dipole, characterised by anomalously warm SSTs in the western part of the basin, has been linked to increased summer rainfall over parts of southern Africa[29-31] as well as extreme rainfall events in the region[32]. Increased SSTs in the southwest Indian Ocean have also been associated with an enhancement of the El Niño effect over South Africa.[26] At an intraseasonal timescale, the Madden–Julian Oscillation (MJO) has a noticeable impact on South African convection and rainfall.[33] The MJO is an eastward propagation of large-scale convective clusters in the tropics with a period of 30–60 days. It has been shown that convection over South Africa tends to be more strongly affected by the MJO during warm phases of ENSO and warm tropical Indian Ocean temperatures, such that intraseasonal variability is higher and convection is less active during El Niño events.[33] A further low-frequency mode that is present in the mid-latitudes is the Antarctic Oscillation (AAO), which is defined by pressure anomalies between Antarctica and the southern hemisphere mid-latitudes. There is some indication of a link between a positive phase of the AAO and enhanced rainfall over central South Africa, which tends to be stronger during La Niña years.[34] It has also been shown for the winter rainfall region of the southwestern Cape that particularly wet winters are associated with a negative phase of the AAO and vice versa.[35]

Beyond the interannual timescale are decadal-scale variations in climate which provide a slowly evolving background around which higher-frequency modes oscillate. For example, an approximately 18-year cycle in southern African rainfall has been identified in instrumental and

proxy records extending back as far as 600 years.[36] The cause of this oscillation is not clear, but an 'ENSO-like' multidecadal pattern of variation has been identified at multiple periodicities.[37] Interaction between phases of the multidecadal and interannual variations act to enhance or mitigate regional responses.[37,38] In the context of the trend analysis presented in this study, it is very important to consider the possible influences of low-frequency variations on the calculation of long-term trends.

Data and methods

Station observations were obtained though the Climate Information Portal (CIP) hosted by the University of Cape Town's Climate System Analysis Group (http://cip.csag.uct.ac.za). The data originate from two main sources – the Computing Centre for Water Resources and the South African Weather Service – and were collated and quality controlled prior to being uploaded to CIP. Stations were selected based on their coverage of monthly data for the period 1960–2010 such that any station with 20% or more missing values was excluded from the analysis. Based on this condition, data from 73, 30 and 27 stations were available for rainfall (ppt), tmax and tmin, respectively. The indices presented in this paper are limited to ppt, number of rain days, tmax and tmin, but analysis was also performed for extreme values of rainfall and temperature. Results for the full set of indices are presented in the Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) technical report on climate trends and scenarios for South Africa.[39]

Trends in the indices for the 1960–2010 period were evaluated using a number of approaches. Firstly, the non-parametric Mann–Kendall trend test was applied. This method has the advantages of making no assumptions about the distribution of the underlying data and being relatively insensitive to outliers. In this method, a correlation coefficient, tau, is computed, which has a value between -1 and 1 and denotes the relative strength of the trend in a time series. The probability of this trend occurring by chance is also estimated, from which a measure of statistical significance can be assigned. We used a 5% level of significance, such that if the probability estimate was less than 0.05, the trend was deemed to be significant. Because tau does not provide an estimate of the absolute magnitude of the trend, we also calculated the slope of the trend using Sen's slope estimator, which is the median of the slopes calculated between all pairs of data points in the series. Like the Mann–Kendall test, this method is also statistically robust and insensitive to outliers in the data.

The above trend estimates were calculated for seasonal and annual means for all indices. The results are presented as follows. Firstly, annual and seasonal maps of the Mann–Kendall tau for each station and each variable are shown. These maps depict the relative strength of trends over the historical period at each station and give an indication of any coherent spatial patterns of change. Secondly, annual and seasonal time series plots were generated for six water management zones covering all of South Africa. The zones are those used in the LTAS programme for the assessment of climate change on water resources.[40] To calculate these regional time series, an anomaly time series was computed for each station falling within the region by subtracting the 1960–2010 station mean from each value in the series. The resulting series was then summed and divided by the number of stations in that region, after which trend statistics were calculated for the regional mean series. A smoothed curve was added to the figures using a Loess filter with a bandwidth of 0.25. The resulting figures give an indication of the direction and magnitude of long-term trends as well as illustrate interannual and interdecadal variability in the time series. Two important points should be noted here. Firstly, although the definition of the zones has value in a hydro-climatic context, the zones do not necessarily coincide with homogeneous climates and climatic trends. Opposing trends at stations within the same zone will hence weaken any regional signal. Secondly, the stations falling within a particular zone may not necessarily be a good representation of spatial heterogeneity within that zone. This point is particularly true for indices related to rainfall and for zones in which station coverage is sparse. Nevertheless, some useful information can be extracted from these spatially averaged indices.

To compare the observed trends for the six water management zones to climate model simulations for the same period, results from 11 different GCM simulations were used. The GCM simulations were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) and have been statistically downscaled to the same stations used in the trend analysis. Although more model simulations exist in the CMIP5 archive, we have limited our analysis to those models that are currently available on CIP and have been downscaled to the relevant stations. The GCMs used are listed in Table 1. The method of downscaling is described in Hewitson and Crane[17] and the data are publicly available on CIP. Trends for 1960–2010 were computed using Sen's slope estimator for each downscaled GCM, aggregated over the six zones.

Table 1: Global climate models used in the study

Model name	Institute
BCC-CSM1	Beijing Climate Center, China Meteorological Administration
BNU-ESM	Beijing Normal University
CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CM5	Centre National de Recherches Météorologiques / Centre Européen de Recherches et Formation Avancées en Calcul Scientifique
FGOALS-s1	Institute of Atmospheric Physics, Chinese Academy of Sciences
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
MIROC5	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology
MRI-CGCM3	Meteorological Research Institute, Japan

Results

Observed trends for 1960–2010

The results for ppt, rain days, tmax and tmin are presented in Figures 1 to 8. The main findings that emerged from the analysis are summarised below for each of the six water management zones.

Zone 1: Limpopo and parts of northern Mpumalanga

There is a mixed signal in the spatial distribution of changes in rainfall indices in most seasons, but a tendency for reductions in ppt (Figure 1) at most stations in March–May (MAM), although this reduction is significant at only two stations. A cluster of stations in the Lowveld indicate increased ppt for MAM, but although there is some spatial coherence, the trends are small and not statistically significant. More pronounced trends are seen in the number of rain days (Figure 2), for which a number of stations show significant decreases in the September–November (SON), December–February (DJF) and MAM seasons. Two pairs of nearby stations exhibit contrasting significant trends in rain days. This

result could be because of localised environmental conditions interacting in different ways with larger-scale rainfall processes, but a more detailed study of these locations is required to investigate this result further.

All but one station show significant increases in tmax (Figure 3), with the strongest warming signal occurring in June–August (JJA) and the weakest in DJF. The strongest warming of tmin occurs in DJF and JJA (Figure 4). Regionally aggregated ppt time series for this zone (Figure 5, top row) show large interannual and decadal-scale variability and no significant trends, but significant reductions occur in the number of rain days in DJF and MAM and in the annual mean (Figure 6, top row). The change in annual mean rain days translates to nearly 16 days over the 50-year period. Significant increases occur in tmax in JJA (0.022 °C/year) and in the annual mean (0.018 °C/year) (Figure 7, top row), which represent approximately a 1 °C increase over the 50-year period. Changes in tmin are generally smaller, with a 0.011 °C/year increase in annual mean (Figure 8, top row).

Zone 2: Majority of KwaZulu-Natal and part of southern Mpumalanga

A consistent spatial pattern of decreased ppt is shown for MAM (Figure 1), but the trends are significant at only three stations. In the southern part of the region in SON, a cluster of stations show increased ppt, but none of these trends is significant. Many stations indicate significant changes in rain days, but spatial coherence is weak (Figure 2). There is a suggestion, however, that coastal stations have experienced decreased rain days, whereas inland locations have experienced increases. A cluster of stations in the southern Drakensberg area, which also extends into Zone 5, shows significant increases in rain days in SON and DJF.

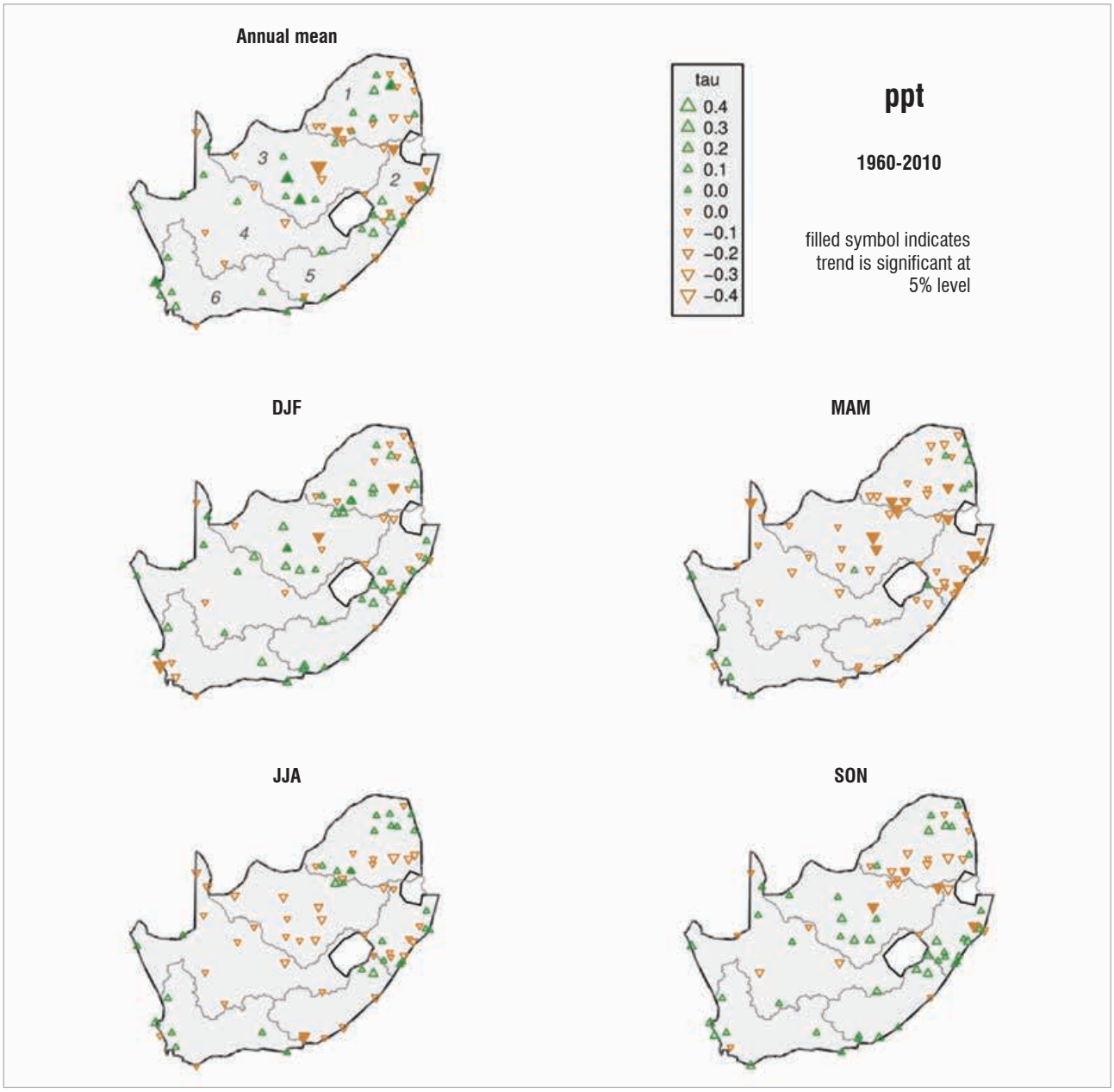

Figure 1: Trends in annual and seasonal mean rainfall (ppt) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

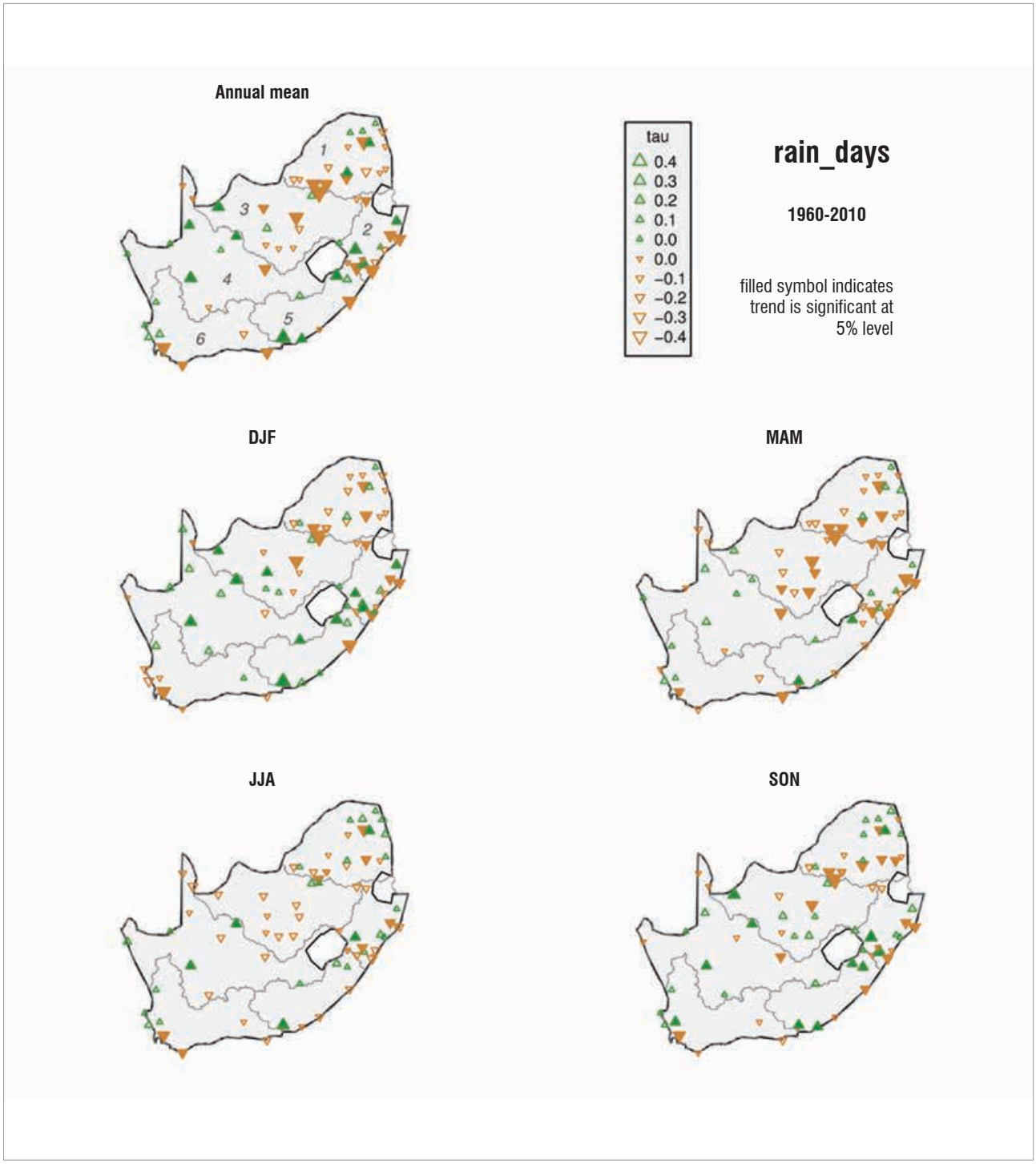

Figure 2: Trends in annual and seasonal rain days (days) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

Data from only three temperature stations were available for this zone, which all show positive trends for tmax (Figure 3) and tmin (Figure 4), but not all of these trends are significant. No regionally averaged trends are seen in ppt (Figure 5, second row), but overall decreases in rain days are shown in DJF and MAM and in the annual mean (Figure 6, second row). It must be noted, however, that spatial variability in the number of rain day trends for this zone is high, which the regional average does not take into account. The average increase in tmax for the three stations in this zone is highest for the MAM season (0.02 °C/year) and is 0.012 °C/year for the annual mean (Figure 7, second row). The increase in annual mean tmin is 0.014 °C/year (Figure 8, second row).

Zone 3: Northern and central interior

Opposing signals are shown at individual stations for ppt (Figure 1), with a rough distinction between increased rainfall in the west and decreased rainfall in the east in DJF. There is, however, a general tendency for

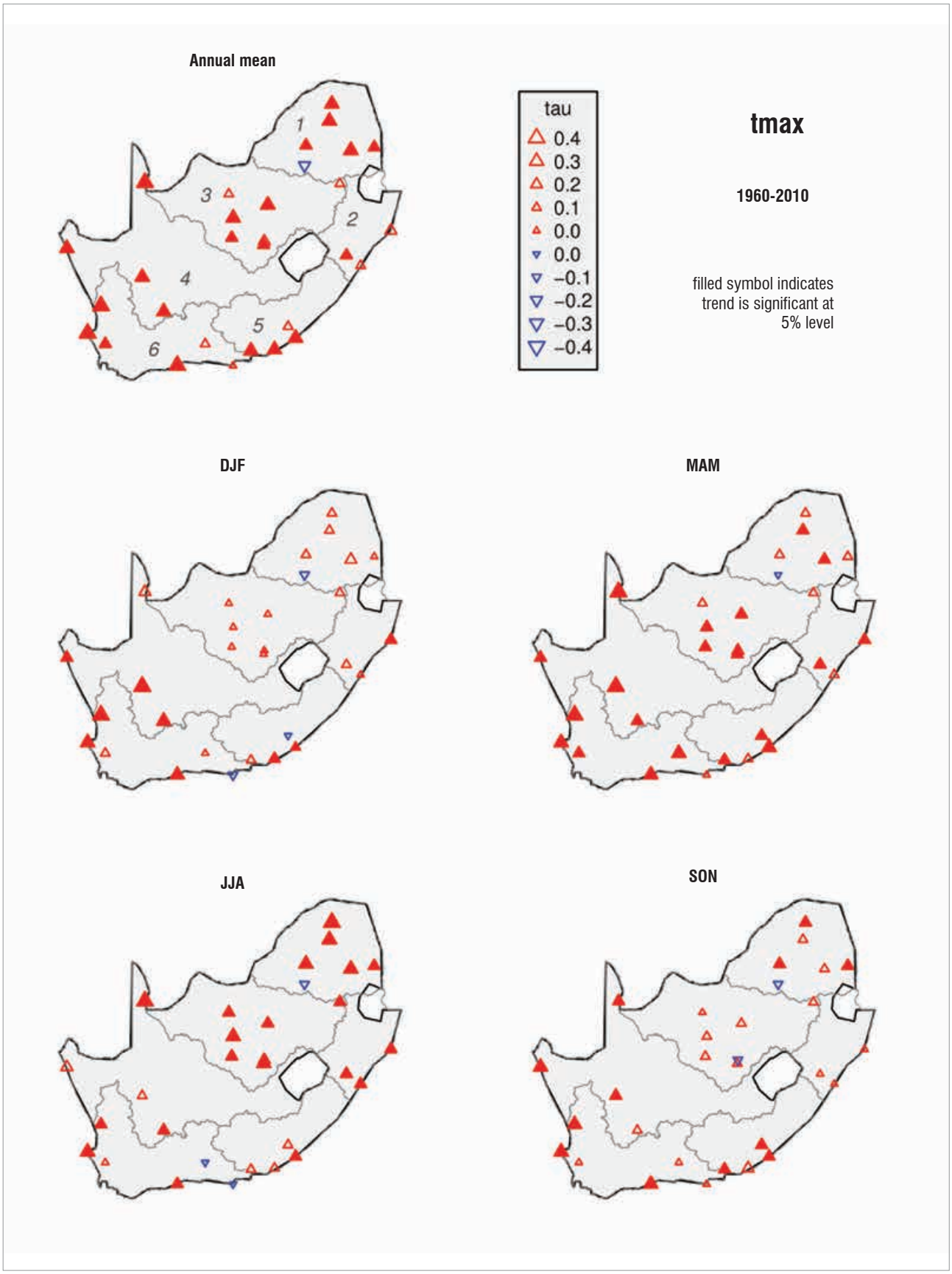

Figure 3: Trends in annual and seasonal mean daily maximum temperature (tmax, °C) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

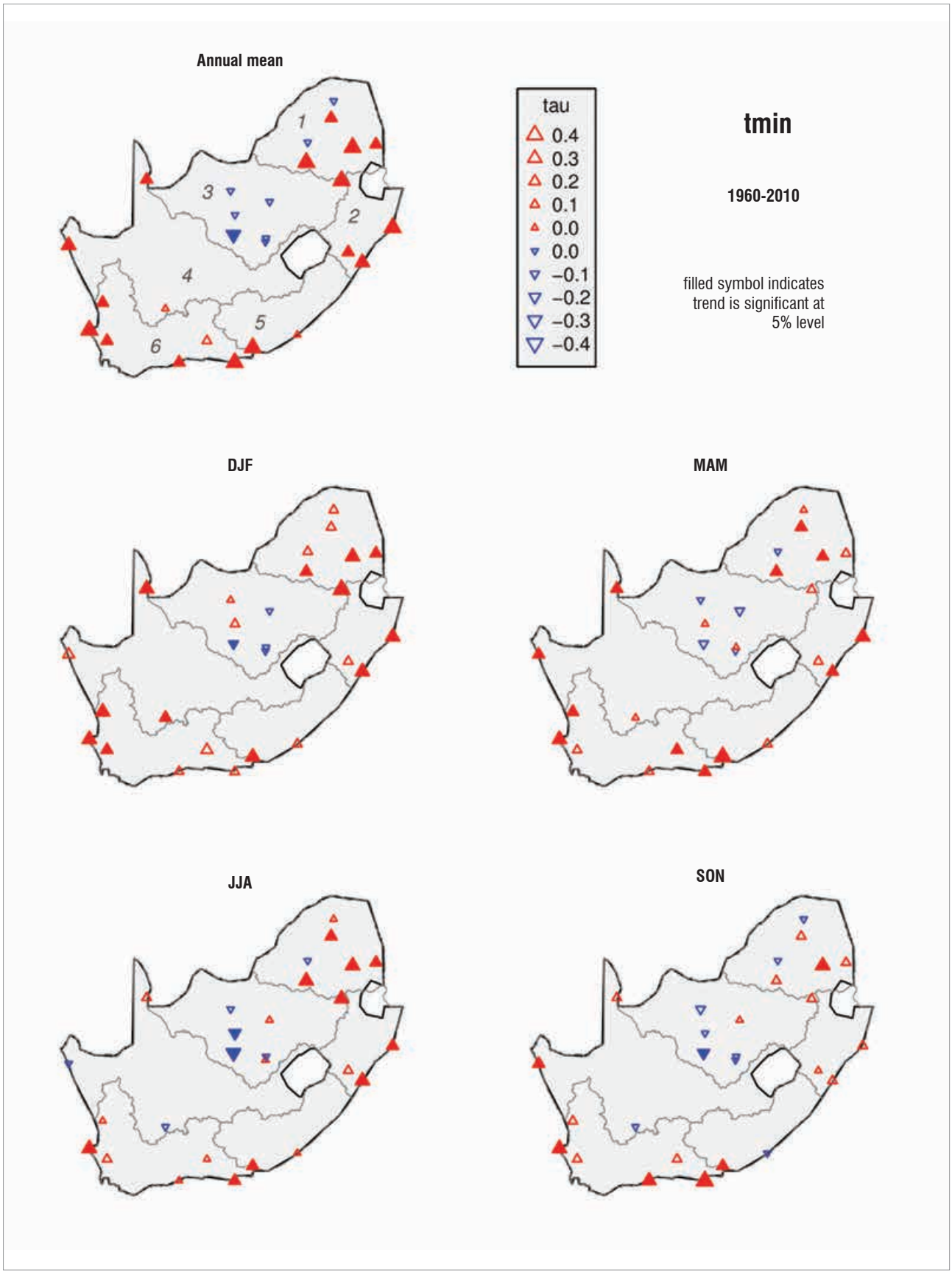

Figure 4: Trends in annual and seasonal mean daily minimum temperature (tmin, °C) for each station according to the Mann–Kendall test. The value of tau represents the direction and relative strength of the trend. Shaded symbols denote trends that are significant at the 5% level. Seasons are summer (DJF), autumn (MAM), winter (JJA) and spring (SON). Grey borders represent boundaries of the six water management regions, which are identified by number (1–6) in the annual mean map.

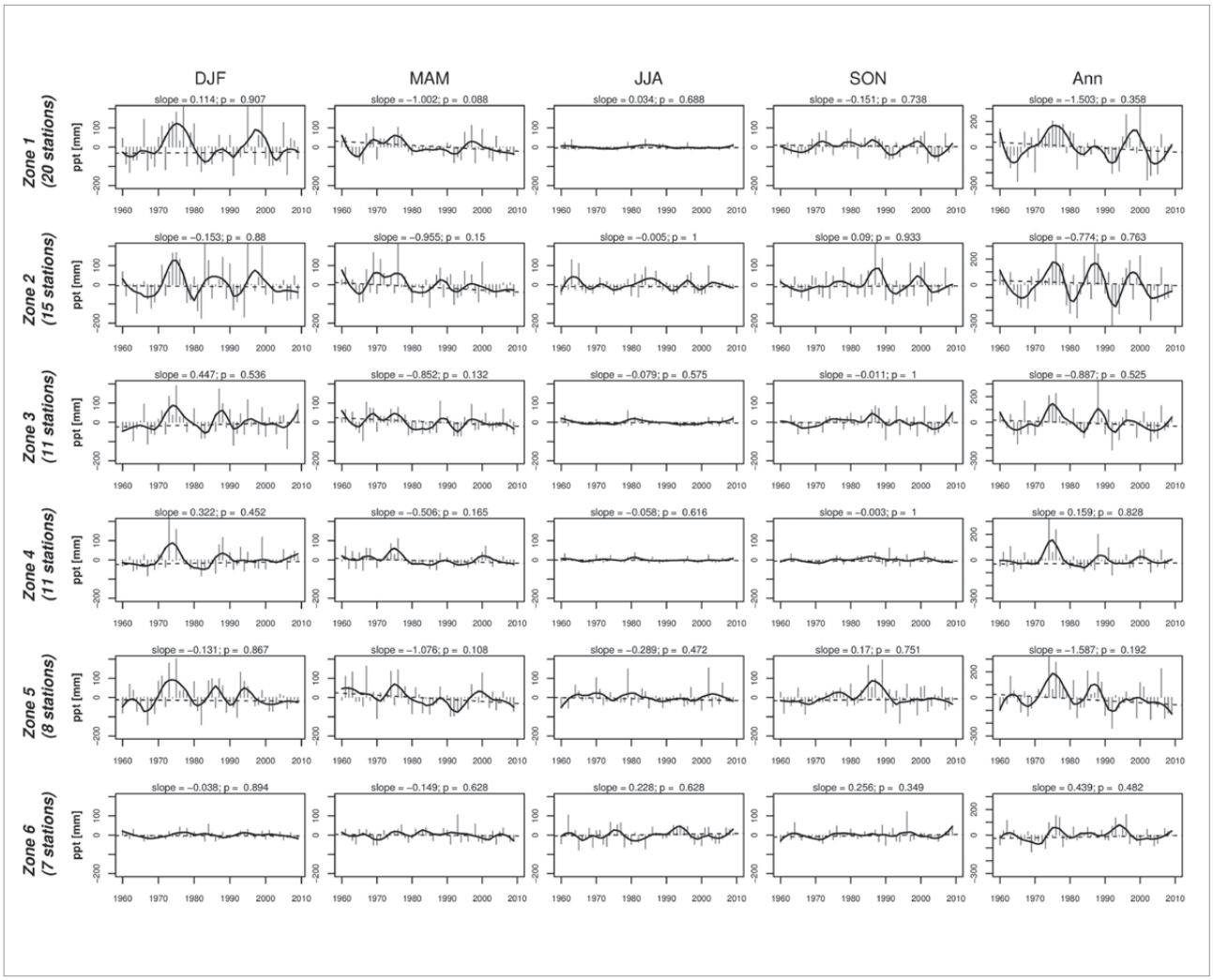

Figure 5: Regional mean time series and trends in total rainfall (ppt) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

decreased ppt in MAM. The pattern is similar for the number of rain days (Figure 2), but more stations show significant decreases for MAM.

Increases in tmax occurred for all seasons, with the strongest trends seen in JJA (Figure 3). There is, however, a general tendency for reductions in tmin in all seasons (Figure 4). Trends in regional mean ppt are not evident (Figure 5, third row), but decreases in rain days in MAM and in the annual mean of about 6 and 13 days, respectively, are seen over the 50-year period (Figure 6, third row). Strong warming trends in tmax of almost 2 °C (0.034 °C/year) in MAM and almost 1.5 °C (0.029 °C/year) in JJA are evident (Figure 7, third row). The decreases in tmin as seen at individual stations are not reflected in the aggregated results (Figure 8, third row).

Zone 4: Northern Cape, southern Free State and parts of Eastern Cape

Trends in ppt are weak for all stations (Figure 1), but some stations show significant increases in rain days in SON, DJF and JJA and one station shows significant decreases in rain days in MAM and SON (Figure 2). Data available from four stations for tmin indicate mostly significant positive trends (Figure 3) but three of the stations show weaker trends, particularly in JJA and SON (Figure 4). This zone is somewhat problematic as it spans a large climatic range and station coverage within this range is sparse. Regional means should therefore be interpreted with caution. Nevertheless, there are no trends in the aggregated time series of rainfall indices (Figures 5 and 6, fourth row).

Tmax shows large significant increases of between 0.025 °C/year and 0.039 °C/year in all seasons, largely as a result of persistently above-average temperatures in the last 10 years of the record (Figure 7, fourth row). Increases in tmin are weaker than those for tmax, ranging from 0.007 °C/year to 0.019 °C/year (Figure 8, fourth row).

Zone 5: Majority of Eastern Cape and southern part of KwaZulu-Natal

Changes in ppt are weak (Figure 1), but there are some significant increases in rain days across the region (southern Drakensberg and southern coastal areas) in all seasons (Figure 2). A single station on the northern coast, however, shows a significant reduction in rain days.

Stations with temperature data are confined to the southern part of the region, where tmax and tmin have generally increased in all seasons (Figures 3 and 4). Regional means show no significant rainfall changes (Figures 5 and 6, fifth row). Significant increases in tmax (from 0.017 °C/year to 0.03 °C/year) have occurred in all seasons except DJF (Figure 7, fifth row). Aggregated increases in tmin are generally weaker than for tmax, ranging from 0.008 °C/year to 0.014 °C/year (Figure 8, fifth row).

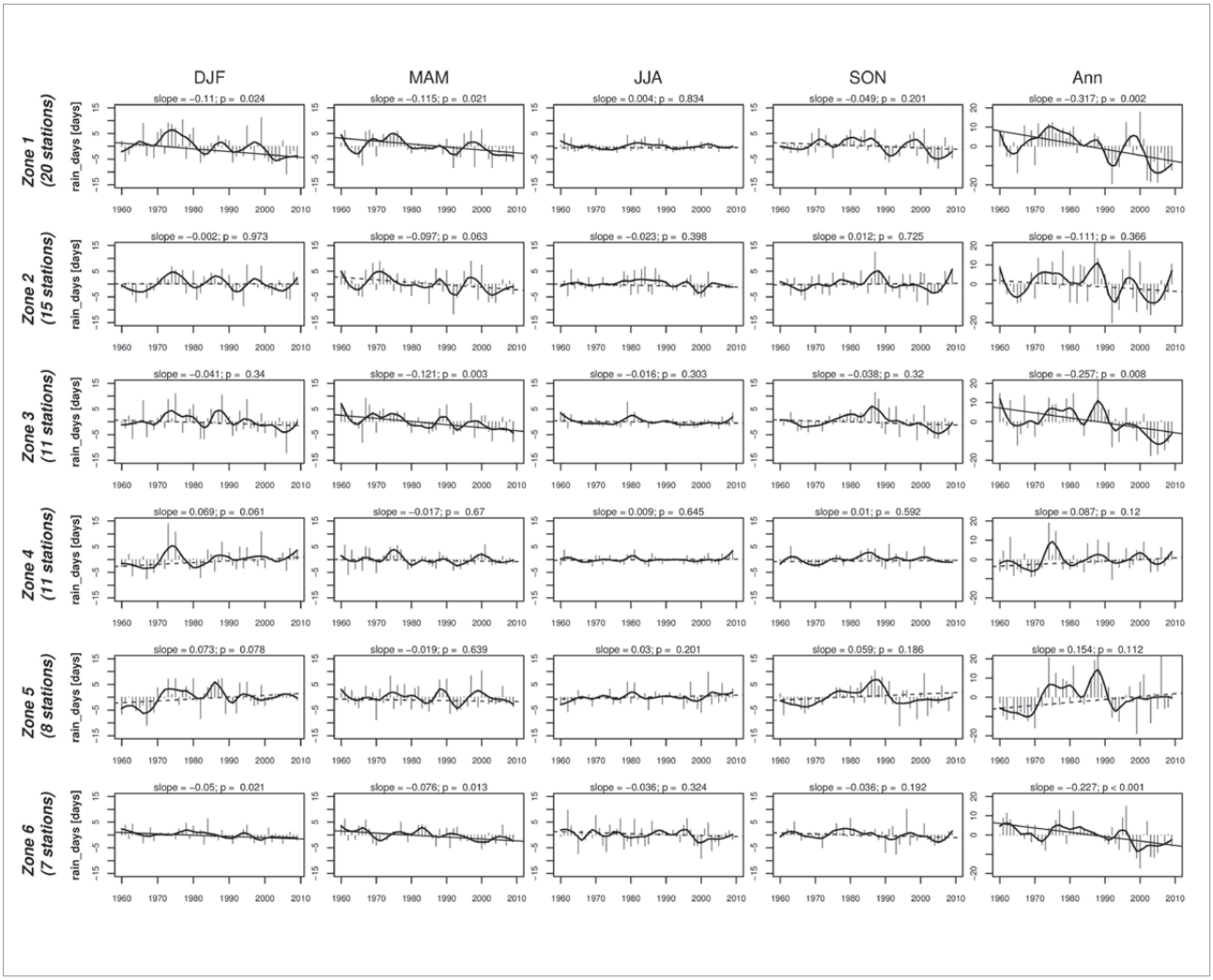

Figure 6: Regional mean time series and trends in number of rain days (days) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

Zone 6: Western Cape and parts of Northern and Eastern Cape

Trends in rainfall indices are generally not significant and show little consistency across the region (Figures 1 and 2). The number of rain days do, however, indicate drier conditions along the southern coastal regions, although the stations near the west coast show a tendency for increased rain days.

Tmax and tmin have increased significantly at almost all stations in all seasons (Figures 3 and 4). The regionally aggregated ppt time series show no significant changes (Figure 5, bottom row), but rain days have decreased significantly in DJF (2.5 days) and MAM (3.5 days) and the annual mean has decreased significantly by 11.3 days over the 50-year record (Figure 6, bottom row). Significant increases in tmax are seen for all seasons and range from 0.015 °C/year to 0.027 °C/year, with strong warming occurring in the last 10–12 years of the record (Figure 7, bottom row). Increases in tmin are mostly smaller (0.011 °C/year to 0.021 °C/year) and are not significant for JJA (Fugure 8, bottom row).

Comparison of model and observed trends for 1960–2010

Figure 9 shows a comparison of observed versus modelled trends aggregated for each of the six zones. This comparison gives an indication of whether or not the models captured the long-term trends that emerged from the analysis of observations. Both observed and modelled results represent the same stations and same period, so a direct comparison can be made between the two. Some interesting points can be made. The reductions in ppt for MAM that are evident in the observed trends for almost all regions is not captured by the models. In fact, the models tend to show an opposite trend. Similarly for rain days, the negative trends in Zones 1, 2, 3 and 6 fall outside the range of model simulations. In contrast, for SON, where observed trends are weak, the models show a tendency for reduced ppt in all regions. Strong trends in observed annual rain days lie well outside the model ranges. Overall, the observed trends in rainfall indices are poorly represented by the model simulations. Observed temperature trends generally fall within the range of model simulations, with the notable exception of tmin in Zone 3. Zone 3 is the region for which decreases in tmin were observed and it is interesting that none of the models is able to simulate this decrease. Tendencies for the models to over- or underestimate trends in tmin and tmax vary according to season, region and variable, but some consistencies are apparent – for example, a general underestimation of tmax in MAM and JJA, but an overestimation for both tmin and tmax in DJF.

Discussion

Rainfall indices are particularly influenced by multi-year variations and therefore are highly sensitive to the temporal coverage of observations used. As expected, we demonstrated weak or non-

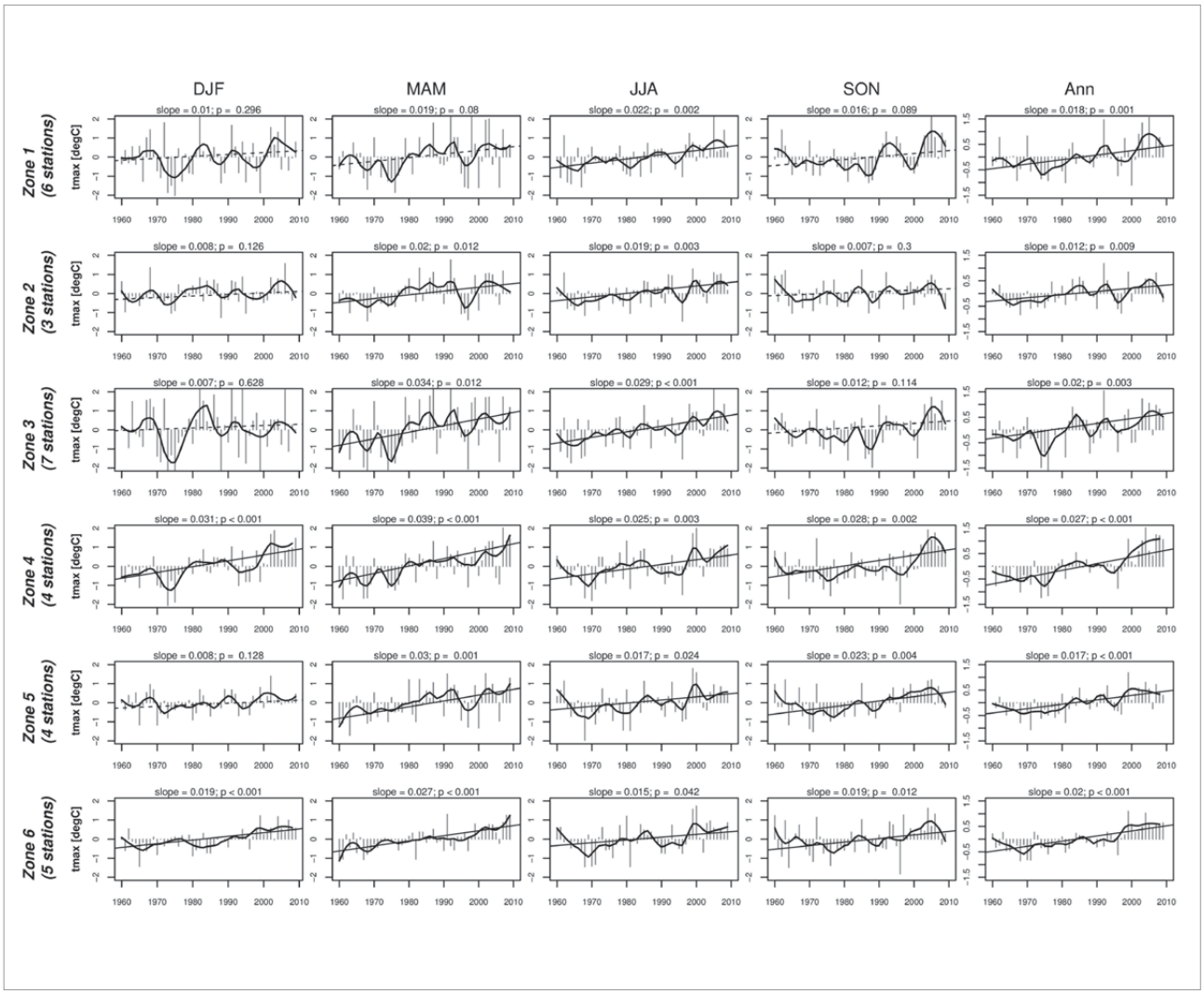

Figure 7: Regional mean time series and trends in mean daily maximum temperature (tmax, °C) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

existent trends in regionally aggregated ppt, which is consistent with previous analyses.[6-8] More pronounced trends are seen at individual stations, with the most spatially coherent result being an overall tendency for decreased ppt in MAM and a reduction in rain days over the central and northeastern parts of the country. Our results also show a strong and cohesive tendency toward increased rain days, and to a lesser degree ppt, around the southern Drakensberg in DJF and SON. This summer increase is consistent with results previously shown for this location,[7] and the springtime increase is suggestive of an earlier seasonal onset. Although other authors[9,10,13] have reported increases in rainfall extremes during the 20th century for eastern South Africa, our analysis of the 90th percentile rainfall events (not shown in this paper) do not show much spatial coherence in trends, except for MAM, for which widespread decreases have occurred in line with the decreases shown for ppt and rain days.

For the temperature indices, a significant warming trend in tmax is shown for almost all stations, which is in line with recent global and regional warming trends.[23] The strongest regionally averaged increase in tmax over the 50-year analysis period reached close to 2 °C in the central interior in autumn, whereas the weakest increase (0.35 °C) occurred in the same region in summer. An interesting result for the central interior is that it experienced a cooling trend in tmin, thus resulting in an increased diurnal temperature range (dtr). The reasons for this finding have not been rigorously explored in this study, but it is possibly related to a reduction in nocturnal cloud cover, more stable ambient atmospheric conditions, or both. Decreases in the number of rain days for much of this region suggest that cloud cover may indeed have been reduced, which would allow for greater radiative cooling of the surface at night. The cause of a reduction in cloud cover could in turn be an enhancement of the mid-tropospheric high pressure system as demonstrated by Engelbrecht et al.[41] for a warming climate. Even in the absence of a change in cloud cover, an increase in atmospheric subsidence can promote stable conditions and the formation of nocturnal temperature inversions[42] which trap cold air near the surface.

We extended our analysis by comparing the observed trends to simulated trends for the same stations and same period from 11 downscaled GCMs. This analysis revealed stark differences in the modelled and observed trends in rainfall indices, but closer agreement for temperature indices. One possible reason for the disagreement in rainfall trends is that the observed trends are not attributable to the effects of increased radiative forcing from greenhouse gases. Although we did not set out to make any robust statements regarding attribution, our findings are consistent

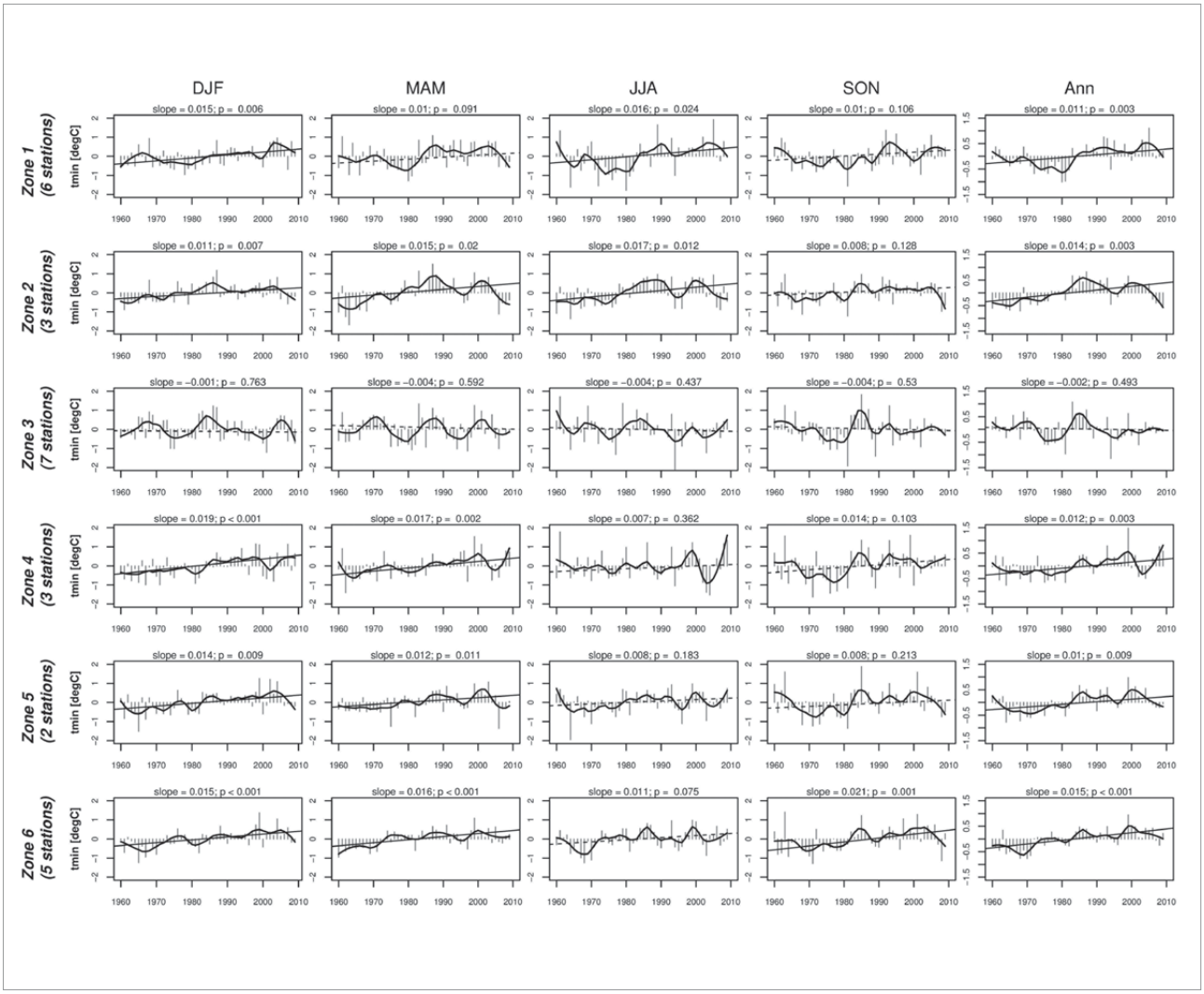

Figure 8: Regional mean time series and trends in mean daily minimum temperature (tmin, °C) for stations in the six water management zones for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Grey bars represent departures from the 1960–2010 mean for each year. Black curves are a Loess smoothing of the yearly data with a bandwidth of 0.25. Trend lines are shown for the Sen's slope estimate. Solid trend lines indicate the trend is significant at the 5% level and dashed lines are not significant at this level.

with those of Hoerling et al.[20] who found similar inconsistencies between observed and GCM-simulated rainfall in southern Africa. Other studies, however, do find a detectable anthropogenic signal in rainfall at larger scales.[21,22] Other potential causes of the discrepancies lie in either the GCM formulations themselves, or in the method that has been used to downscale the GCM results to the individual stations. As the downscaling method does not directly use the modelled rainfall, but rather a selection of variables representing regional atmospheric circulation (eg. wind fields and temperature lapse rate),[17] these poor results cannot be blamed on the GCM formulation of cloud and rainfall processes. Likely causes are rather (1) poorly replicated atmospheric circulation patterns by the GCMs, (2) an inadequate empirical model linking the circulation fields to local-scale rainfall, or (3) differences in the interannual and decadal-scale temporal variations in climate. The latter point can be interpreted as either the models' inability to adequately represent the regional impact of global climate phenomena such as ENSO, or simply that the temporal evolution of low-frequency climate variations differs markedly from observed (in a freely evolving long-term climate simulation, such variability should not be expected to match observed). In any case, this disagreement between models and observations has implications for assessing projections of future climate over South Africa.

Despite the challenges of identifying (and modelling) long-term trends in rainfall over South Africa, there is nevertheless a clear signal of increased temperatures since 1950. This finding has important implications for the functioning of natural systems and related societal impacts and sets a precedent for likely future changes resulting from further anthropogenic global warming.

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Authors' contributions

N.M. wrote the manuscript, performed the analysis and produced the figures; M.N. provided conceptual oversight; and C.J. provided conceptual input and technical support.

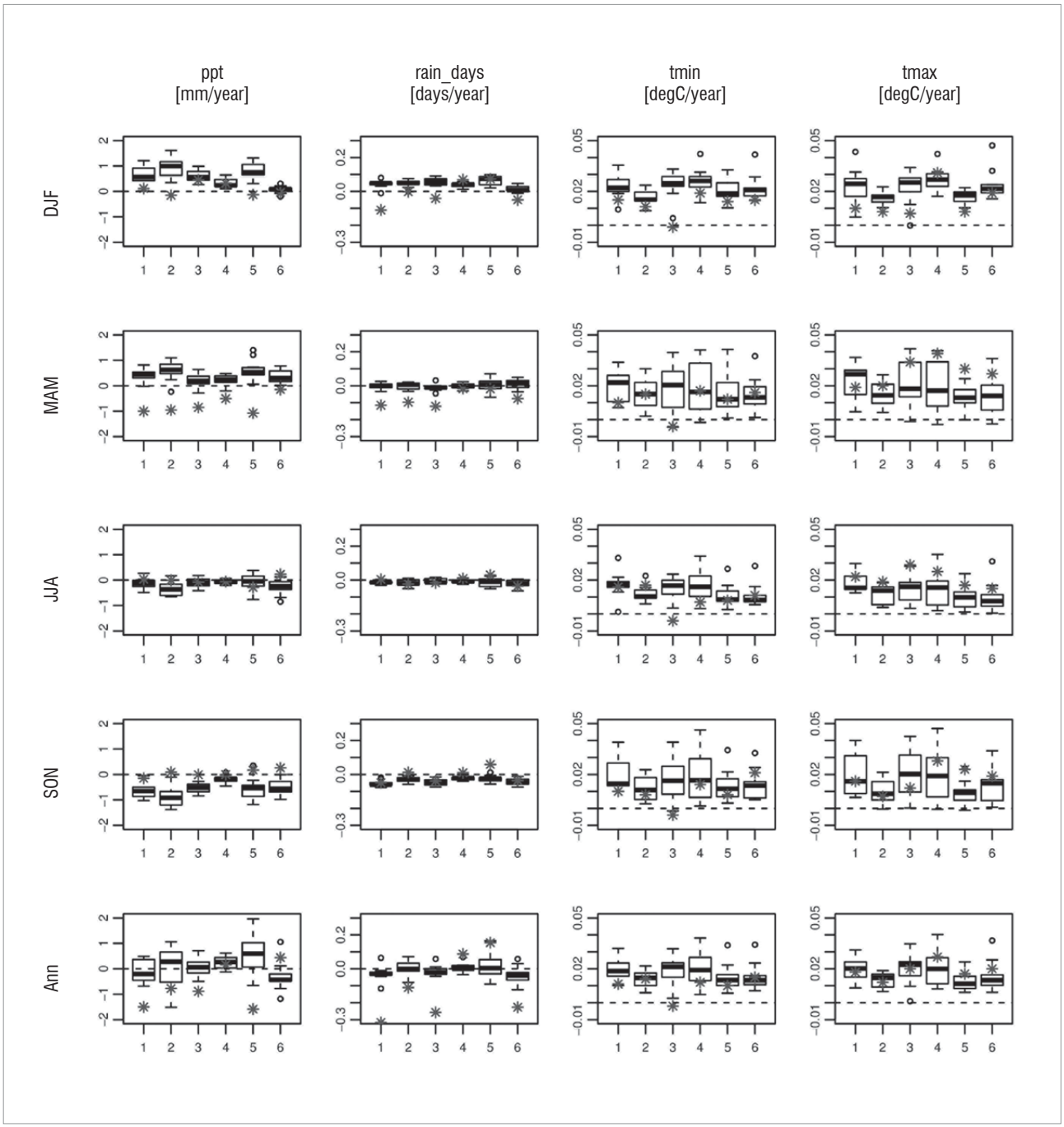

Figure 9: Correspondence between observed trends and downscaled global climate model trends for 1960–2010. Trends are averages for stations in each of the six water management regions (abscissa) for summer (DJF), autumn (MAM), winter (JJA), spring (SON) and annual (Ann) means. Asterisks show observed trend and box-and-whisker plots represent the 11 downscaled model trends. Black circles indicate models lying outside 1.5 times the interquartile range.

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Arsenic residues in soil at cattle dip tanks in the Vhembe district, Limpopo Province, South Africa

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Arsenic-based compounds have been used for cattle dipping for about half a century to combat East Coast Fever in cattle in South Africa. The government introduced a compulsory dipping programme in communal areas to eradicate the disease in 1911. Concern has been raised regarding the ecological legacy of the use of arsenic-based compounds in these areas. We investigated the incidence of arsenic residue in soil at 10 dip sites in the Vhembe district of Limpopo Province, South Africa. We found high levels of arsenic contamination at a depth of 300 mm at some sites. Control samples indicated that these high arsenic levels are the result of the application of inorganic arsenic. Variation of arsenic concentrations is attributed to duration of exposure to the chemical, soil properties and distance from the dip tank. Concerns are raised regarding the structural condition of the dip tanks, encroaching villages and possible health threats to the human population in the area.

Introduction

We report on arsenic levels in soil around cattle dip tanks in the Vhembe district of the Limpopo Province, South Africa. Here, as was the case elsewhere in South Africa, arsenic-based dipping compounds were used for many decades to combat East Coast Fever (ECF) among cattle.

Arsenic compounds are divided into three major groups: inorganic arsenic compounds, organic arsenic compounds and arsine gas. Inorganic arsenic is more toxic than the organic variant; and arsenite (AsO_3^{3-}) is more toxic than arsenate (AsO_4^{3-}).[1,2] Arsenic in the environment is of either geogenic or anthropogenic origin. Arsenic with a geogenic origin is usually related to background material and minerals such as antinomy, copper, iron, lead, nickel and silver. Anthropogenic sources of arsenic include the mining and smelter industry, burning of coal, treatment of wood, tanneries, the pharmaceutical and glass industries, and pesticides.

Arsenic is a dangerous, persistent, non-biodegradable and accumulative substance. In the United States of America (USA) it is classified as a class A carcinogen. In humans, high concentrations cause arsenic poisoning with detrimental effects.[2,3] Because of the intrinsic danger of arsenic to society, the World Health Organization has expressed a safe maximum permissible value for drinking water of 0.01 mg/L or parts per million.[4] The fatal dose for humans of ingested arsenic is between 70 mg and 180 mg.[1] Human consumption of arsenic-contaminated foods over a long time may lead to arsenocosis, a chronic illness that produces skin disorders, gangrene and cancer of the kidneys and bladder.[5] Where it accumulates in the nervous system, arsenic may induce mental-related problems. Chronic exposure to small amounts of arsenic in drinking water increases the risk of cancer and other diseases in humans.[6]

Most of the evidence on geogenic arsenic contamination relates to Asia.[7,8] In southeast Bangladesh, arsenic contamination of water sometimes exceeds 1000 mg/L. In contrast, arsenic concentrations in uncontaminated soil in North America generally do not exceed 15 mg/kg, while in the United Kingdom, the mean arsenic concentration in rural soil is 10 mg/kg.[2,9] In areas considered unlikely to have been exposed to anthropogenic sources of arsenic, median concentrations of 3.9 mg/kg and 0.6 mg/kg were, respectively, found at 15 sites in South Australia and at 6 sites in Tasmania.[10] Arsenic concentrations in soil in rice fields in China varied between 1.29 mg/kg and 25.28 mg/kg with a mean of 6.04 mg/kg, well below the $\leq$30 mg/kg arsenic soil limits stipulated for agricultural land in that country.[5]

In areas such as Australia, New Zealand and the southern states of the USA, past livestock dipping practices are often blamed for high arsenic concentrations in soil.[11,12] Soil samples from seven sheep dip sites in Australia and five cattle dip sites in Florida (USA) revealed arsenic concentrations between 31.3 mg/kg and 2143 mg/kg.[13] Consequently, a number of countries have laid down guidelines for the management of arsenic-contaminated soil at dip sites. The Australian and New Zealand Environment and Conservation Council (ANZECC), for example, has determined Interim Sediment Quality Guidelines (ISQGs) for arsenic in soil with an ISQG-low of 20 mg/kg and an ISQG-high of 70 mg/kg.[14] The ANZECC policy states that when the measured arsenic concentration in soil is below 20 mg/kg no action is required; when it is between 20 mg/kg and 70 mg/kg it should be assessed against background concentrations; and when the measurement exceeds either the ISQG-high or both the ISQC-low indicator and the background concentration, an assessment of bioavailability should be conducted.

East Coast Fever, cattle dipping and arsenic in South Africa

Arsenic-based animal dipping compounds were introduced in South Africa in 1893. Following the outbreak of ECF in 1901, cattle dipping became general practice in this country. Towards the end of the South African War in 1902, there was a shortage of cattle in the country. Imported cattle en route from Australia and India were sometimes offloaded for grazing at Mombasa – an ECF endemic area – before proceeding to South Africa and then Rhodesia (now Zimbabwe).[15,16] The disease first appeared at Mutare in Rhodesia in 1901 and at Komatipoort in South Africa in 1902. Thereafter, it spread rapidly along transport routes from the coast inland.[17] Between 1901 and 1960, when ECF was finally eradicated in southern Africa, approximately 1.5 million cattle either died from the disease or were slaughtered to prevent the spread of infection.[16]

Compulsory dipping for ECF was originally introduced in terms of the *Stock Disease Act of 1911*. The former Venda area of South Africa (now the Vhembe district of Limpopo Province) is infested with the brown ear tick

(*Rhipicephalus appendiculatus*), which is a vector of *Theileria parva* – the parasite that causes ECF. The region was therefore subjected to the ECF national dipping programme, starting in 1915 when the first dip tank was erected.[18,19] The dipping programme in communal areas (such as Venda) was administered by the Department of Native Affairs with technical services provided by the Division of Veterinary Services. Thousands of dip tanks were built and by the 1920s all affected areas had on average one tank for every thousand head of cattle. By around 1960, when ECF was finally eradicated in southern Africa, 10 million cattle were being dipped every 7–14 days.[20] Arsenic oxide (As_2O_5) and trioxide (As_2O_3) compounds were most commonly used in the dipping programme.[21] Despite the eradication of ECF, compulsory cattle dipping continued in communal areas to prevent the outbreak of foot and mouth disease (FMD).

Although the use of arsenic-based animal dipping compounds was banned in 1983, the after-effects of arsenic compounds still pose a threat because of the adverse characteristics of the chemical. It is envisaged, for example, that indigenous yellow- and red-billed oxpeckers (*Buphagus africanus* and *Buphagus erythrorhynchus*, respectively) could soon become extinct in South Africa as result of arsenic poisoning.[22] Concern about the impact of arsenic-based dipping compounds on human health in South Africa was expressed as early as the 1940s.[23] Present-day research on arsenic contamination in South Africa includes the search for arsenic-resistant bacterial genes in mining ash and the pollution levels in treated wood.[24-27] However, research in the field of arsenic contamination of soil at dip tanks – the focus of our study – has been limited. However, one study, conducted by Moremedi and Okonkwo[28] at Ka-Xikundu village close to the Luvuvhu River, also in the Vhembe district, reported high arsenic levels (above >1000 mg/kg) close to a dip site at the surface, and at 50-mm and 100-mm depths, and a significantly lower concentration of about 0.15 mg/kg at a control site some distance away. The authors recommended that the risk posed by historical arsenic-based dip operations to the immediate environment, water resources and vegetation be investigated. We aim to extend the work on arsenic contamination in soil resulting from past cattle dipping practices.

Material and methods

Study area

The Vhembe district is, apart from a few towns such as Thohoyandou, largely a rural area under communal occupation. Prior to the South African War, various skirmishes occurred between the Vhavenda and the South African Republic. After the war, the Vhavenda tribe was subjugated in 1905 by the victorious British government.[19,29] In 1910, Venda became part of a unified South Africa. From 1979 the area was administered as an 'independent' homeland before being incorporated into a re-united South Africa in 1994. For the Vhavenda, cattle are an indication of wealth. Apart from their monetary value, cattle also are used as an important currency for various social activities. The Vhavenda therefore resisted confinement to a limited territory, the forced reorganisation of their agricultural system through 'betterment planning', and being forced by the state to comply with compulsory cattle dipping.[30,31] However, over time, through the introduction of incentives and the involvement of tribal chiefs, the dipping programme gathered momentum.

Distribution of sample sites

Soil samples were collected from 10 dip sites in the Vhembe district. The selection of the dip sites was based on the dates of construction of the various dip tanks, soil characteristics and ecoregions. The respective dip sites include a group of 54 tanks that were established in the study area between 1915 and 1955. The dip tanks are situated at the villages of Khubvi, Mukula, Rambuda, Sambandou, Thengwe, Tshandama, Tshifudi, Tshikuwi, Tshituni and Tshivhulani (Table 1).

The Water Research Commission classifies the Vhembe district into three ecological regions.[32] In Ecoregion 2.01 (central highland area), the soil around the Khubvi and Mukula dip tanks is highly weathered and consists of compacted red clay; around the Tshifudi dip tank, sandy loam with organic matter is prevalent; and around the Tshivhulani dip tank, deep red clays predominate. In Ecoregion 5.04 (northeastern area), the soil around the Rambuda dip tank is red and loamy with a high content of organic matter; around the Sambandou tank, the soil is sandy loam with high levels of organic matter; and the Thengwe and Tshandama dip tank areas have sandy soil with little organic matter. In Ecoregion 5.03 (western area), red loam soil, heavily weathered because of compaction, is found around the Tshikuwi dip tank; and soil at the Tshituni dip tank is gravelly, with traces of brown clay.

Sampling and testing

The points where soil samples were collected to investigate the horizontal distribution of arsenic were within a radius of 100 m from each tank. A normal dip site in communal areas covers an area of approximately 1 ha. The level of arsenic concentration was measured at distances of 5 m, 20 m and 100 m from the respective dip tanks. The 5-m collection site is the splash area and close to the poison hole where the solution is discarded when the tanks are cleaned (Figure 1). The 20-m distance covers a draining pen in which the cattle cluster whilst still wet with dip solution. The 100-m distance covers a radial area around the tanks

Table 1: Locations and features of 10 dip tank sites in the Vhembe district, Limpopo Province of South Africa

Sites	Latitude	Longitude	Established	Ecoregions and soil
Established before 1948				
Tshivhulani	22 55.35 S	30 30.12 E	Early 1920s	Ecoregion 2.01 (central highland): deep red clays predominate
Khubvi	22 49.52 S	30 34.03 E	1923	Ecoregion 2.01 (central highland): heavily weathered, compacted red clay
Rambuda	22 47.05 S	30 27.06 E	1940	Ecoregion 5.04 (northeastern area): red loam with high content of organic matter
Tshikuwi	22 53.83 S	29 58.91 E	1940	Ecoregion 5.03 (western area): heavily weathered, compacted red loam
Tshituni	22 56.82 S	30 02.57 E	1940	Ecoregion 5.03 (western area): gravelly with traces of brown clay
Established from 1948 onwards				
Sambandou	24 49.59 S	30 39.33 E	1948	Ecoregion 5.04 (northeastern area): sandy loam with very high content of organic matter
Tshifudi	22 48.24 S	30 43.27 E	1948	Ecoregion 2.01 (central highland): sandy loam with organic matter prevalent
Mukula	22 51.00 S	30 36.59 E	1948	Ecoregion 2.01 (central highland): weathered, compacted red clay
Thengwe	22 49.59 S	30 32.58 E	1950	Ecoregion 5.04 (northeastern area): sandy with little organic matter
Tshandama	22 30.07 S	30 45.05 E	1950	Ecoregion 5.04 (northeastern area): sandy with little organic matter

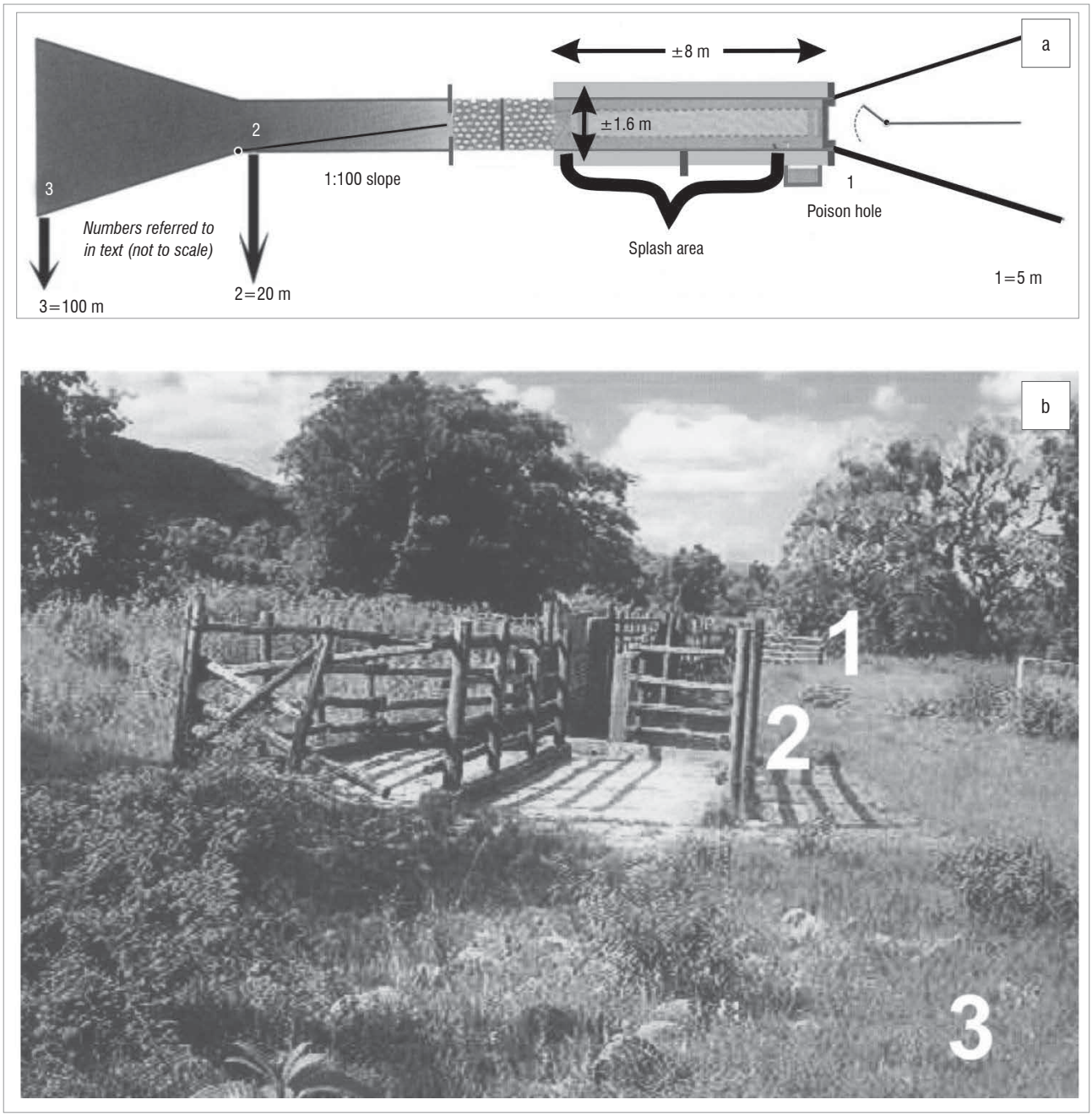

Figure 1: (a) Schematic of the aerial view of the dip tank layout and (b) a photo of a dip tank showing the sampling distances at points 1 (5 m), 2 (20 m) and 3 (100 m).

from where the cattle disperse. The 100-m distance was used as the control site.

Single, linear point soil samples following the contours of the terrain were taken at the sampled dip sites. The samples were taken at a depth of 300 mm, and placed in clean, labelled plastic bags.

The packaged soil samples were chemically analysed for arsenic by the accredited soil laboratory of the Agricultural Research Council. The analysis was performed using a semi-quantitative scan of an ammonium EDTA extract. An ammonium EDTA solution was added to soil samples, and the solution was filtered to isolate the chemicals.

Results and discussion

Figure 2 displays the average levels and spatial distribution of arsenic at the 10 dip sites.

Absolute concentration of arsenic residues

Surface soil around the 10 dip sites depicted enhanced arsenic values (Table 2), which ranged from 0.001 mg/kg to 46.76 mg/kg at a 5-m distance from the tanks (Figure 2). Sambandou had the highest mean concentration (18.24 mg/kg) and Tshandama the lowest (0.002 mg/kg). Five of the 10 dip sites (Khubvi, Rambuda, Sambandou, Tshifudi and Tshivhulani) displayed moderate to high concentrations (>3 mg/kg) of arsenic residues at the 5-m distance.

A first observation is that the arsenic concentrations measured in this study are definitively lower than those found in the 2007 study at the Luvuvhu River.[28] When excluding other variables, the difference in arsenic concentrations may be explained by the depth at which soil samples were extracted. While Moremedi and Okonkwo[28] took their samples at a maximum depth of 100 mm, samples for the purpose of our study were taken at a depth of 300 mm.

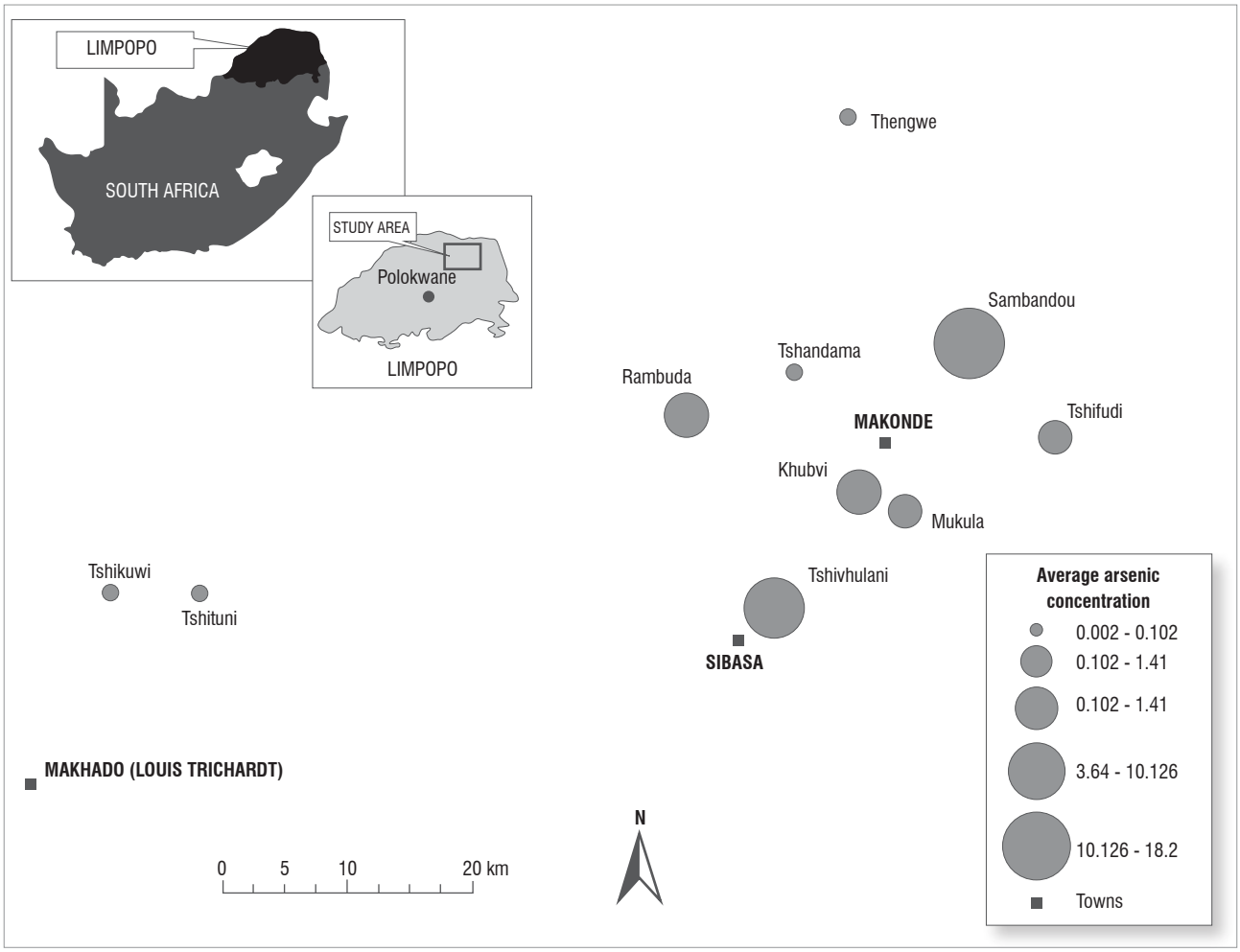

Figure 2: Average arsenic concentrations (mg/kg) in soil at 10 dip sites in the Vhembe district, Limpopo Province, South Africa.

Table 2: Concentration† of arsenic residues in mg/kg at the 10 dip tank sites

Dip site	5 m (A)	20 m (B)	100 m (control) (C)	Mean = A+B+C/3	Trends		
					B-A	C-B	C-A
Sambandou	46.76	6.88	1.09	18.24	-39.88	-5.79	-45.67
Tshivhulani	30.18	0.19	0.01	10.12	-29.99	-0.18	-30.17
Rambuda	3.53	3.63	3.70	3.62	0.10	0.07	0.17
Khubvi	3.65	3.69	3.60	3.65	0.04	-0.09	-0.03
Tshifudi	3.85	0.23	0.15	1.41	-3.62	-0.08	-3.7
Mukula	2.30	1.20	0.08	1.19	-1.1	-1.12	-2.22
Thengwe	0.14	0.07	0.09	0.10	-0.07	0.02	-0.05
Tshikuwi	0.08	0.12	0.02	0.07	0.04	-0.1	-0.06
Tshituni	0.02	0.06	0.01	0.03	0.04	-0.05	-0.01
Tshandama	0.002	0.003	0.002	0.002	0.001	-0.001	0.0
Mean	9.05	1.61	0.88		-7.44	-0.73	-8.17

†*Values rounded to two decimal places.*

Relative concentration of arsenic residues

The relative distribution of arsenic residues can be explained by a number of factors, namely duration of exposure, distance from dip tank and the properties of the receiving soil.

Duration of exposure

Duration of exposure only partly explains the differences in arsenic concentrations. If 1955 is taken as the year when the use of arsenic-based dipping compounds was discontinued, the average exposure of dip sites for which the five lowest concentrations were detected is 9.4 years (σ=4.63) and that of the tanks for which the five highest concentrations were found is 18.6 years (σ=11.32). At Sambandou, where the highest readings (46.76 mg/kg at 5 m and 6.88 mg/kg at 20 m) were recorded, the dip was in use for only 7 years before 1955, compared to approximately 32 years for the site with the second highest readings, Tshivhulani. The tanks constructed before 1948 ranked second, third and fourth for arsenic concentrations at the 5-m distance.

Distance

Arsenic contamination was generally higher closer to the tanks (Figure 3). However, the decline in contamination with distance varied. Concentrations at Sambandou (the site with the highest mean) declined by 39.88 mg/kg from the 5-m to the 20-m location, and by a further 5.79 mg/kg from the 20-m to the 100-m distance. The concentration at 5 m was about 43 times higher than that at 100 m. At Tshivhulani, the site with the second highest mean concentration, the measurement declined by 29.99 mg/kg from the 5-m to the 20-m distances and by a further 0.18 mg/kg from the 20-m to the 100-m distances. At this site, the concentration at 5 m was more than 3000 times higher than the concentration at 100 m. A trend of declining arsenic concentrations with distance was also found at two other sites – Tshifudi and Mukula. The high levels of contamination closer to the tanks could be attributed to two factors: firstly, the practice for many decades of disposing of spent dip sludge by discarding it onto the ground or into nearby 'poison holes' when the tanks were cleaned, and, secondly, splashing of dip solution over the sides of the dip tanks every time cattle entered the tanks.

Measurements at the other six sites revealed different patterns. At Khubvi (ranking third in mean concentrations), the concentration first increased from the 5-m to the 20-m point before it declined at the 100–m point, with an overall decline of 0.03 mg/kg from 5 m to 100 m. Concentrations measured at Rambuda (with the fourth highest mean concentration) showed a general increase of arsenic levels with distance, although the overall increase was small (0.17 mg/kg from 5 m to 100 m). The difference from the overall pattern of declining arsenic concentrations with distance at Khubvi and Rambuda tanks could be attributed to human activity: the area around Khubvi tank has subsequently been turned into a maize field, whilst an area adjacent to the Rambuda tank is used for the manufacture of mud bricks. These activities might have shifted the soil downslope, and, consequently, assisted in the migration of arsenic. In addition, the poison hole at Rambuda tank is situated at its lower side, approximately 20 m away from the tank, and is joined to the tank by a narrow furrow. As a result, dip effluent was prevented from soaking into the ground before it reached the poison hole.

Soil properties

It is accepted worldwide that there is a positive correlation between relatively higher arsenic concentrations and clay, silt and organic matter and, specifically, iron and aluminium oxides in soil.[2,5,6,33] A high concentration of arsenic is mainly found in the top layers in areas with clayey soil. By contrast, arsenic is easily leached or washed into deeper layers in areas where large-grained sandy soil occurs, because of the lower absorption capacity of this type of soil. Flooding and weathering also appear to enhance the horizontal distribution of arsenic in soil, with

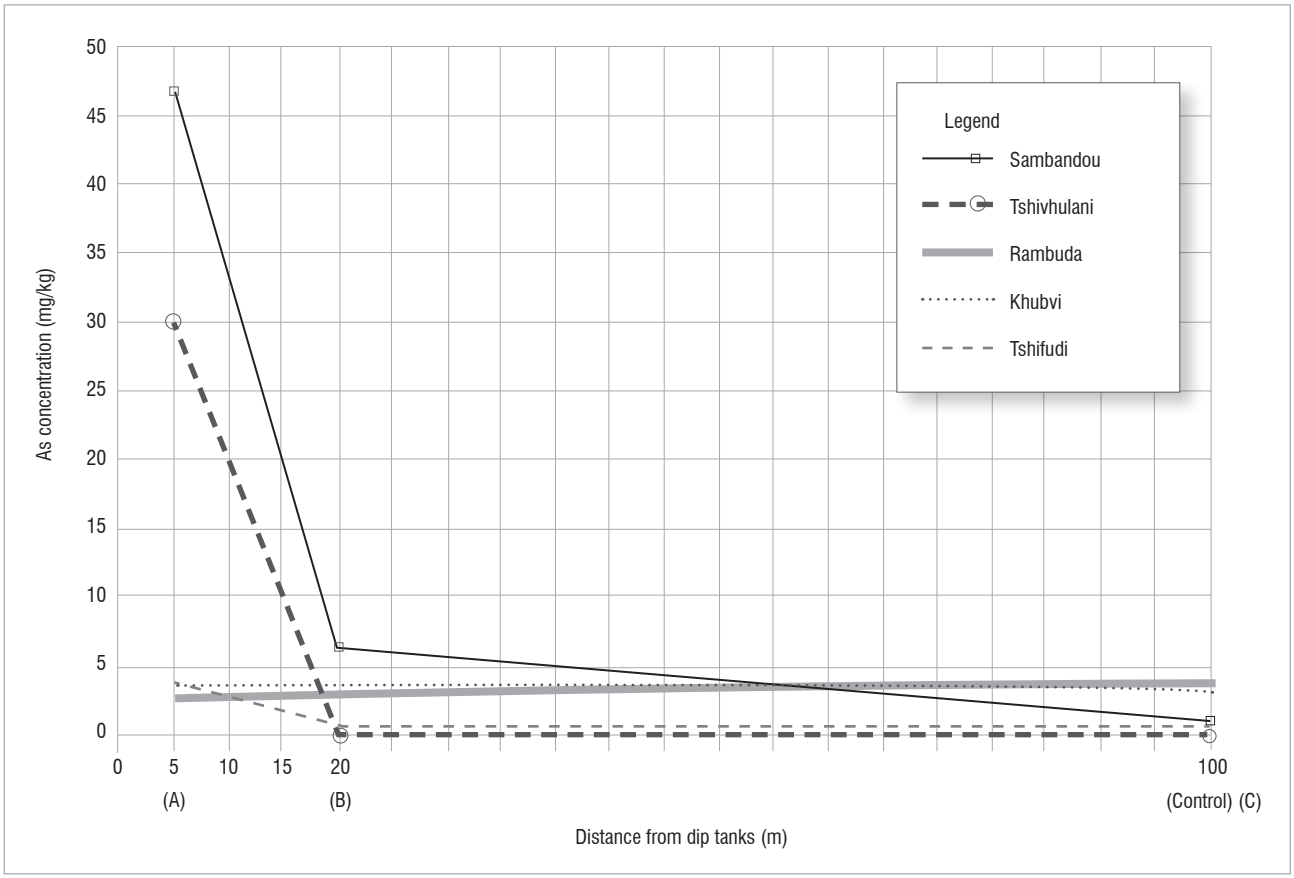

Figure 3: Arsenic concentration in soil at 5-m, 20-m and 100-m distances from dip tanks at five sites in the Vhembe district, Limpopo Province, South Africa.

both of these processes contributing to the deeper penetration of arsenic into the soil profile.[34]

The findings of our study generally confirm previous observations, that is, either clay or a high content of organic matter were prevalent at the five sites with the highest arsenic concentrations (Table 3). The loamy and clay rich soil at Khubvi, Rambuda, Sambandou, Tshifudi and Tshivhulani had higher arsenic concentration levels than Tshandama, Thengwe, Tshikuwi and Tshituni, where sandy and rocky soil is more dominant.

Table 3: Arsenic concentrations at 5 m from the dip tank and surrounding soil characteristics

Arsenic (mg/kg) at 5 m	Site	Soil characteristics
46.76	Sambandou	Sandy loam with very high content of organic matter
30.18	Tshivhulani	Deep red clay
03.85	Tshifudi	Sandy loam with prevalent organic matter
03.65	Khubvi	Heavily weathered, compacted red clay
03.53	Rambuda	Red loam with high content of organic matter

Summary, discussion and conclusion

We investigated the arsenic contamination of soil at cattle dip tanks in the Vhembe district of Limpopo where arsenic-based dipping compounds were used from the 1910s to the mid-1950s. The main findings of the study are:

- High concentrations of arsenic residues (>3 mg/kg) were found at a depth of 300 mm at a number of dip tank sites, namely Khubvi, Rambuda, Sambandou, Tshifudi and Tshivhulani. It is assumed that arsenic concentrations could be much higher at shallower depths.
- Differences in the concentrations at the 10 dip sites are ascribed to (1) the period of exposure to arsenic-based dipping compounds (with dip tanks constructed before 1948 generally having a higher level of contamination than dip tanks constructed after this date), and (2) soil properties (with clay soils and high levels of organic matter correlating with higher arsenic concentrations).
- A decline in arsenic concentration with distance from the dip tanks was evident, indicating that soil contamination is spatially localised.
- The contribution of inorganic arsenic-based dipping compounds to arsenic concentrations in the soil is evident, with mean values of 9.05 mg/kg at 5-m distances compared to 0.88 mg/kg at 100-m distances from the 10 dip tanks.

The detected levels of arsenic contamination are concerning. The first and immediate danger is direct human contact with contaminated sites. Of particular concern are encroaching villages, the health of dip operators and water resources. None of the sites referred to in this study were fenced. In the cases of Sambandou (46.76 mg/kg at 5 m) and Rambuda (3.53 mg/kg at 5 m), the nearest houses were 70 m and 30 m from the dip tanks, respectively. Children were observed playing in the vicinity of the dip tanks and they often assisted with dipping operations without skin protection. Oral accounts by informants confirmed that throughout various decades, and even until recently, dip assistants had not received proper training on the dangers of the chemicals applied during dipping and seldom wore protective clothing. Water courses, wells, springs and boreholes could also be threatened because of the soluble nature of arsenic-based dipping compounds. In addition, there is a danger of spillage and spread of residues through flooding. The Tshivhulani dip tank is, for example, only 20 m from the nearest water course. Moreover, a government report indicated that already in 1951 several dip tanks, including those in Mukula, Rambuda, Tshifudi and Tshivhulani, needed urgent repairs.[35] Our inspection revealed that dip tanks in the district are generally in a poor structural condition with most showing deep cracks. Crops are being cultivated closer and closer to dip tank sites, and, in the case of Rambuda, the tank is located within the boundary of a crop field.

However, the possible transfer of arsenic residues into the food chain should be treated with caution. It depends on a variety of factors including the total arsenic in soil (bioavailability), bioaccessibility of the substance, transfer of soil arsenic to the edible parts of plants (bioaccumulation), and the human intake of arsenic.[5,36] Although clay and organic matter have a higher adsorbing capacity for arsenic than sand, these materials are weakly correlated with bioaccessibility as a result of the bonding strength of soil particle bound arsenic.[13] Sheppard[33] concluded that inorganic arsenic was five times more toxic to plants in sand than in clay, because sandy soil generally contains lower amounts of iron and aluminium oxides than clayey soils. Thus, although certain crops, such as rice, display higher bioaccumulation of arsenic than other crops, care should be taken in correlating arsenic concentrations in soil with a perceived presence in food sources.[2,5]

In conclusion, although the eradication of ECF was achieved and foot and mouth disease prevention was facilitated, the ecological legacy of arsenic-based dipping compounds still lingers in the communal areas of South Africa. A widespread, detailed investigation in communal areas, taking into account the factors identified in this study, should be undertaken to provide more detail about the health threats of arsenic contamination at dip sites in the country.

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Authors' contributions

M.R.R. was the principle researcher, conducted the fieldwork and supervised the laboratory testing. A.C.H. extended the literature survey, helped with the interpretation of the data and prepared the final version of the manuscript.

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Assessing leaf spectral properties of *Phragmites australis* impacted by acid mine drainage

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The decanting of acid mine drainage (AMD) from the Western Basin on the Witwatersrand in late 2010 raised concerns about AMD risks in other gold, coal and copper mining areas of South Africa. Field spectroscopy and the use of vegetation indices could offer an affordable and easy means of monitoring the impact of mine water and/or AMD on vegetation. The impact of raw and treated mine water or contaminated soil on wetland vegetation often manifests in growth inhibition and reduction of foliar pigments and nutrient levels. Surveying the impact on wetland vegetation or underlying soils can be difficult and expensive considering the cost of laboratory analysis of samples. The potential of field spectroscopy for detecting the impact of mine water on wetland vegetation was examined by assessing (1) whether there was a significant difference in leaf spectra between sites receiving mine water and a non-impacted control site and (2) whether there was a gradation of vegetation condition downstream from the decanting site. Two vegetation indices were derived from portable field spectrometer-measured spectra of five green leaves of *Phragmites australis* – the chlorophyll red edge position (REP) and the normalised difference vegetation index (NDVI) – for two dormant (winter) and peak growth (summer) seasons in 2011–2012. Mean REP and NDVI values were significantly ($p<0.05$) lower for affected sites compared to the control site for both seasons and years. The range of REP values for young green leaves in winter for affected sites was 695–720 nm compared to the narrower range of 705–721 nm for the control site. The mean REP values for young green leaves in winter was 708 nm for the affected sites compared to 716 nm for the control site. The downstream gradation, however, fluctuated for REP and NDVI over the study period. We conclude that field spectroscopy shows potential to serve as a relatively quick and affordable means to assess the condition and health of vegetation affected by AMD.

Introduction

The decanting of acid mine drainage (AMD) from the Western Basin gold mining void in South Africa, in late August 2010, highlighted the environmental risks of AMD.[1-3] AMD occurs through the exposure to oxygenated water of the naturally occurring mineral iron disulphide (FeS_2).[4,5] A number of chemical reactions result in the formation of ferrous iron, sulphate and acidity.[4,5] The solubility of trace and heavy metals in the environment increases when exposed to AMD,[2] which results in increased levels of these metals in water, sediments or vegetation. The exceptionally high rainfall since 2009 in the Witwatersrand region increased the groundwater discharge and enhanced the formation of AMD in the historical gold mining voids. Existing pump and treatment facilities could not accommodate the increased AMD volumes which decanted through historical incline and ventilation shafts.[2,3] Other sources of AMD are open-cast coal and copper mines elsewhere in South Africa, as well as mine dumps, that contain iron disulphide and are exposed to oxygenated rainwater.[1,3] AMD decants into natural wetland systems, and affects natural ecosystems and agricultural lands.[3,6] The extent and magnitude of the impacts of AMD need to be determined and monitored to provide a basis for effective management.

Vegetation serves as the first trophic level linking the physical environment and the upper trophic levels of the food chain.[7,8] Therefore, monitoring of the condition and health of vegetation impacted by AMD could assist in the identification of the extent and degree of affected areas in support of selecting appropriate management intervention measures. Metal uptake into plant parts is dependent on aspects such as species, bioavailability and state of the metal, preference of metals for certain vegetation species, metal speciation, soil organic matter, soil moisture, as well as water or soil pH levels.[9-12] Plant species less tolerant of mine water conditions such as low pH, high sulphate levels and exposure to trace and/or heavy metals would show signs of toxicity, whereas some species have the ability to adapt to these conditions and even experience stimulated growth.[11] At low concentrations, Al, Co and Ni have been reported to stimulate growth in some plant species.[13,14] On the other hand, high concentrations of metals such as Al (at low pH), As, Cd, Cr, Cu, Hg, Mg, Ni and Pb are likely to show toxicity impacts on plants including significant changes in biochemical and physiological responses, and the modification of several metabolic processes.[10,15] Chlorosis may result from the inhibition of essential macronutrients in the presence of some toxic trace elements in the water or substrate, or through the substitution of essential ions.[8,16] For example, high levels of Cu can substitute the Mg^{2+} molecule in chlorophyll, affecting photosynthesis negatively.[17] Several species have developed adaptive ways to tolerate metal toxicity, such as selective absorption, excretion, avoidance of translocation to aerial parts through storage in roots, and the development of enzymes or proteins as means to adapt to increased levels.[8,16]

Assessing the geographical extent and degree of impact of mine water on vegetation is time consuming and costly, considering the deep intricate root systems of macrophytes and trees. Often, contaminated soils are covered by vegetation and difficult to access.[18,19] The cost of laboratory analysis of samples for various minerals or chemicals can hugely increase the cost of assessments and continuous monitoring. Monitoring techniques for assessing vegetation health should consider feasible, practical and affordable solutions, even if these are mere surrogates of vegetation health.

Remote sensing offers an alternative means of monitoring vegetation health in areas impacted by mine water. Research has highlighted specific absorption features in the electromagnetic spectrum that are highly correlated with foliar biochemicals, such as carotenoids, chlorophyll and nitrogen.[20] An increase in foliar chlorophyll levels, for example, results in higher absorption levels in the red region (reduced reflection), whereas increases in biomass and leaf structure increase reflection in the near-infrared (NIR) region.[21] Furthermore, high chlorophyll levels cause the broadening of the absorption pit in the red (660–680 nm) and a shift of the red edge reflectance slope (680–760 nm) and the point of maximum slope in the red edge known as the chlorophyll red edge position (REP) towards the longer wavelengths, referred to as a red shift.[22,23] On the other hand, decreasing chlorophyll causes an increase in reflectance in the red region of the electromagnetic spectrum, and a shift of the red edge slope and REP towards the shorter wavelengths – a blue shift. A number of vegetation health indices have been developed in earth observation studies to assess both plant pigment and nutrient status, and variability in leaf structure or biomass using the red, REP and NIR bands.[21]

Trace and heavy metal contamination in the receiving water or substrate or adsorbed into the plants can cause varied responses in vegetation spectra.[18,24,25] Zn was found to cause a traditional blue shift in the REP with a decrease in the NIR[24], and similarly the radionuclides Cs and Sr at Chernobyl were highly negatively correlated to the REP, green and NIR regions[26]. An opposite trend was observed in plants exposed to Cd[24], Pb[27], a combination of heavy metals (As, Cd, Cr, Cu, Pb and Zn)[18] and radionuclides[26], in which the REP decreased and the NIR increased with exposure. Chlorophyll response was found to correlate only partly with metal contamination[18,19], in some instances estimated as merely 30%[28]. This finding may be attributed to the unique absorption patterns and storage location of heavy metals in plants[12,29], hence spectral responses may also be unique to plant species[25]. The efficiency of remote sensing may require that relevant indices be investigated for each site, species and set of mine water conditions prior to use in monitoring.

Phragmites australis, *Typha capensis* and alien poplar trees (*Populus x canescens*) are known to tolerate conditions associated with mine water.[19,30] These species are largely found in natural wetlands in South Africa. *Phragmites australis,* known to be tolerant to low pH levels, reduces the uptake of heavy metals through plaque formation at its roots[30], yet still adsorbs a significant amount and releases a low amount of heavy metals, and so is considered appropriate for use in phytoremediation[31-36]. Metals are mostly stored in rhizomes, with lower concentrations in stems and leaves, although certain metals are exceptions.[35,37-40] Compared to *Phragmites australis, Typha capensis* and poplars are less prevalent across both disturbed and pristine wetland types in South Africa, and therefore provide less opportunity for monitoring downstream from a decanting site. Poplars are also less suitable for monitoring because they often are targeted for invasive alien species control.

The aim of our research was to assess whether leaf-level spectroscopy could serve as a means of assessing and monitoring vegetation health impacted by AMD. Leaf reflectance of *Phragmites australis* sites affected by a combination of raw and treated mine water was compared to that of a control site to determine if there were differences in spectral indices of vegetation health. Green leaves in the dormant and peak growth seasons were sampled for a 2-year period. Two vegetation indices were derived from the leaf spectra: the chlorophyll REP[41] and the normalised difference vegetation index (NDVI)[42,43]. The variation of these indices was also assessed per site to determine a gradation of vegetation condition with distance downstream from the mine water source.

Materials and methods

Study area and background

The study area was located along the Tweelopiespruit (around 26°06'S and 27°43'E) situated west of Johannesburg, South Africa (Figure 1). The word 'spruit' refers to a creek or small tributary stream. The Tweelopiespruit is the first drainage to receive mine water discharge from the West Rand Goldfield (i.e. the Western Basin), and joins its main stem – the Rietspruit – some 6 km to the north of the mine water source (Figure 1). The region experiences a mean annual rainfall of ~700 mm[44] with characteristically wet summers and dry winters. The geohydrology of the study area is complex, comprising contiguous dolomitic karst aquifers and quartzitic fractured rock aquifers which produces complicated drainage patterns and varied groundwater recharge dynamics.[2,45] Dolomitic springs along the reach of the Tweelopiespruit contribute ~2 ML/day to this drainage.

Mine water decants onto the surface commenced in August 2002 via boreholes and shafts (two ventilation shafts – Winze 17 and Winze 18) and an abandoned incline (the Black Reef Incline).[45] A high density sludge (HDS) treatment plant with a capacity of ~12 ML/day was commissioned to manage this decant, and the neutralised product is then released into the Tweelopiespruit, generating a perennial flow of similar magnitude. Natural run-off during the rainfall season increased the stream discharge to ~24 ML/day for a mean annual flow of ~18 ML/day. These circumstances prevailed until early 2010, when recharge during an abnormally wet summer precipitated unmanageable quantities (>40 ML/day) of raw mine water discharge.[46] A return to pre-2010 water chemistry and flow conditions was only achieved in mid-2012 as a result of a combination of factors, most notably a reduction in rainfall and the commissioning of a refurbished HDS treatment plant with a greater capacity of ~24 ML/day.

The circumstances described above gave rise to surface water chemistry discharges characteristic of AMD into the Tweelopiespruit. Prior to 2010, the dominant treated mine water chemistry was characterised by a circumneutral pH of 7, sulphate concentrations of ~2500 mg/L, and iron and manganese concentrations of <1 mg/L and <20 mg/L, respectively.[46] In early 2010 to mid-2012, the dominant raw mine water chemistry was reflected in a pH value of ~3, electrical conductivity (EC) levels of ~300 mS/m, sulphate levels of ~3 000 mg/L, and iron and manganese concentrations of ~200 mg/L and ~60 mg/L, respectively.[46]

The hillslopes on the mine property are dominated by grassland, except for the narrow artificial wetlands in the stream channel, which are primarily dominated by *Phragmites australis*. Downstream of the mine property, the combination of treated and untreated mine water flows through artificial wetlands in the Krugersdorp Municipal Nature Reserve for a distance of about 5 km. Being a relatively small sub-catchment (38 km^2), run-off and potential contamination from adjacent land uses are minimal. The wetlands are primarily dominated by *Phragmites australis* and large stands of *Populus x canescens*. The Tweelopiespruit exits the reserve prior to its confluence with the Rietspruit (Figure 1).

Our sampling sites were designated Sites 1 to 9, and two additional sites (Sites 10 and 11) were added as controls (Table 1; Figure 1). Control Site 10 was chosen for comparison of the water chemistry and trace element levels in the sediment and *Phragmites australis* as it had similar geology to the Tweelopiespruit. Control Site 11 was chosen for comparison of the leaf spectra results to the Tweelopiespruit. Control Site 11 (Figure 1, inset map 1) is located approximately 24.5 km north-northeast in the valley of the Skeerpoort River (25° 53' 40" S; 27° 45' 48" E), which flows through the John Nash Nature Reserve. This area receives a similar mean annual rainfall of ~700 mm.[44] The Skeerpoort River, fed by dolomitic springs yielding a total discharge[2] of 9.5 Mm^3/annum, is considered to be in a near pristine condition. The site has shown no land use impact for the past 50 years, and, in particular, has not experienced any AMD impacts. Average water chemistry (measured since 1964) shows mean pH as above 7, EC at 32.4 mS/m (s.d.=2.58) and mean sulphate levels as 8 mg/L (s.d.=3.8). The control *Phragmites australis* population occurs here on the edge of an artificial wetland.

Data collection

A study was conducted in 2009 to compare the AMD chemistry of the Tweelopiespruit sites with a non-AMD control site. Water, sediment and plant material were collected in the winter of 2009 from five sites along the Tweelopiespruit (Table 1, Sites 1–5) and at a control site (Site 10). At each site, sediment was collected from 100 mm below the water

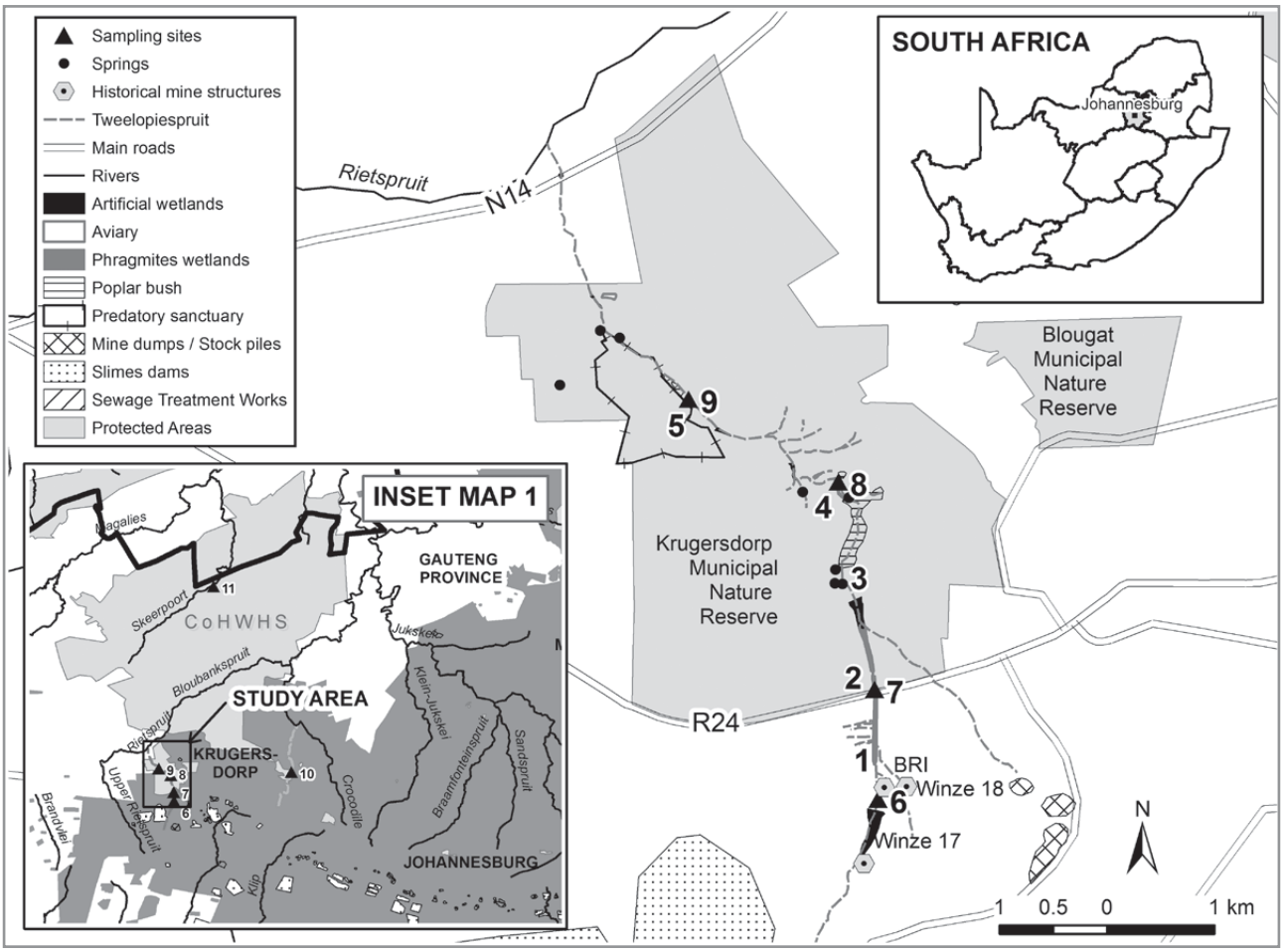

Figure 1: Inset map SOUTH AFRICA: Orientation map of Johannesburg in relation to South Africa. Inset map 1: The study area is located in the Gauteng Province to the west of Krugersdorp and Johannesburg. Mine dumps and slimes dams follow the watershed running from east to west, indicating historical and current mining operations on the Witwatersrand. Control Site 11 is located in the Skeerpoort River in the Cradle of Humankind World Heritage Sites (CoHWHS). Main map: The Tweelopiespruit drains from the mine property on the watershed northwards through a nature reserve to the confluence with the Rietspruit. Acid mine drainage was decanted at the Black Reef Incline (BRI) and at two ventilation shafts (Winze 17 and 18) in 2010 into the Tweelopiespruit. Dolomitic springs contribute fresh water to the surface stream. Sites 1 and 6 are located on the mine property and Sites 2–9 in the nature reserve along the stream where *Phragmites australis* occurs.

Table 1: Sample sites along the affected Tweelopiespruit and two unaffected control sites

Site numbers	Location	Treatment	Sampling
1–5	Tweelopiespruit	Acid mine drainage	Once-off analysis of water, sediment and plant material (2009) to determine chemistry and mineral contents
6–9	Tweelopiespruit	Acid mine drainage	Spectral analysis of *Phragmites australis* leaves in winter and summer over 2 years (2011–2012)
10	Muldersdrift se loop in the Walter Sisulu Botanical Gardens	Control (near-pristine conditions – no acid mine drainage)	Once-off analysis of water, sediment and plant material (2009) to determine chemistry and mineral contents
11	Skeerpoort River valley in the John Nash Nature Reserve	Control (pristine conditions – no acid mine drainage)	Spectral analysis of *Phragmites australis* leaves in winter and summer over 2 years (2011–2012)

column, in close proximity to *Phragmites australis*. Specimens of the rhizomes, stems and leaves of *Phragmites australis* were also collected at each site and subsequently dried in an oven at 65° C for 3 days. Water samples were analysed for pH, EC and sulphates (SO_4), while element concentrations in the water, sediment and plant material were assessed using inductively coupled plasma elemental analysis.

Green leaves of *Phragmites australis* were sampled in 2011–2012 to compare the physiological differences between the sites affected by AMD (Sites 6–9) and a site not impacted by AMD (control Site 11). Sites 6–9 are situated on the Tweelopiespruit (Figure 1) and control Site 11 in the unspoilt Skeerpoort River valley (Figure 1, inset map) in the John Nash Nature Reserve at the chalets. *Phragmites australis* occur here on the sides of an artificial wetland flanked on both sides by indigenous trees.

At each sampling site, sampling points were selected based on the availability and accessibility of green leaves during the dry period (June 2011). Sampling was carried out in the dormant (winter) and peak growth (summer) periods of 2011 and 2012 (Table 2). At each sampling point, five green leaves were collected for leaf level spectral reflectance measurements from five different stems of *Phragmites australis* within an area of 4 m². In the winter, these leaves were primarily small green leaves of new growth, whereas in the summer they were large mature leaves.

Table 2: Number of samples per site, season and year

	Year 1 (2011)		Year 2 (2012)	
	Winter	Summer	Winter	Summer
Site 6	24	24	24	24
Site 7	1	7	7	7
Site 8	19	19	19	19
Site 9	12	12	12	12
Site 11	10	8	8	9

Leaf level spectral reflectance measurements

An analytical spectral device, the FieldSpec Pro spectroradiometer (Analytical Spectral Devices Inc, Boulder, CO, USA), was used to record the leaf spectra of the five collected green leaves of *Phragmites australis*. The instrument has a spectral range of 350–2500 nm and a bandwidth of 3 nm re-sampled to 1 nm (http://www.asdi.com). A contact probe was used for spectral reflectance measurements to avoid external factors (such as light illumination differences). The contact probe enables calibration with a white reflectance panel, and has a dark panel for measuring reflectance. For each sampling point, the five leaf spectra were leaf averaged. The REP linear extrapolation method[41] was derived from the spectral measurements using a three-step procedure:

Calculate maximum first derivative spectrum

$$FDR_{(\lambda i)} = (R_{\lambda(i+1)} - R_{\lambda(i)})/\Delta\lambda \quad \text{Equation 1}$$

Calculate the reflectance at the inflexion point

$$R_{re} = (R_{670} + R_{780})/2 \quad \text{Equation 2}$$

Calculate the red edge position

$$REP = 700 + 40\ ((R_{re} - R_{700})/(R_{740} - R_{700})). \quad \text{Equation 3}$$

The NDVI was derived from the spectral measurements according to the formula

$$NDVI = \frac{R_{845} - R_{665}}{R_{845} + R_{665}} \quad \text{Equation 4}$$

Data analyses

The raw and derivative reflectance spectra were used to explore the differences between sites and seasons. For each vegetation index, the mean and standard deviation values were derived for sites affected by mine water and for the control site for the two seasons and years. A one-way analysis of variance (ANOVA) and post-hoc Tukey honest significant difference (HSD) test were performed in Statistica (version 7, StatSoft Inc.) to assess the significance of differences between the sites affected by mine water and the control site.

In addition, the mean and standard deviation values were calculated for each site for the two seasons and years to investigate the variation in gradation from upstream to downstream. ANOVA and post-hoc Tukey HSD tests were repeated to assess differences between sites for the sampling periods.

Results

Element analysis of water, sediment and plant material

The pH and EC show an improvement downstream of the decant site (Table 3), yet no consistent trend is shown in sulphate levels downstream. A high concentration of heavy metals (Table 3) was found in sediments and the rhizomes, stems and leaves of *Phragmites australis*. Sediment samples taken from the top 100 mm on the sides of the wetlands show that the highest values for As and Fe were recorded at the decanting site (Site 1) and Site 5, whereas Al was the highest at Sites 2 and 5. Cr, Pb and Zn measured highest at Site 4. Site 5 (or Site 9) show the highest measurements for Cu, Mn, Ni and U, although Cr, Pb and Zn also were high at Site 5. Metals accumulated primarily in the rhizomes of the reeds with lower concentrations in the aerial parts. No consistent trend could be noted for all the metals downstream from the decant site.

A tier 1 risk assessment, where site concentrations are rated in respect to regulatory standards, was done of the top 0.5 m of wetland sediment (below 1 m the water surface) at three sites in the Tweelopiespruit. This assessment also indicated high levels of Ni and U above acceptable standards of the European Union and the South African National Nuclear Regulator.[47]

Green leaf spectra of affected sites compared to the control site

Overall, the average reflectance spectra of green leaves for both winter and summer of the 2 years show normal vegetation curves peaking in the green, absorbing in the red and having high reflectance in the NIR region (Figure 2). The average reflectance spectra for the affected sites are higher than that of the control site in the visible region (VIS) over the two winter periods, although are very similar in the NIR. Both summer periods show higher average reflectance spectra in the VIS and NIR for the affected sites in comparison to the control site.

Both winter and summer seasons over the 2 years show a blue shift for the affected sites, compared to control Site 11 (Figure 3). The double peak feature[41,48] and blue shift is particularly visible in the winter season of the first year (Figure 4), and less obvious in the second year.

The behaviour of the double peak feature of the first derivative in the red edge region between 660 nm and 780 nm was captured in the linear extrapolation REP model by Cho and Skidmore[41]. The dominance of the first peak (at around 700 nm) is associated with low chlorophyll and the dominance of the second peak is associated with high levels of chlorophyll.[41] The control site shows a dominance of the second derivative peak (at about 725 nm) in the red edge region when compared to the affected site (Figure 6). Hence, the control site shows high levels of chlorophyll for all the sampling periods, compared to the affected sites. In the winter of both years the differences between control Site 11 and affected sites are particularly visible, with the affected sites showing medium levels of chlorophyll compared to the control site, which shows higher levels of chlorophyll (Winter Year 1 and Year 2 in Figure 4).

Green leaf spectra of individual sites compared to the control site

When comparing the average green leaf reflectance of each site over the two seasons and years, the control site seems to have lower reflectance in the VIS region than the other sites throughout the time periods (Figure 5). The control site shows more dominance of the second red edge derivative peak around 720 nm when compared to the affected site. In winter, the control site reflectance lies within the range of the other sites for the NIR region of the spectrum. In summer, however, it is lower in the NIR compared to the other sites. None of the affected sites show particular differences compared to the others in average reflectance spectra over the sampling period.

Most of the sites show a blue shift for the winter and summer seasons over the 2 years, compared to the control site (Figure 6). Leaves of the control site seem to have higher chlorophyll absorption levels compared to the affected sites in both winters (Figure 7). In the summer months, the affected sites appear to have slightly higher chlorophyll absorption levels compared to the control site. In the winter of Year 1, Site 7 shows the most stress. Only a single new green leaf was available at this site for sampling. The leaf structure is least developed (Figure 6, Year 1 Winter, Site 7) and chlorophyll levels are much lower compared to all the other sites. These observations support the circumstances that describe the period of greatest raw mine water discharge into the Tweelopiespruit.

Table 3: Water chemistry and metal concentrations in sediments and rhizomes, stems and leaves of *Phragmites australis*, sampled in the winter of 2009 along five sites downstream of the decant site in the Tweelopiespruit. Control Site 10 was located in the Walter Sisulu Botanical Gardens. Elevated concentrations of sulphates, Al, Cu, Mn, Ni and total U are seen when comparing the Tweelopiespruit to the control site. Fe is high at both sites, testifying to the naturally high Fe content of the geology. Control Site 10 has high Al, which can be attributed to a sewer pipe leak in the stream draining through the Botanical Gardens.

Constituents	Site 1	Site 2	Site 3	Site 4	Site 5	Control Site 10
Water chemistry:						
pH	4.7	7.5	7.3	7.4	7.2	7.9
EC	143	287	261	256	266	14.1
SO_4	720	2 022	1 897	1 474	1 685	7
ICP water scan (mg/L):						
Al	16	0.17	0.32	0.10	0.11	0.10
As	0.32	<DL (0.010)	<DL	<DL	<DL	<DL
Cr	<DL (0.025)	<DL	<DL	<DL	<DL	<DL
Cu	0.345	<DL (0.025)	0.169	<DL	<DL	<DL
Fe	460	2.61	34	0.09	0.38	0.23
Mn	46	5.8	6.6	1.1	6.5	0.03
Ni	3.6	0.09	0.55	0.13	0.19	<DL (0.025)
Pb	0.05	<DL (0.02)	<DL	<DL	<DL	<DL
Zn	2.3	<DL (0.025)	0.26	<DL	<DL	<DL
Total U	0.002	0.001	<DL (0.001)	<DL	<DL	<DL
Sediment samples (mg/kg):						
Al	12 100	26 700	275	13 800	19 200	14 600
As	427	26	3	17	171	5
Cr	44	54	4	86	75	142
Cu	40	67	36	45	189	26
Fe	53 500	24 900	5 700	18 800	32 400	31 400
Mn	2 200	3 400	274	635	24 100	804
Ni	318	280	27	57	565	55
Pb	19	19	<DL (2)	19	38	23
Zn	246	114	21	340	316	94
Total U	24	19	5	10	122	1
Rhizomes:						
Al	607	11 800	1 400	844	8 000	305
As	22	14	3	4	23	1
Cr	9	38	16	5	32	8
Cu	13	39	8	10	46	4
Fe	32 400	14 600	1 900	4 300	15 800	757
Mn	3 900	701	621	208	3 400	37
Ni	43	125	23	10	119	3
Pb	1	9	3	1	10	1
Zn	53	73	27	97	118	8
Total U	1	16	4	2	20	0.1
Stems:						
Al	18	32	12	17	11	61
As	<DL (1)	<DL	<DL	<DL	<DL	<DL
Cr	<DL (2.5)	<DL	<DL	<DL	<DL	5.4
Cu	5	4	<DL (2.5)	<DL	6	<DL
Fe	66	173	7	10	86	129
Mn	96	113	32	81	50	32
Ni	<DL (0.025)	<DL	<DL	<DL	3	<DL
Pb	<DL(2)	<DL	<DL	<DL	<DL	<DL
Zn	44	39	17	122	90	21
Total U	<DL (0.1)	<DL	<DL	<DL	<DL	<DL
Leaves:						
Al	105	99	61	43	164	49
As	<DL (1)	<DL	<DL	<DL	<DL	<DL
Cr	<DL (2.5)	<DL	<DL	3.4	5.6	2.3
Cu	3	4	<DL (2.5)	4	8	3
Fe	193	155	90	83	320	177
Mn	964	386	878	920	568	132
Ni	<DL (2.5)	3	3	<DL	9	<DL
Pb	<DL (2)	<DL	<DL	<DL	<DL	<DL
Zn	136	35	35	146	100	8
Total U	1	<DL (0.1)	<DL	<DL	<DL	<DL

EC, electrical conductivity (mS/m); ICP, inductively coupled plasma; DL, detection limit.

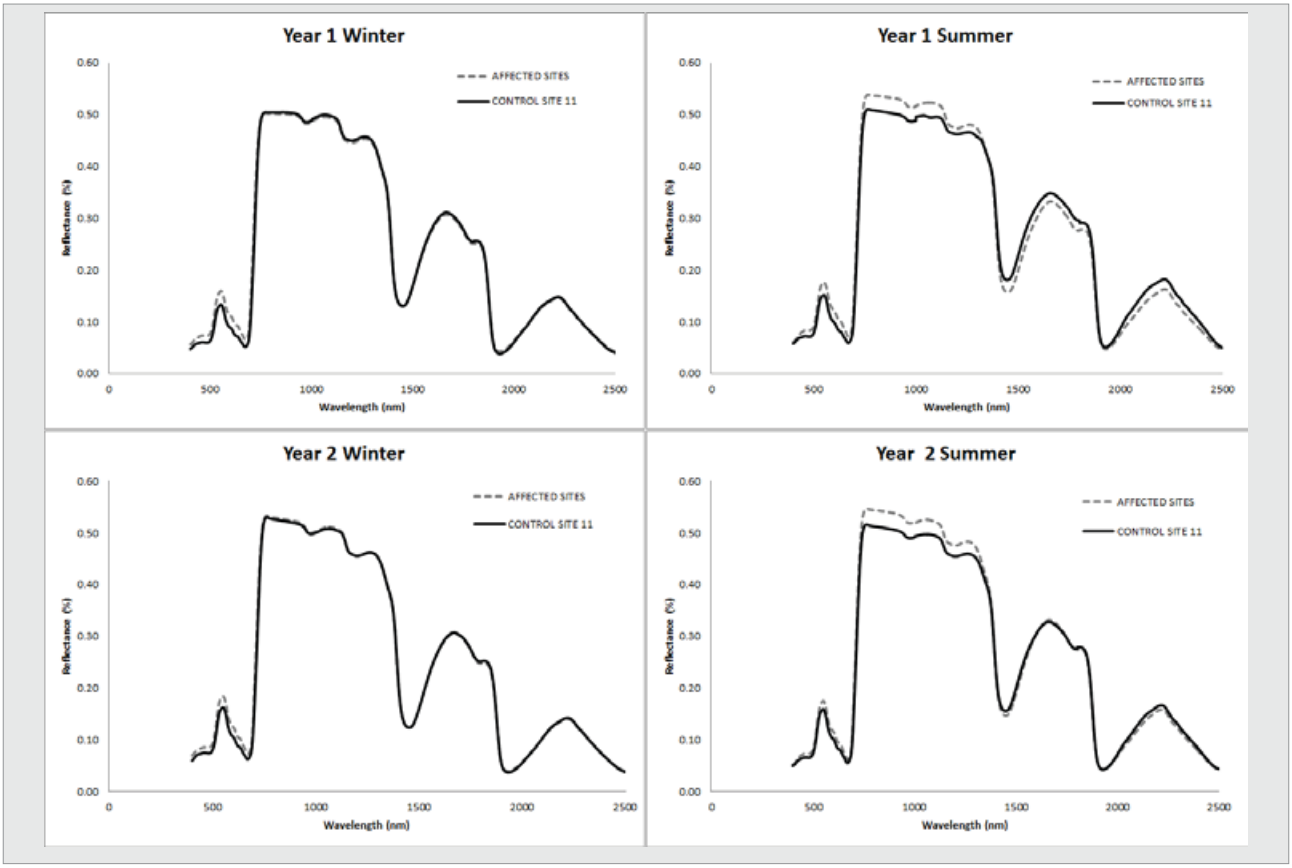

Figure 2: Average leaf reflectance (%) of green leaves at sites affected by acid mine drainage compared to the control site, per season and year.

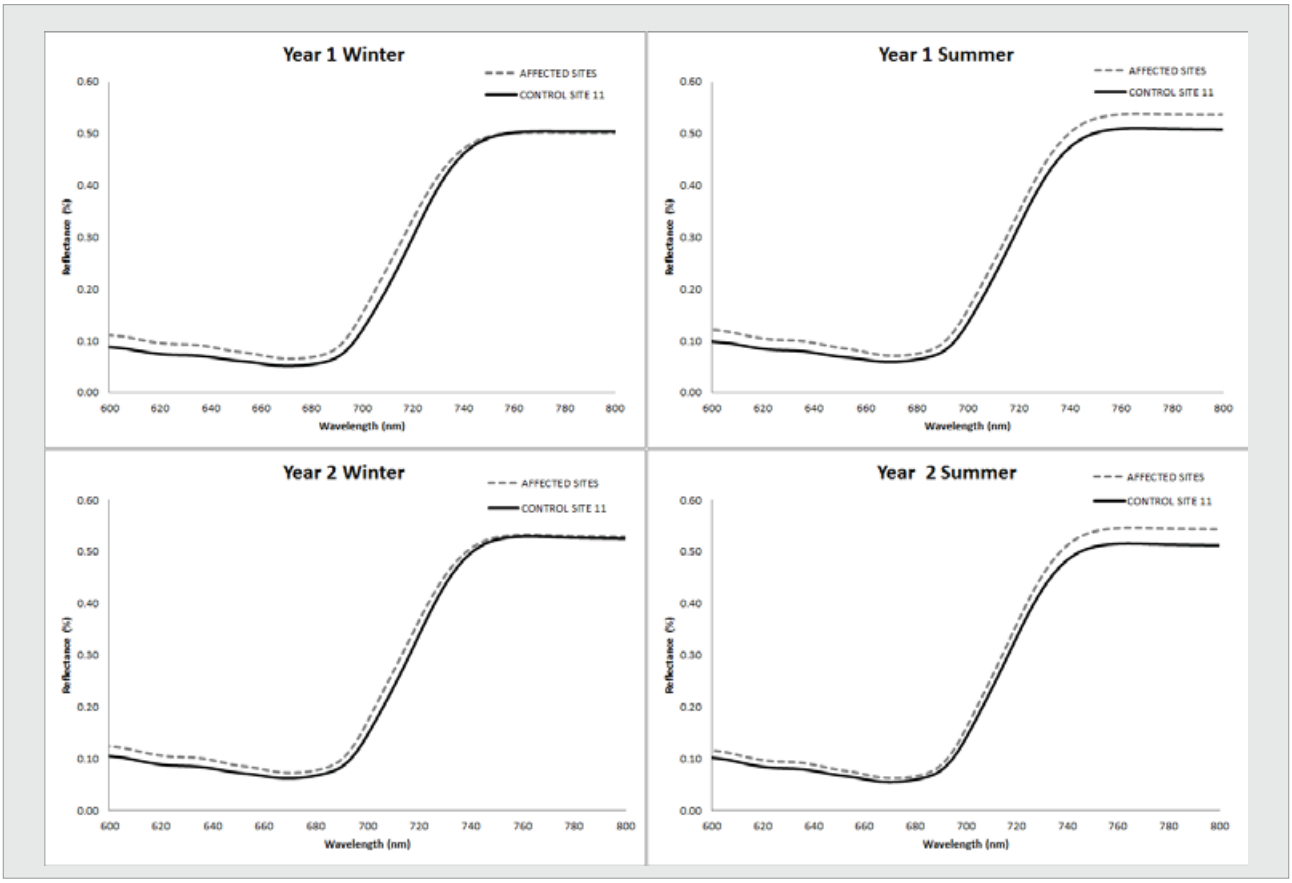

Figure 3: The chlorophyll red edge region for affected sites and the control site.

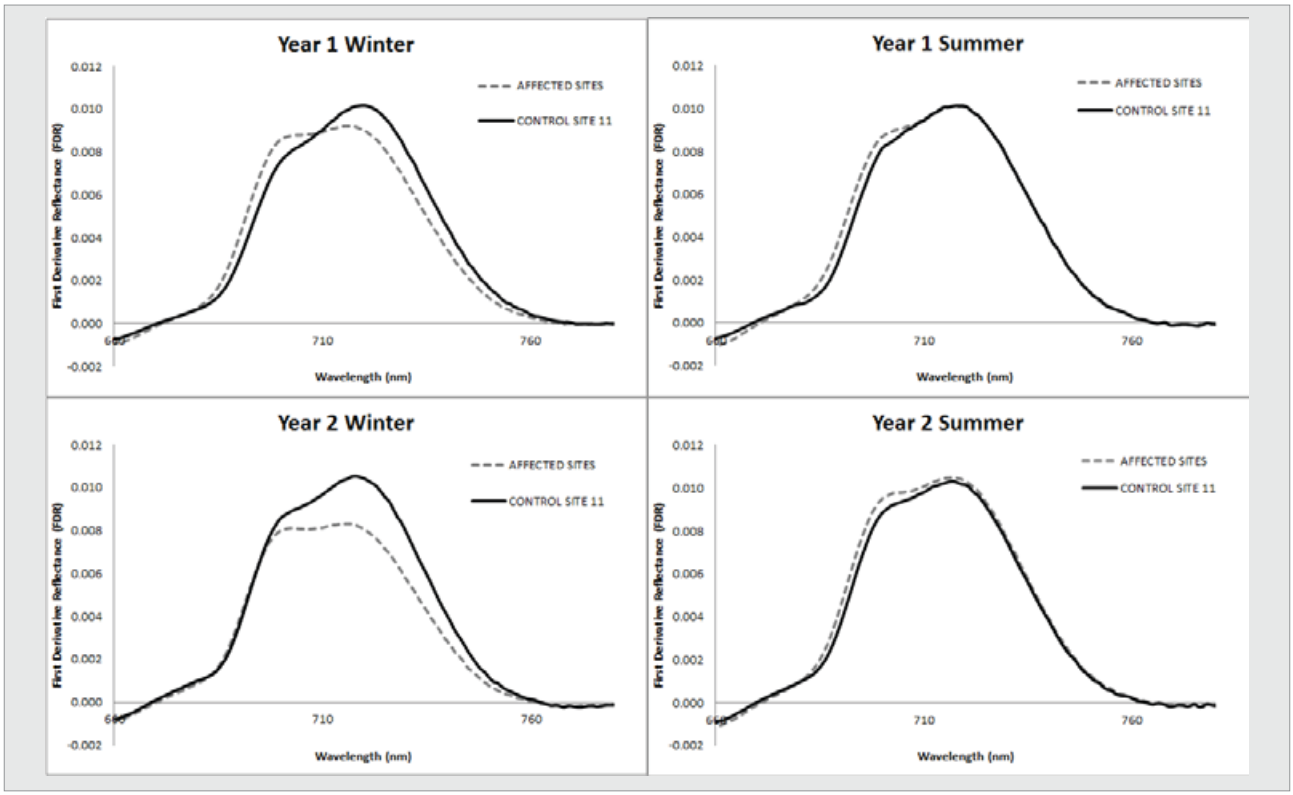

Figure 4: Comparison of first derivative reflectance curves of affected sites and the control site. The dominance of the first peak (at around 700 nm) is associated with low chlorophyll levels and the dominance of the second peak is associated with high levels of chlorophyll. The control site consistently shows dominance of the second peak over all seasons and years.

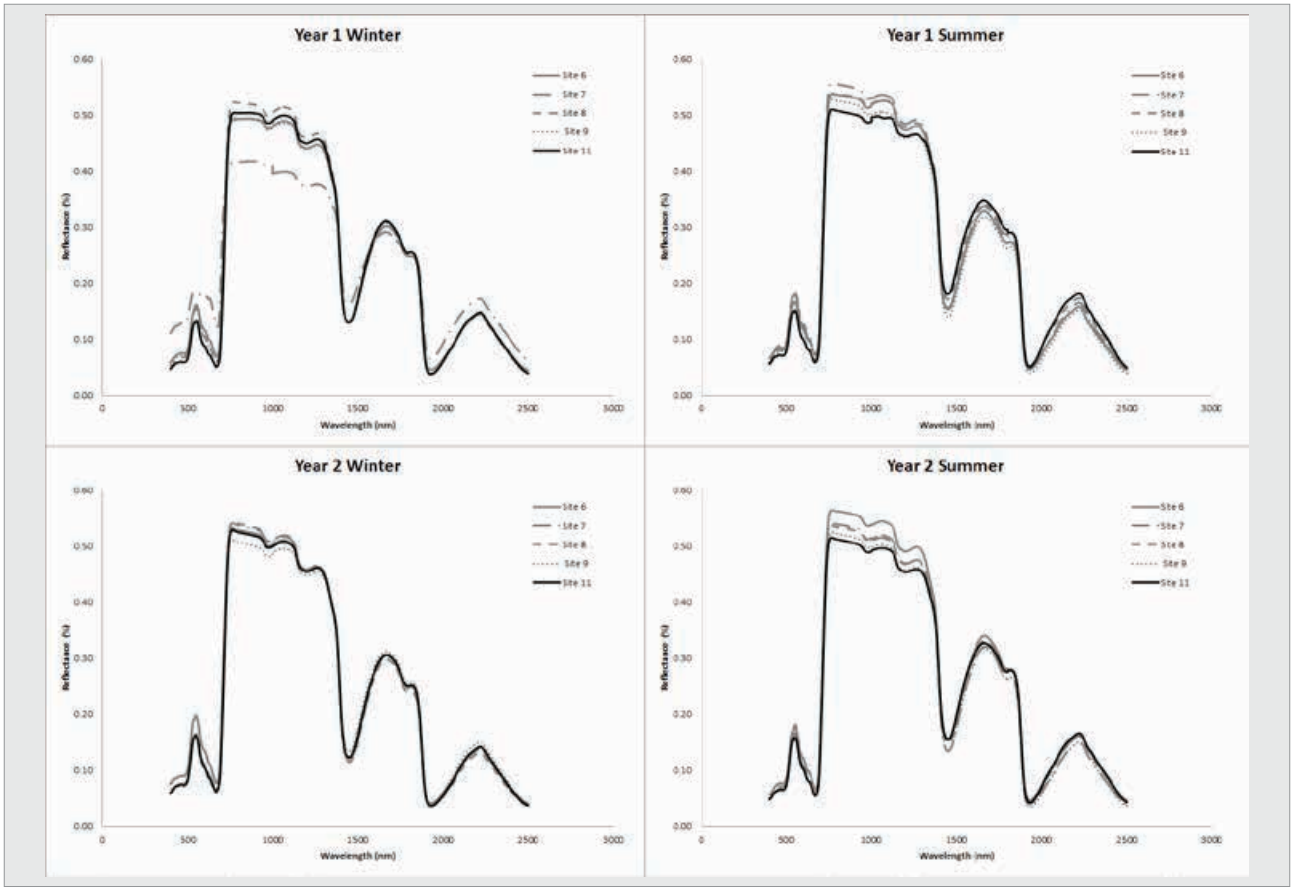

Figure 5: Average reflectance (%) of green leaves per sampling site for both seasons and years. Only a single new growth green leaf was available on the day of sampling for Site 7 in winter of Year 1.

The single leaf sampled in Year 1 Winter at Site 7 also is evident in Figure 7, where the second derivative peak shows a blue shift towards 690 nm and no double peak feature. There is a greater variation of chlorophyll absorption levels, the location of the second derivative peak and the double peak feature between sites during the winter season (Figure 7, see Year 1 and 2) compared to the variation of these features between sites in the summer seasons. In the winter, Site 6 shows a double peak feature in the second red edge derivatives, with the change in the first peak around 695 nm more prominent compared to the second peak near 720 nm. In the winter of Year 2, Site 9 follows a similar pattern. In contrast, Site 8 matches the slope of the control site more closely for both winters, with the peak near 720 nm.

In the summer seasons, the profile of the second red edge derivative peaks are closely matched for all sites. The affected sites tend to medium levels of chlorophyll (a double peak profile), compared to the higher chlorophyll levels of the control site (profile skewed towards second peak) for the summers of Years 1 and 2. The affected sites show more change in the second derivative profile around the first peak, near 690 nm, compared to the control site. For all the sites, the control shows the strongest dominance of the second derivative peak, indicating the highest levels of chlorophyll.

Variation of spectral indices between affected and control sites

REP and NDVI values between the affected sites and the control site for each season and year show significant differences ($p<0.05$). Sites affected by mine water had significantly lower REP values ($p<0.05$) over the two seasons and years compared to the control site (Table 4). Sites affected by mine water show a higher variability of REP values in winter compared to the summer seasons. The average REP value increased from winter to summer for the affected sites, and decreased slightly in the control site for the same period.

NDVI values also show a greater variation in the winter period for the affected sites compared to the control site (Table 4). In all instances, the ranges of NDVI values of the affected sites and control site overlap largely for both seasons and years. Average NDVI values in the winter were significantly lower ($p<0.05$) for affected sites than for the control site, whereas the average NDVI values in the summer were closer in value.

Downstream gradation of spectral indices

Generally, average REP and NDVI values in winter increase from Site 6 to Site 8 (downstream) and drop at Site 9 (Table 5), except for Site 2 in the winter of Year 1, where only one new green leaf was available. In summer, an opposite trend is noted for average REP values: in general, the average REP decreases downstream from Site 6 to Site 8 and then increases again at Site 9. Average NDVI in summer shows less distinct patterns downstream of Site 1. For the first three sites (6, 7 and 8), average REP in summer decreased from Year 1 to Year 2, whereas the average NDVI values decreased in winter and increased in summer. There appears to be a gradient of the REP values only in the winter of Year 1. On average, the control site values change slightly over the 2 years; however, affected sites (Sites 6–9) show more fluctuation, particularly in REP values.

When comparing all sites to one another (a combination of 10 pairs; Bonferroni-corrected $p<0.005$), Sites 6 and 11 are significantly different from one another in both seasons and years for both REP (Table 6) and NDVI (Table 7). Sites 6 and 8 also differ significantly for both seasons and years for REP. Few significant differences between sites are noted for NDVI.

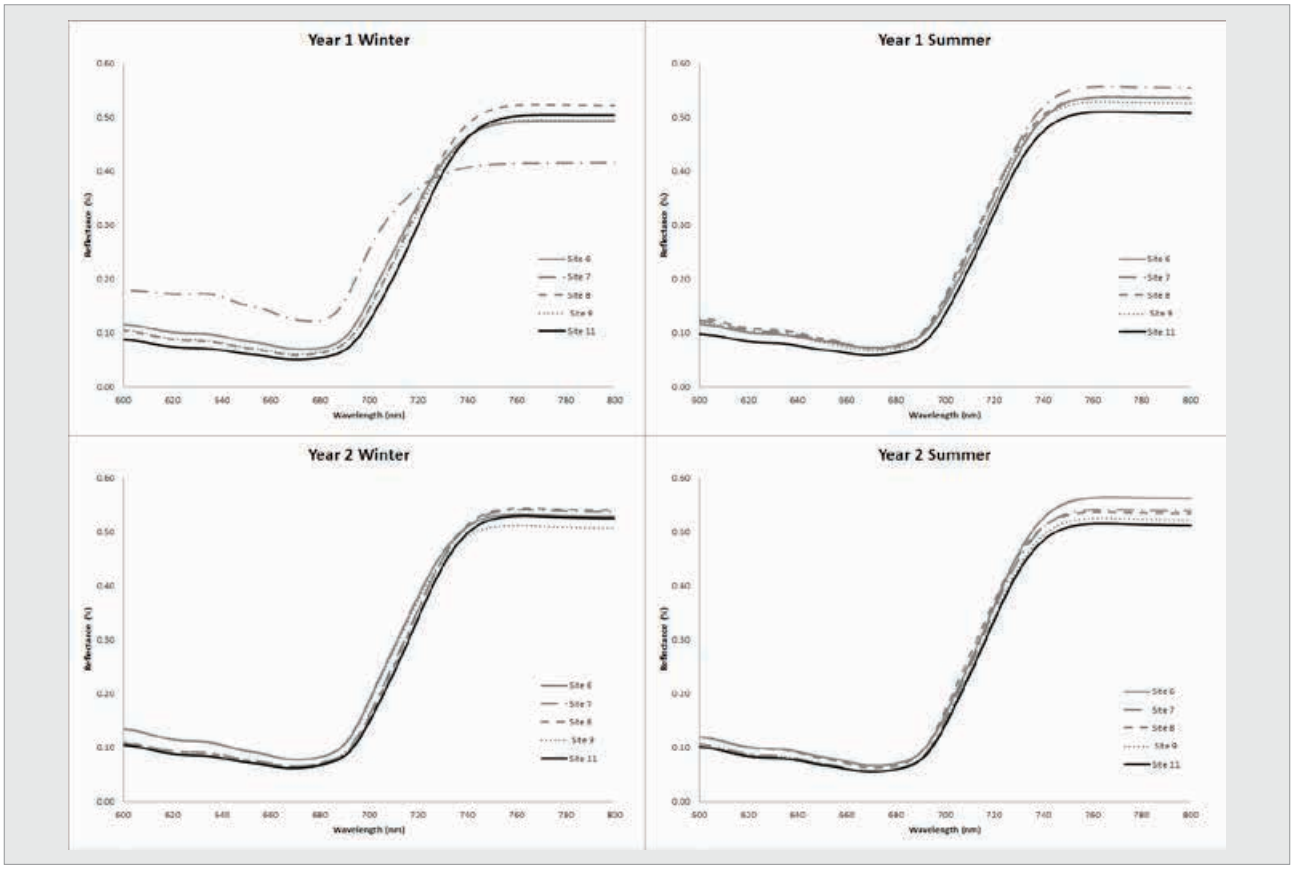

Figure 6: The chlorophyll red edge region for Sites 6–9 and 11. A blue shift in the red edge region of the Tweelopiespruit sites is visible, indicating lower chlorophyll levels. A higher reflectance in the near-infrared region is visible for the Tweelopiespruit sites in both seasons and years. The control site shows a red shift in the red edge region in both seasons and years, indicating higher chlorophyll levels. Control Site 11 shows a lower reflectance in the near-infrared region in the summer seasons of both years.

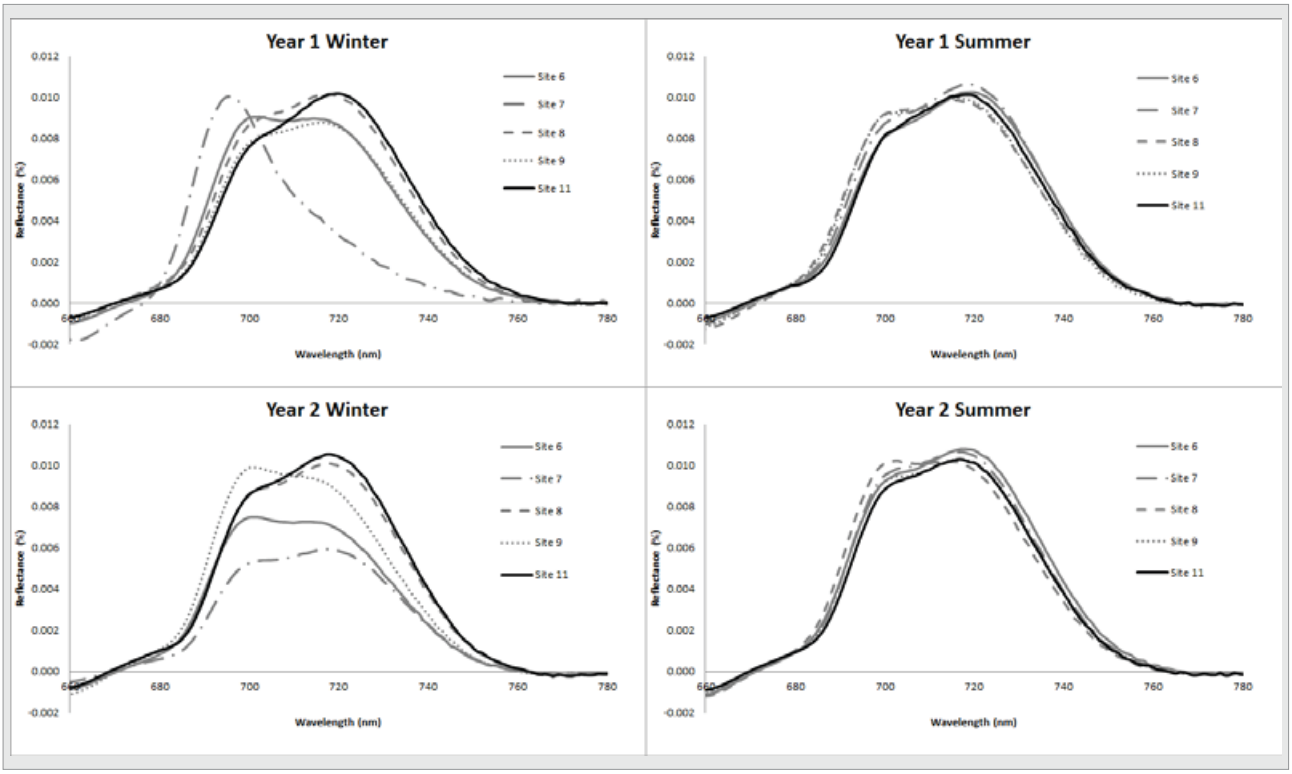

Figure 7: Comparison of first derivative reflectance (FDR) curves for Sites 6–9 and 11. Only a single new growth green leaf was available on the day of sampling at Site 7 in winter of Year 1. In winter, Site 6 shows a dominant first peak in the FDR whereas the control and Waterfall sites show dominance of the second peak of the red edge in the FDR. In the summer of both years, chlorophyll levels increased, as is shown by the dominance of the second peak for most sites. Control Site 11 shows consistency in the second peak of the red edge FDR for both seasons and years.

Table 4: Means and standard deviations for red edge position (REP) and normalised difference vegetation index (NDVI) values for sites affected by acid mine drainage and an unaffected control site, in winter and summer over 2 years

Vegetation index	**REP**				**NDVI**			
Year	Year 1		Year 2		Year 1		Year 2	
Season	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Affected sites	708.17±5.9	710.86±4.5	707.27±6	708.98±3.5	0.76±0.02	0.76±0.05	0.74±0.03	0.78±0.02
Control Site 11	715.85±2.7	714.20± 2.5	713.17±4	711.66±4	0.81± 0.01	0.78±0.01	0.77±0.01	0.79±0.01

Table 5: Means and standard deviations for red edge position (REP) and normalised difference vegetation index (NDVI) values for each site affected by acid mine drainage and an unaffected control site, in winter and summer over 2 years

Vegetation index	**REP**				**NDVI**			
Year	Year 1		Year 2		Year 1		Year 2	
Season	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer
Site 6	705.46±5.5	714.13±3.4	704.49±5.6	710.86±3.1	0.75±0.05	0.75±0.02	0.73±0.03	0.78±0.02
Site 7	686.95*	712.14±2.6	710.61±.0	709.46±1.5	0.54*	0.76±.02	0.77±0.03	0.80±0.01
Site 8	711.31±2.4	707.69±2.6	711.73±3.1	705.60±2.8	0.79±0.02	0.76±0.01	0.77±0.02	0.78±0.02
Site 9	710.09±4.8	708.60±5.1	703.66±4.3	710.32±2.1	0.77±0.04	0.76±0.02	0.72±0.01	0.79±0.02
Control Site 11	715.85±2.7	714.20±2.5	713.17±4.0	711.66±4.0	0.81±0.01	0.78±0.01	0.77±0.01	0.79±0.01

**Only a single new growth green leaf was available on the day of sampling for this season and year.*

Table 6: One-way analysis of variance (Tukey's honest significant difference test) results of comparisons between red edge position values at sites affected by acid mine drainage and that of an unaffected control site, in winter and summer over 2 years

	Winter					Summer				
	Site	Site 6	Site 7	Site 8	Site 9	Site	Site 6	Site 7	Site 8	Site 9
Year 1	Site 6					Site 6				
	Site 7	0.001572*				Site 7	0.979306			
	Site 8	0.000260*	0.000142*			Site 8	0.000128*	0.287634		
	Site 9	0.015534	0.000171*	0.892458		Site 9	0.000278*	0.757268	0.242868	
	Control Site 11	0.000128*	0.000128*	0.096354	0.026698	Site 11	0.982198	0.997376	0.000143*	0.010255*
Year 2	Site 6					Site 6				
	Site 7	0.051613				Site 7	0.981764			
	Site 8	0.000227*	0.737012			Site 8	0.000224*	0.833052		
	Site 9	0.998182	0.044005	0.000411*		Site 9	0.999469	0.990858	0.001677*	
	Control Site 11	0.000378*	0.902817	0.939755	0.000531*	Site 11	0.585091	0.795103	0.000162*	0.547314

**Significant at Bonferroni corrected p<0.005.*

Table 7: One-way analysis of variance (Tukey's honest significant difference test) results of comparisons between normalised difference vegetation index values at sites affected by acid mine drainage and that of an unaffected control site, in winter and summer over 2 years

	Winter					Summer				
	Site	Site 6	Site 7	Site 8	Site 9	Site	Site 6	Site 7	Site 8	Site 9
Year 1	Site 6					Site 6				
	Site 7	0.000144*				Site 7	0.937296			
	Site 8	0.001675*	0.000128*			Site 8	0.255557	0.999973		
	Site 9	0.221851	0.000128*	0.633513		Site 9	0.020227	0.994186	0.635443	
	Control Site 11	0.000636*	0.000128*	0.737477	0.172045	Site 11	0.000427*	0.817806	0.037587	0.538753
Year 2	Site 6					Site 6				
	Site 7	0.064084				Site 7	0.199364			
	Site 8	0.000143*	0.892472			Site 8	0.480289	0.467222		
	Site 9	0.871981	0.029987	0.000140*		Site 9	0.005334	0.924787	0.184808	
	Control Site 11	0.000291*	0.946163	0.996746	0.000180*	Site 11	0.004045*	0.971400	0.114219	0.993404

**Significant at Bonferroni corrected p<0.005.*

Discussion and conclusions

Field spectroscopy shows potential as a means to assess the impact of mine water on wetland vegetation and to monitor impact over time. The REP and NDVI values for affected sites were significantly lower compared to the control site for both winter and summer seasons over the 2 years. The mean and standard deviation of REP and NDVI can therefore potentially serve as surrogates for establishing impact on wetland vegetation and monitoring vegetation condition over time in other areas of South Africa. It remains to be established whether the method is site and species specific, or whether it also applies to other sites regardless of mine water characteristics and environmental conditions.

Winter seasons presented more distinct differences in REP and NDVI values between affected sites and control Site 11. In addition, leaves of control Site 11 seemed to have higher chlorophyll absorption in the winter of both years, based on the dominance of the second derivative peak of the first derivative spectra of the REP region. The opposite trend of an increased reflectance in the NIR (i.e. biomass) and a reduction in chlorophyll (or REP values) was, on the other hand, particularly visible in the summer months, similarly to findings reported by others.[24,27] The pattern was, however, less distinct in winter months, although leaf maturity may influence the responses in both the red and NIR regions in this instance.

Both REP and NDVI showed significant differences between the affected and control Site 11; however, in comparison, REP and NDVI values for individual sites yielded fewer significant differences between affected sites and control Site 11. The inconsistent responses of REP values of individual sites affected by AMD compared to control Site 11 are similar to those noted for *Phragmites australis* at two affected sites compared to a control site in Hungary.[19] Regardless, the presence of high levels of, among others, Al, As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn and total U in the soils found in parts of the Tweelopiespruit[47] may have a toxic effect on plants, hence at some sites the REP and NDVI indices show significant differences from control Site 11. Metal concentrations in sediments at particular sites were found to vary, not only as noted by Venter et al.[47] at, for example, the Hippo Dam wetland, but also between the two studies at similar sampling points. Variation in metal concentrations may be attributed to the natural variation of water depth, flow and presence of vegetation in parts of a wetland. Variations in stream flow and pH during rainfall periods, when a larger volume of raw mine water and AMD floods through the spruit, would also cause changes in the bioavailability of metals from the stream bed and vegetation, contributing to further temporal and geographical variations in metal concentrations. In any event, the differences between sites are difficult to explain and can be attributed to a number of possible factors influencing the signatures. Further exploration of temporal and spatial variation of the metal concentrations and affected vegetation is essential to further the understanding of the impact of AMD in the Tweelopiespruit.

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Authors' contributions

H.v.D. contributed to the experimental and project design, undertook the fieldwork and statistical analysis, and wrote and revised the manuscript. M.A.C. was responsible for the experimental and project design, and the paper structuring, editing and revision.

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Craniodental continuity and change between Iron Age peoples and their descendants

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The appearance of the Iron Age of southern Africa early in the first millennium AD is associated with the migration of Bantu speakers who were broadly ancestral to present-day Bantu speakers. While there is sufficient genetic, physical anthropological and cultural evidence to support general continuity into contemporary populations, the extent to which events since colonialism have affected morphological variation is poorly understood. We used dental anthropological techniques and three-dimensional craniomandibular metrics to examine biological relationships among Iron Age farmers, a historical 19th-century Ndebele sample and 20th-century Bantu speakers. We show that, although Iron Age and modern morphologies are generally similar, there are differences. Moreover, the historical sample falls between the precolonial and modern samples, suggesting increased genetic exchange from the 19th century onwards. These results suggest that recent historical events altered the genetic make-up of Bantu speakers and that, as a result, extrapolations from modern groups to the past should be done with caution as morphological variability is relative to historical context.

Introduction

In southern Africa over the last 2000 years, there have been several significant demographic shifts that imply gene flow or exchange at several different geographical scales. Early in the first millennium AD, the Iron Age appears rapidly in this region and is identified archaeologically through a 'package' of agropastoralist elements associated with permanent and semi-permanent settlements.[1-4] These elements include a distinctive ceramic style (the Chifumbaze complex) that is widespread in East and southern Africa, and metallurgical skill. The archaeological and linguistic evidence indicates that the abrupt introduction of this 'Iron Age package' is associated with the migration of farmers who spoke Bantu languages and that there is a general continuity through to Bantu speakers in present-day southern Africa. This scenario is also supported by genetic evidence from modern-day descendants, which indicates recent and common origins throughout much of southernmost Africa.[5-8]

Debate concerning the cultural continuity between the Early Iron Age (EIA) and historical Bantu speakers[5,9,10] considers that EIA people did not arrive and develop in isolation; the evidence for intermarriage and cultural exchange with Stone Age hunter–gatherers is clear.[5,11] Additionally, the shift in ceramic style between the EIA and Later Iron Age (LIA) early in the second millennium AD[12] is associated with further migration from east Africa. Blackburn ceramics (ancestral Nguni speakers) appear in KwaZulu-Natal from around 1100 AD and Moloko ceramics (ancestral Sotho–Tswana speakers) appear north of the Soutpansberg from around 1300 AD.[12-15] Furthermore, Sotho–Tswana and Nguni ancestors colonised the southern grasslands, south of the Vaal River[16], and the Eastern Cape from the 16th century[12]. Once again, linguistic, cultural and genetic evidence shows considerable interaction with San hunter–gatherers. Significant shifts among agropastoralists, especially Nguni diasporas from northern KwaZulu-Natal from the 16th century AD, may have been prompted by climatic change and the introduction of maize via the Portuguese.[12]

Demographic movement increased from the early 19th century as colonial expansion intensified from the southeast African coast and from the Cape. This expansion contributed to the early 19th-century mfecane/difaqane (troubled times) during which there was considerable demographic movement and change.[12] Colonial encroachment and intensified trade demands for ivory and labour contributed to agropastoralist political centralisation in the west, the development of large Tswana towns[17] and the establishment of the Zulu state in northern KwaZulu-Natal[18,19]. These events exacerbated a demographic 'swirl' and Nguni speakers, for example, moved into southwestern Zimbabwe as well as northern Malawi and southern Tanzania. Despite the colonial characterisation of this period as savage and chaotic, the movement of people and the negotiation of new political arrangements elsewhere simply continued from previous political processes that underpinned inclusiveness. The *Land Act of 1913* and the establishment of apartheid homelands during the 20th century collapsed identity into an immutable package of race, culture and language.

While the historical and archaeological record indicates overall continuity through the EIA and into the present there has been gene flow from both closely related groups and more distantly related ones (e.g. Khoesan, colonists) and this is likely to have influenced the biological composition of these peoples over time.[8,20] Although studies of the remains of Iron Age peoples have the potential to contribute to our understanding of biological continuity (or change) over time, to date the contribution of physical anthropology to the question of temporal continuity is limited. Analyses of morphological variability within and between Iron Age human samples, as well as between Iron Age and later samples, are rare (but see Ribot et al.[21]). Because Iron Age human burials are typically dispersed within a settlement (in a patterned way according to gender and status), it is unlikely that more than a few burials are discovered and excavated per site.[22] The exceptions are the burials excavated from the early second millennium AD Mapungubwe and K2 capitals, which have been analysed and shown to be within the range of variation expected in modern Bantu speakers.[22-25] These specimens have since been reburied.[26]

Additionally, a number of studies have looked at skeletal variation in modern Bantu-speaking peoples. A large-scale study on variability between Bantu speakers, using linguistic identity as a proxy for 'tribal' affiliation was conducted by De Villiers[27], based on cranial metric and non-metric analyses[27]. Her study showed that there is low variation

between recent historical South African Bantu speakers and that many features were similar between these groups and the Khoesan (suggesting admixture). This finding was supported by a more recent study using geometric morphometrics.[28] Dental anthropology on modern Bantu groups conducted by Jacobson[29] and Irish[30,30] also support conclusions of low inter-population variability[29-31]. These conclusions are supported by the genetics[32], although later research suggests that the level of admixture varies between groups, indicating that differences between southern Bantu and more northern populations result from the intensity of interaction and intermarriage with Khoesan[28,33].

In this study, we compared modern and archaeological Iron Age human samples, as well as an historical Ndebele sample, in order to assess the degree of morphological continuity among these broad groups. These analyses focus on cranial and dental morphology for two reasons. Firstly, in other studies on both contemporary and archaeological human samples,[23,28,33-40] both dental and cranial morphology have been shown to be population-specific indicators of identity. Secondly, teeth are better preserved in the archaeological record than the postcranial skeleton and therefore comprise a larger sample size. Our main objective in this study was to characterise cranial and dental variability within Iron Age and more contemporary Bantu speakers, and identify differences in variation that may have arisen as a result of recent historical processes influencing gene flow. As within-group variability in both the Iron Age and modern Bantu speakers has been shown to be small,[27,29,30,38,41] we considered them as cohesive entities. Significant differences between these larger temporal groups is likely to have arisen during the colonial and post-colonial periods, represented here (albeit incompletely) by the historical Ndebele (Historic Cave) sample. More broadly, this research will allow us to evaluate the assumptions that can be made of historical groups using contemporary Bantu-speaking populations.

Materials and Methods

Specimens

The sample is separated into three groups: Iron Age, historical and modern. The Iron Age specimens ($n=142$) come from a number of sites and are housed in the following institutions: University of Cape Town, the Natal Museum, the University of the Witwatersrand, the University of Pretoria, the National Museum of Cultural History (Ditsong Museums of South Africa) and the University of Botswana (in association with the Botswana National Museum). Sites from where the samples originate range from as far north as Zambia (Ingombe Ilede and Isamu Patu), east into the Kalahari of eastern Botswana (Toutswemogala sites) and along the KwaZulu-Natal (eastern) coast of South Africa. All these sites date to between 1600 and 150 BP, and consequently straddle both the EIA and LIA. Because current research suggests that morphological variability (both temporal and geographical) between groups in the Iron Age is low,[41] the Iron Age is treated as a single group for comparisons within this study. The historical specimens are Ndebele peoples from Historic Cave, located in the Makapan Valley in South Africa, and date to a historically documented siege by the Trekboers in 1854.[18] The sample consists mostly of loose teeth (166 teeth in total). While the Historic Cave sample is clearly not representative of the entire colonial period, it does provide a useful and interesting marker with which to compare the modern and Iron Age samples.

Data for the modern sample were collected from the Raymond A. Dart Collection of human skeletons at the University of the Witwatersrand. The full sample consists of 39 individuals derived from southern Bantu-speaking groups. These specimens are classified as Zulu, Sotho and Xhosa in the catalogues; however, it is important to remember that many of the specimens within the Raymond A. Dart Collection of human skeletons have been classified into these groups on the basis of language, and more specifically surnames,[42] so these affiliations may not be entirely accurate. Details for the list of specimens, including descriptions of individual specimens (Iron Age and modern) can be found in Warren[41]. Sex was not taken into account in the analyses as a large portion of the sample consists of individual teeth and there are currently no reliable metrical methods for determining sex from teeth available for South Africa. Only adult crania and teeth (including adult teeth from subadult individuals) were used for morphological and dental analyses.

Dental anthropology

Both metric and non-metric data were collected to examine dental variability among the Iron Age, historical (19th century) and modern Bantu speakers (cadavers from the Dart Collection). Non-metric dental traits were scored according to the Arizona State University Dental Anthropological System.[43] These procedures were calibrated with external researchers (Ms Wendy Black who, herself, calibrated with Dr Joel Irish) to increase accuracy to within 93%. Sample sizes varied for each trait within each group, based on presence of tooth and the visibility of the trait. The modern group ranged from 12 to 39 specimens, the historical sample from 1 to 25 specimens, and the Iron Age sample from 47 to 108 specimens. Two dental calliper measurements – buccolingual and mesiodistal lengths – were also taken on each available tooth. Statistical analyses were performed using *t*-tests (in Microsoft Excel) conducted between each group for all comparable traits. Chi-squared tests were performed in Microsoft Excel on the non-metric traits in order to compare trait frequencies between groups. Testing multiple hypotheses is problematic by nature. If no corrections are made for multiple comparisons, significant findings may be observed by chance – i.e. it is too easy to make a Type I error. By contrast, if corrections for multiple comparisons are made, power to detect real differences is lost – i.e. it is too easy to make a Type II error. Therefore we report both uncorrected and Bonferroni corrected *p*-values here, for both the chi-squared and the metric comparisons. The mean measure of divergence (MMD; Freeman Turkey transformation) was also calculated using script for R created by A. Soltysiak. MMD was calculated only between the Iron Age and modern samples; MMDs were not calculated using the Historic Cave sample, given the very small sample sizes for some traits. A principal components analysis (PCA) was performed in Statistica (version 11) in order to further illustrate variability between the modern and Iron Age samples. The *t*-tests were conducted on the regression scores in Excel. For the PCA analysis, Historic Cave specimens were not included because of small sample sizes.

Craniomandibular metrics

A NextEngine 3D Laser Scanner and Scanstudio HD software (version 1.1) were used to create three-dimensional scans of the available cranial and mandibular material. Three-dimensional coordinates for 34 cranial landmarks and 19 mandibular landmarks were then extracted using MeshLab v1.3.1 (Table 1), and a series of Euclidean distances were derived from these landmarks (Table 2). These distances were chosen to capture overall morphology while minimising redundancy. *T*-tests were performed using Microsoft Excel in order to compare the modern and Iron Age sample; Historic Cave specimens were not included as they were represented by teeth only. Again, we report both uncorrected and Bonferroni corrected *p*-values for these comparisons. A PCA was performed in Statistica (version 11) to visually display variation, and *t*-tests were conducted on the regression scores in Excel. Because of missing data, this PCA was by necessity based on only a subset of landmarks.

Results

Dental non-metric results

Table 3 shows the frequencies and sample sizes of the non-metric dental traits for each sample (modern, historical and Iron Age). Table 4 lists the chi-squared *p*-values calculated for each comparison. Between the Iron Age and the modern samples, 6 out of the 25 traits (24%) are significantly different at $p<0.05$. These traits are winging (UI1), UM1 cusp 5, Carabelli's trait, protostylid (LM1), torsomolar angle and LM1 root number. Between the Iron Age and historical samples, only three traits show significant differences (12%) at $p<0.05$. These traits are winging (UI1), canine mesial ridge and LM2 cusp number. Winging is therefore the only trait that is significantly different between Iron Age samples and both the historical and modern samples. However, winging could only be observed on two Historic Cave specimens, the significance of which will be addressed in the discussion. Between the modern and

Table 1: Craniomandibular landmarks extracted from three-dimensional scans

Landmark	Description	Position
Mandible		
GNA	Gnathion	Midline
POG	Pogonion	Midline
INFRA	Infradentale	Midline
MSPIN	Superior mental spine	Midline
MNS	Mandibular symphysis	Midline
MEN	Mental foramen	Bilateral
ALV	Alveolar border of body	Bilateral
IBB	Inferior border of body	Bilateral
GON	Gonion	Bilateral
PGA	Inferior posterior ramus	Bilateral
AJUNC	Inferior anterior ramus	Bilateral
LAT	Lateral mandibular condyle	Bilateral
PSC	Posterior mandibular condyle	Bilateral
COR	Coronoid process	Bilateral
MC	Medial mandibular condyle	Bilateral
MN	Mandibular notch	Bilateral
AR	Anterior ramus	Bilateral
SA	Superior anterior ramus	Bilateral
MFO	Mandibular foramen	Bilateral
Cranium		
ALV	Alveolon	Midline
B	Bregma	Midline
BA	Basion	Midline
G	Glabella	Midline
I	Inion	Midline
INC	Incisivon	Midline
L	Lambda	Midline
N	Nasion	Midline
O	Opisthion	Midline
PR	Prosthion	Midline
NS	Subspinale	Midline
A	Alare	Bilateral
AST	Asterion	Bilateral
D	Dacryon	Bilateral
MXT	Maxillary tuberosity	Bilateral
FMO	Frontomalar orbital	Bilateral
FMT	Frontomalar temporale	Bilateral
FM	Foramen magnum	Bilateral
FMN	Frontal-maxillary-nasal junction	Bilateral
J	Jugale	Bilateral
KR	Krotaphion	Bilateral
MF	Mandibular fossa	Bilateral
MMC	Max maxillary curve	Bilateral
MAS	Mastoidale	Bilateral
OCA	Occipitocondyle (anterior)	Bilateral
OCL	Occipitocondyle (lateral)	Bilateral
ORI	Orbitale (inferior)	Bilateral
ORB	Orbitale (superior)	Bilateral
POR	Porion	Bilateral
SPH	Sphenion	Bilateral
TF	Temporal fossa (posterior)	Bilateral
JRI	Jugular ridge (inferior)	Bilateral
ZY	Zygion	Bilateral
MAX	Maxillary foramen	Bilateral

Table 2: Craniomandibular measurements

	Measurements		
Mandibular	GNA-POG	MEN_R-ALV_R	IBB_R-GON_R
	POG-MNS	INFRA-ALV_L	GON_L-PGA_L
	POG-INFRA	INFRA-ALV_R	GON_R-PGA_R
	GNA-IBB_L	ALV_L-AJUNC_L	PGA_L-PSC_L
	GNA-IBB_R	ALV_R-AJUNC_R	PGA_R-PSC_R
	IBB_L-MEN_L	IBB_L-GON_L	PSC_L-LAT_L
	IBB_R-MEN_R	LAT_L-MC_L	PSC_R-LAT_R
	MEN_L-ALV_L	MSPIN-MFO_L	COR_R-MN_R
	LAT_R-MC_R	MSPIN-MFO_R	COR_L-SA_L
	LAT_L-COR_L	MFO_L-MN_L	COR_R-SA_R
	LAT_R-COR_R	MFO_R-MN-R	SA_L-AR_L
	LAT_L-MN_L	MFO_L-GON_L	SA_R-AR_R
	LAT_R-MN_R	MFO_R-GON_R	AR_L-AJUNC_L
	COR_L-MN_L	AR_R-AJUNC_R	
Cranial	G-N	J_R-MAX_R	NS-MXT_R
	N-FMN_L	FMT_L-J_L	BA-O
	N-FMN-R	FMT_R-J_R	FM_L-O
	N-D_L	SPH_L-KR_L	FM_R-O
	N-D_R	SPH_R-KR_R	FM_L-BA
	N-NS	J_L-MF_L	FM_R-BA
	NS-PR	J_R-MF_R	FM_L-FM_R
	NS-A_L	ZY_L-JRI_L	OCA_L-FM_L
	NS-A_R	ZY_R-JRI_R	OCA_R-FM_R
	D_L-FMO_L	ZY_L-MF_L	OCA_L-OCL_L
	D_R-FMO_R	ZY_R-MF_R	OCA_R-OCL_R
	ORB_L-ORI_L	MF_L-POR_L	OCL_L-FM_L
	ORB_R-ORI_R	MF_R-POR_R	OCL_R-FM_R
	D_L-ORI_L	SPH_L-B	BA-NS
	D_R-ORI_R	SPH_R-B	PR-NS
	D_L-ORB_L	KR_L-AST_L	NS-ALV
	D_R-ORB_R	KR_R-AST_R	I-AST_L
	FMO_L-FMT_L	AST_L-MAS_L	I-AST_R
	FMO_R-FMT_R	AST_R-MAS_R	NS-MXT_L
	ORI_L-MMC_L	POR_L-MAS_L	L-I
	ORI_R-MMC_R	POR_R-MAS_R	I-O
	MMC_L-JRI_L	AST_L-L	A_R-MMC_R
	MMC_R-JRI_R	AST_R-L	J_L-MAX_L
	A_L-MMC_L	L-B	

Table 3: Sample size and frequencies for each trait for each sample

		Modern	Iron Age	Historic Cave
Winging UI1	%	16.0	2.1	0.0
(+ = ASU 1,2 and 4)	*n*	25	47	2
Shovel UI1	%	8.7	7.4	0.0
(+ = ASU 3+)	*n*	23	54	12
Double Shovel UI1	%	0.0	0.0	0.0
(+ = ASU 2+)	*n*	22	63	12
I and C td UI2	%	19.4	12.0	22.2
(+ = ASU 3+)	*n*	31	75	9
C mesial ridge UC	%	91.2	97.1	100.0
(+ = ASU 1+)	*n*	34	68	9
CDAR UC	%	73.5	70.7	85.7
(+ = ASU 2+)	*n*	34	58	7
Hypocone UM2	%	64.9	98.9	100.0
(+ = ASU 3+)	*n*	37	87	5
Cusp 5 UM1	%	84.2	83.9	87.5
(+ = ASU 1+)	*n*	38	93	8
Carabelli UM1	%	92.1	77.3	50.0
(+ = ASU 3+)	*n*	38	75	6
Parastyle UM3	%	0.0	2.8	0.0
(+ = ASU 2+)	*n*	37	108	7
Root no. UM2	%	9.4	7.7	0.0
(+ = ASU 3+)	*n*	32	91	5
P ling cusp LP2	%	0.0	1.0	0.0
(+ = ASU 2+)	*n*	38	100	7
Tome root LP1	%	0.0	1.1	0.0
(+ = ASU +)	*n*	34	88	25
Groove pattern LM2	%	0.0	0.0	0.0
(+ = ASU Y)	*n*	38	76	9
Cusp no. LM1	%	97.4	91.9	90.9
(+ = ASU 5+)	*n*	39	74	11
Cusp no. LM2	%	97.1	96.4	70.0
(+ = ASU 5+)	*n*	34	84	10
Def wrinkle LM1	%	40.0	55.7	66.7
(+ = ASU 2-3)	*n*	35	79	3
DT crest LM1	%	100.0	100.0	100.0
(+ = ASU +)	*n*	33	77	2
Protostylid LM1	%	17.6	12.5	0.0
(+ = ASU 1+)	*n*	34	56	1
Cusp 6 LM1	%	29.0	18.5	0.0
(+ = ASU 1+)	*n*	31	81	1
Cusp 7 LM1	%	91.2	84.2	50.0
(+ = ASU 2+)	*n*	34	76	2
Torso. angle	%	63.6	36.8	0.0
(+ = ASU +)	*n*	33	76	2
Root no. LM1	%	75.0	59.5	54.5
(+ = ASU 3+)	*n*	36	84	11
Root no. LM2	%	63.2	50.0	72.7
(+ = ASU 2+)	*n*	38	90	11
Peg, absent UM3	%	100.0	98.0	100.0
(+ = ASU -)	*n*	12	98	7

Table 4: Chi-squared *p*-values for non-metric dental comparisons among the modern, historical and Iron Age samples

	Iron Age/modern	Iron Age/historical	Modern/historical
Winging UI1	0.027	0.019	0.673
Shovel UI1	0.847	0.331	0.293
Double shovel UI1	—	—	—
I and C td UI2	0.323	0.390	0.850
C mesial ridge UC	0.195	0.000	0.001
CDAR UC	0.770	0.401	0.494
Hypocone UM2	0.962	0.787	0.814
Cusp 5 UM1	0.017	0.908	0.119
Carabelli UM1	0.000	0.257	0.534
Parastyle UM3	0.764	0.520	0.475
Root no. UM2	0.139	0.408	0.180
P ling cusp LP2	0.957	0.642	0.612
Tome root LP1	0.661	0.101	0.565
Groove pattern LM2	0.177	0.653	0.290
Cusp no. LM1	—	—	—
Cusp no. LM2	—	0.003	0.071
Def wrinkle LM1	0.087	0.192	0.048
DT crest LM1	0.448	0.785	0.482
Protostylid LM1	0.001	0.743	0.173
Cusp 6 LM1	0.151	0.201	0.056
Cusp 7 LM1	0.105	0.752	0.194
Torso angle	0.000	—	—
Root no. LM1	0.000	0.574	0.070
Root no. LM2	0.617	0.703	—
Peg, reduced absent UM3	0.536	0.790	—

historical samples, two traits (8%) are significantly different at $p<0.05$: LM1 deflecting wrinkle and canine mesial ridge. Of these, canine mesial ridge was also significantly different for the comparison between the Iron Age and historical material. For the trait deflecting wrinkle the historical sample was once again very small ($n=3$). Because the chance of calculating at least one significant *p*-value (0.05) between any two samples is high (72%), we further adjusted the *p*-value to the Bonferroni correction, at $p=0.002$. Four traits remain significantly different between the Iron Age and modern samples (Carabelli UM1, protostylid LM1, torsomolar angle and LM1 root number), while canine mesial ridge is still significantly different between the Historic Cave sample and both the Iron Age and modern samples. Although correcting the values confirms that the samples are different, it is nonetheless important to look at each trait (e.g. at $p=0.05$) to identify the manner in which these samples differ. The MMD (i.e. phenetic distance) between the modern and Iron Age samples is low at 0.088, again suggesting only a small amount of difference between these groups.

Dental metric results

The 32 dental metric comparisons are shown in Table 5. Between the Iron Age and modern samples, 11 measurements (34%) show significant differences at $p<0.05$. For buccolingual measurements, the first and second molars (upper and lower) are all significantly different. For mesiodistal length, the premolars (upper P1 and P2, lower P1 and P2), the lower canines, the lower first molar and upper first incisor are significantly different. Between the Iron Age and historical samples, 5 of the 30 measurements (17%) were significantly different at $p<0.05$. These measurements are buccolingual lengths of the upper first premolar, lower first and second incisors, lower M2, and the mesiodistal length of the upper P2. Of these, mesiodistal length of the upper second premolar and buccolingual length of the lower second molars are also significantly different for the Iron Age versus modern comparison. Between the historical and modern comparisons, four measurements (13%) are significantly different at $p<0.05$: mesiodistal measures of the upper canine and second premolar and the lower canine and lower second premolar. Of these, mesiodistal measurement of the lower canine and lower second premolar are also significant for the Iron Age versus modern comparison. Mesiodistal length of the upper second premolar is significant for all three comparisons.

Although the use of $p=0.05$ for significance is useful when comparing individual traits, the chances of calculating one significant *p*-value when the samples are actually similar is as high as 80%. In order to detect any real difference between the samples themselves (and not just the traits), the *p*-value was corrected to 0.0016. When this correction was done, only a single measurement differed significantly between the modern and Iron Age samples (buccolingual LM1), and between the Historic Cave and modern samples (mesiodistal UP2). There is no significant difference between the Historic Cave and Iron Age samples. Whether this finding is a result of a small sample size, close biological relationships or a combination of both, is unknown.

Figure 1 shows the dental metric covariance PCA for factor 1 versus factor 2 for the Iron Age and modern specimens. Coefficient ellipses (95%) surround each group. PC1 shows loadings that are all positive, ranging from only 0.030 (mesiodistal lower first premolar) to 0.179 (buccolingual upper second molar), indicating that PC1 is a size variable. PC1 includes 67% of the variance and PC2 includes 7% of the variance (total 74%). The greatest contributions to the first PC are from the buccolingual upper second molar (0.179 loading proportion) and mesiodistal lower second molar (0.159). The smallest contributions to

Table 5: The *p*-values for *t*-tests for each dental metric comparison

	t-test	Modern/Iron Age	Iron Age/historical	Historical/modern
Buccolingual	I1	0.529	0.742	0.739
upper	I2	0.761	0.173	0.402
	C	0.129	0.886	0.380
	P1	0.137	0.043	0.308
	P2	0.395	0.954	0.519
	M1	0.026	0.333	0.980
	M2	0.022	0.080	0.538
	M3	0.572	0.126	0.545
Mesiodistal	I1	0.013	0.655	0.305
upper	I2	0.150	0.739	0.082
	C	0.057	0.156	0.023
	P1	0.006	0.386	0.556
	P2	0.002	0.006	0.000
	M1	0.142	0.994	0.746
	M2	0.627	0.218	0.510
	M3	0.552	0.344	0.440
Buccolingual	I1	0.180	0.018	0.293
lower	I2	0.149	0.029	0.352
	C	0.387	0.963	0.780
	P1	0.244	0.136	0.273
	P2	0.684	0.599	0.698
	M1	0.000	0.141	0.536
	M2	0.005	0.010	0.237
	M3	0.867	—	—
Mesiodistal	I1	0.326	0.876	0.602
lower	I2	0.901	0.306	0.400
	C	0.007	0.089	0.003
	P1	0.034	0.474	0.060
	P2	0.006	0.457	0.031
	M1	0.014	0.924	0.508
	M2	0.103	0.816	0.572
	M3	0.149	—	—

PC1 come from the buccolingual (0.043) and mesiodistal (0.03) lower first premolars. For PC2, the mesiodistal upper second molar contributes the largest proportion (0.613), with buccolingual and mesiodistal upper first premolars contributing the least (less than 0.01). Figure 1 indicates that although there is much overlap between the modern and Iron Age samples, there are some differences in both size and shape, as indicated by the placement of modern specimens at the lower right of the graph. The *t*-tests on the regression scores indicate that the two samples are significantly different for PC1, 2 and 6 (size and two shape factors) at $p<0.05$. At the Bonferroni corrected value of $p<0.005$, differences for PC2 are still significant, indicating shape differences between the Iron Age and modern samples.

Craniomandibular metric results

Table 6 shows the results of *t*-tests between the Iron Age and modern samples for a series of craniomandibular measurements (there were no complete adult cranial or mandibular historical specimens from Historic Cave, only isolated teeth). The table shows the measurements used, sample sizes for each measurement for each category and the mean measurement (in millimetres) for each sample. Sample sizes vary between measurements, depending on preservation and visibility of the landmarks. For the modern sample, each measurement was taken on between 33 and 40 specimens (Table 6). For the Iron Age sample, each measurement was taken on between 25 (NS-PR and INFRA-ALV) and

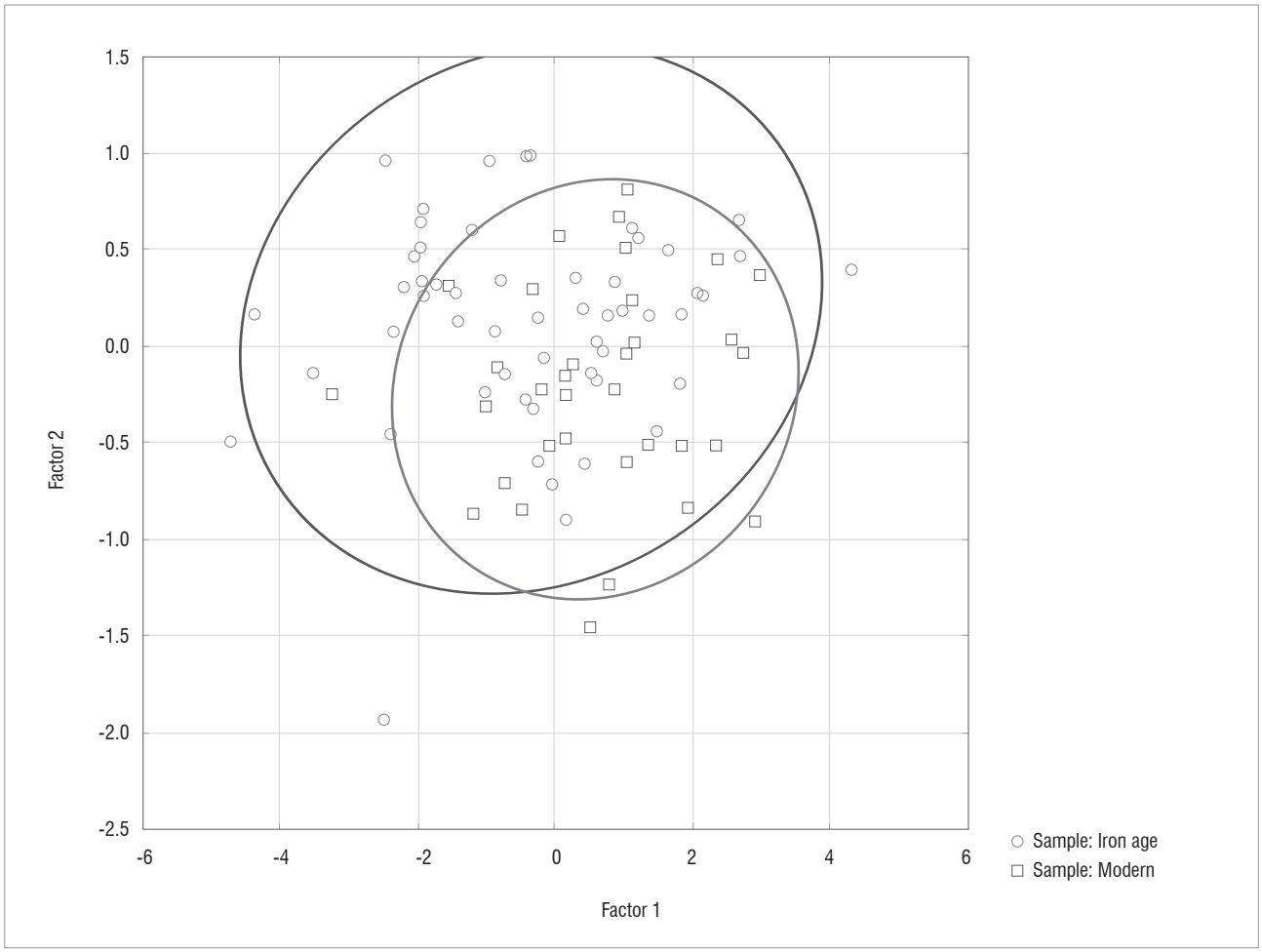

Figure 1: Principal components analysis of dental metric results: scatterplot of factor 1 (67% variance) against factor 2 (7% variance).

61 (SA-AR and AR-AJUNC) specimens. Out of the 62 measurements, 22 (35%) are significant at $p<0.05$ and 17 (27%) are significant at $p<0.01$. Although only 22 measurements are mandibular, 16 of these measurements (73%) show significant differences ($p<0.05$).

Figure 2 shows the results of the craniomandibular metric PCA. To maximise sample size, only 13 measurements, mostly mandibular, were used in this analysis. The first three PCs account for 27%, 18% and 16% of the variance, respectively (total 61%). The other PCs each contribute less than 10% of the variance. For the first component, mandibular ramus (SA-AR; 0.361) and mandibular foramen to gonion (0.197) contribute the most. Gnathion to pogonion, pogonion to the inferior posterior ramus, coronoid process to mandibular notch and mandibular foramen to poronion measurements contribute the least to PC1 (less than 0.005). For PC2, the inferior border of the body to the gonion contributes the most (0.366) and pogonion to mandibular symphysis, coronoid process to mandibular notch and mandibular foramen to poronion contribute the least (less than 0.005). PC3 has large contributions from gonion to inferior posterior ramus (0.254) and mandibular foramen to gonion (0.296). Figure 2a shows PC1 against PC2 for modern and Iron Age specimens. Although there is much overlap, modern specimens are more concentrated on the left of the graph and Iron Age specimens on the right (i.e. along PC1). Figure 2b (PC2 against PC3) illustrates complete overlap between the Iron Age and modern samples for either PC2 or PC3, although the Iron Age sample does appear to be more variable than the modern one (this pattern is also seen in Figure 2a). The *t*-tests conducted on the factor scores derived from the craniomandibular measurements of the specimens reveal that PC1 (size) and PC4 show significant difference between the Iron Age and modern samples at $p<0.05$. PC1 remains significantly different when the Bonferroni *p*-value is adjusted to 0.004, showing that differences between these groups are statistically meaningful.

Discussion

The results indicate that there is a large amount of phenotypic (and presumably underlying genetic) similarity among the Iron Age, historical and modern samples. This finding is consistent with archaeological research as well as previous genetic and linguistic work that support continuity between precolonial and modern Bantu-speaking peoples and/or cohesion among modern Bantu-speaking peoples.[7,20,27-29,32,45] Continuities through the ceramic sequence suggest that ancestral forms of Shona were spoken in the first millennium AD[12], and, more specifically, the archaeology shows direct cultural continuity between second millennium AD agropastoralists and historical Sotho–Tswana[15] and Nguni speakers[13]. Despite these overall continuities, significant regional demographic shifts resulted in linguistic and cultural entanglements, and the creation of new identities (e.g. a Venda identity emerged in the 16th century AD from intermarriage between Shona and Sotho speakers[46]).

It is not surprising that the data in this study indicate homogeneity in the measured traits between the Iron Age and historical samples. The violent nature of the mfecane early in the 19th century led to the dispersal of people, the fragmentation of polities and the reformulation of people into new political units. The small group of Ndebele, estimated to be about 300, who left KwaZulu-Natal under the leadership of Mzilikazi, increased to about 20 000 in the late 1820s – in the early years of the Ndebele state in the present-day Rustenburg area.[47] This example underpins that while the initial numbers were low, Mzilikazi 'accumulated' people as his settlement focus shifted further to the west and included a significant number of Sotho–Tswana speakers. While the scale of these

Table 6: Craniomandibular measurements, associated sample sizes and means (in mm) of the modern and Iron Age samples

	Modern (*n*)	Iron Age (*n*)	Mean, modern	Mean, Iron Age
G-N	40	40	8.9	9.8
N-FMN	40	40	6.3	6.4
N-D	40	41	11.7	11.6
N-NS	38	33	50.2	49.3
NS-PR	34	25	17.7	18.9
NS-A**	37	39	19.4	18.3
D-FMO**	40	39	42.7	44.2
ORB-ORI	40	41	35.6	35.7
D-ORI	40	41	33.8	33.5
D-ORB	40	40	27.5	27.8
FMO-FMT	40	38	6.7	6.8
ORI-MMC	39	47	22.1	23.2
MMC-JRI	39	49	12.2	11.8
A-MMC	38	45	27.3	28.4
J-MAX*	38	30	13.5	15.5
FMT-J	40	35	22.3	21.8
SPH-KR	36	43	9.1	8.9
J-MF**	40	34	42.8	45.5
ZY-JRI*	40	26	36	40.2
ZY-MF	40	26	24.8	25.4
MF-POR	40	51	13.7	14.1
SPH-B	37	40	92.4	91.3
KR-AST	36	41	84	86.4
AST-MAS	40	45	46.4	48
POR-MAS	40	52	31.3	31.6
AST-L	39	42	86.9	85.4
L-B	39	41	112.6	113.3
L-I	39	44	63.2	66.5
I-O	40	38	45.3	44.2
NS-ALV	35	27	45.3	46.6
I-AST*	40	47	66.3	63.4
NS-MXT	35	34	54.4	55.8
BA-O	40	32	39.6	40.3
FM-O	40	33	27.1	30.2
FM-BA	40	34	24.4	27.5
FM-FM	40	33	31.8	34.8
OCA-FM	39	36	19.8	22.7
OCA-OCL	38	40	15.1	15.3
OCL-FM	39	36	13	16.7
BA-NS	38	25	92.2	94.5
GNA-POG**	38	58	8.7	9.5
POG-MNS	37	56	14.7	14.3
POG-INFRA*	34	30	22.6	24
GNA-IBB	38	52	25.6	25.5
IBB-MEN**	38	65	13.8	14
MEN-ALV**	37	52	15.5	16.3
INFRA-ALV	33	25	26.7	27.2
ALV-AJUNC**	33	47	33.1	34
IBB-GON**	38	60	59.5	61.9
GON-PGA	38	62	18.7	17.4
PGA-PSC**	38	40	37.4	40.3
PSC-LAT	35	36	14.9	14.6
LAT-MC**	34	31	19	20.1
LAT-COR**	35	38	32.1	34.5
LAT-MN*	35	37	20.5	21.6
COR-MN**	38	52	19.6	20.7
COR-SA	38	58	12.4	13.8
SA-AR**	38	61	10.4	13.8
AR-AJUNC**	34	61	20	15.9
MSPIN-MFO**	38	48	74	74.8
MFO-MN**	38	52	21.9	22.7
MFO-GON**	38	60	21.5	23.2

*$p<0.05$; **$p<0.01$

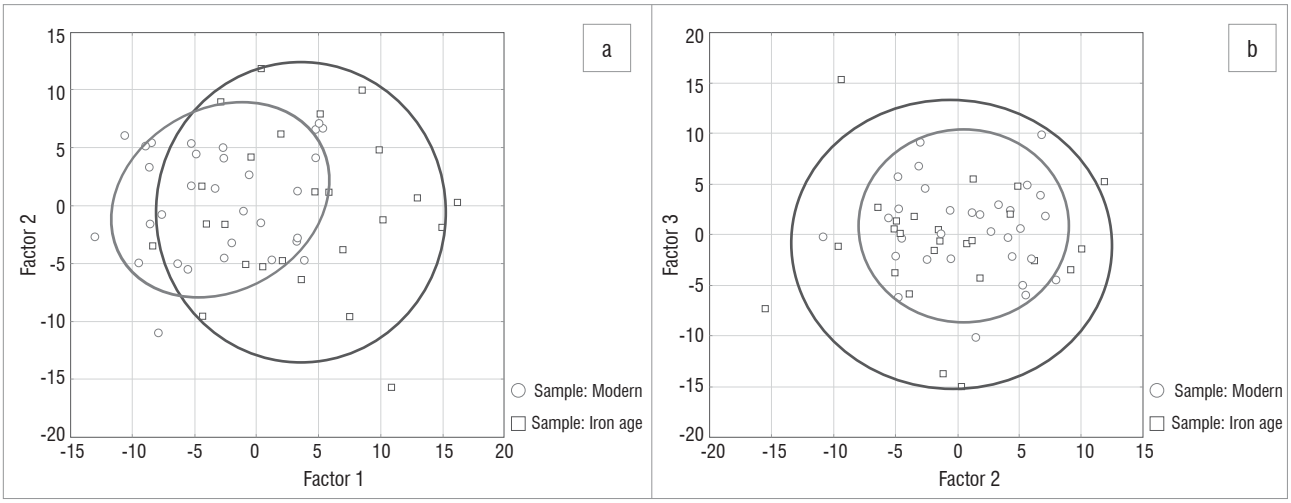

Figure 2: Principal components analysis of craniomandibular dental metric results: (a) scatterplot of factor 1 (27% variance) versus factor 2 (18% variance) and (b) factor 2 versus factor 3 (16% variance).

demographic shifts in the early 19th century may have been larger, the archaeology of both first and second millennium agropastoralists shows that regional demographic movement was essential to the political process. The examples of the origins of Venda and the earlier precolonial Nguni diasporas underpin demographic and cultural fluidity.[12]

Despite this overall pattern of similarity among the Iron Age, historical and modern samples, there are some important differences among these groups. Where dental traits do differ (both discrete and metric), the Iron Age sample tends to be more similar to the historical sample than it is to the modern one, suggesting recent, continuous gene flow from other populations in historical and modern times. This increasing gene flow could stem from a number of historical causes. For example, interaction between hunter–gatherers and farmers is observed frequently in the archaeological record,[5,12,45,48] and it is possible that admixture occurred throughout this period and may have increased because of more recent historical pressures. This scenario is supported by ongoing research on the dentition of Khoesan people that indicates that there is more similarity between a recent Khoesan sample and modern Bantu speakers than between the Khoesan sample and the Iron Age samples studied here.[41] The relationship between the Historic Cave sample and the other samples might reflect increasing population pressures and interactions through time, resulting in them being morphologically intermediate between the Iron Age sample and modern Bantu speakers. This Historic Cave sample comes from the siege of October 1854 when the Kekana (a Ndebele group) took refuge in this large cavern complex in the Makapan valley as a response to a Boer commando seeking revenge for the murder of Trekboers in the previous month.[18,49] There was substantial mortality during this siege. It is important to note that while the results do indeed indicate an intermediate position for the Historic Cave material, larger samples (and more sites) are needed in order to better evaluate this interpretation. Further research on the dentition of other colonial period peoples is necessary to advance our understanding of variation and morphological affinities at this time.

In more recent times, our expectation is that admixture increases, which again may explain the continued divergence of the modern samples from the archaeological ones. The metric and non-metric dental comparisons show a greater similarity between the Iron Age and Historic Cave samples than between the modern and Historic Cave samples, supporting increased levels of gene flow into these groups in recent times. The intensification of trade (particularly in ivory and slaves) in the second half of the 18th century and through the 19th century took place in a context of expanding European mercantile interests and both 19th-century historical contexts mentioned above were inextricably linked to this context.[18,47] Despite the negative interactions there was also admixture between Bantu speakers and Europeans, which is clearly evident in the modern sample and has also been observed in Mozambican populations.[20] This admixture is typically sex biased (European Y-chromosome haplotypes), which is not surprising given that Europeans, specifically the Portuguese, colonised the coast and parts of the interior of Mozambique from the 17th century.[50]

In addition to offering insight into the morphological effects of admixture as detailed above, this study is also important because it is the first to apply standardised dental anthropology techniques to investigate historical relationships between present-day and archaeological southern African populations. Many dental anthropological studies have focused on modern variation across broad geographical regions, with sub-Saharan Africa representing a distinct dental complex.[30,35,36,38,51] Both non-metric and metric dental studies have also focused on variation among non-sub-Saharan-African archaeological samples, indicating continuity, gene flow and morphological change in archaeological samples over time.[34,37,39,52-54] Although these studies have successfully addressed questions about variability and genetic identity using archaeological and contemporary samples, little work using these methods has been done in southern Africa. Early research by Shaw described the dentition of modern-day Bantu speakers,[55,56] but was unstandardised. Additionally, Jacobson's study which shows there is low variability among modern Bantu speakers, is difficult to compare with more recent standardised dental research.[29] Kieser et al.[57] evaluated changes in tooth size between living and recent-historical Bantu speakers drawn from the Dart Collection,[57] indicating larger mesiodistal and buccolingual lengths within the 19th century. This study, however, is the first to extend dental comparisons into archaeological samples.

Finally, this study has important implications for understanding variation within the modern sample. The research presented here – not unexpectedly – shows a degree of historical admixture in the Raymond A. Dart Collection of human skeletons. But, importantly, it also suggests that it might be possible to use archaeological samples to better understand the biological affinities of these modern specimens using skeletal indicators. This is relevant because there is not necessarily a relationship between the biological history and 'tribal' identities of specimens in the Dart Collection because they are categorised based on surnames.[42] Consequently, the biological distinction between the modern and Iron Age samples is a further reminder that modern samples do not provide a comparative baseline for the past.

Conclusion

Three important conclusions can be made from this research. Firstly, there is general similarity between Iron Age farmers, modern Bantu speakers and an historically very specific Ndebele group. This similarity supports a general genetic continuity between precolonial and historical agropastoralists and modern people in southern Africa.

Secondly, despite these similarities, there are more differences between the Iron Age and modern samples than expected, given the seeming homogeneity of both Iron Age and modern Bantu speakers indicated by previous research. This observation demonstrates gene flow between Iron Age descendants and other groups in historical and modern times, and cautions against using modern Bantu speakers as baselines for understanding variation in the past. Finally, the Historic Cave sample appears to be morphologically intermediate between the Iron Age and modern samples, once again supporting the conclusion of increasing gene flow into these groups through time, although small sample sizes reduce the value of this conclusion.

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Authors' contributions

K.A.W. collected the data, analysed samples, performed calculations and wrote the manuscript. R.R.A. conceptualised the project, provided technical and methodological input and helped write the paper. S.H. provided theoretical input and helped write the paper.

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Policy required for entry of DNA profiles onto the National Forensic DNA Database of South Africa

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The recent *Criminal Law (Forensic Procedures) Amendment Act (2013)* provides a definition for forensic DNA profiles and, in so doing, states that medical information about an individual may not be revealed through a forensic DNA profile. Yet chromosomal abnormalities can exhibit as tri-allelic patterns on DNA profiles and such information can expose medical conditions such as Down syndrome. This short report highlights this concern and suggests a policy be created for the entering of such DNA profiles onto the National Forensic DNA database of South Africa.

In South Africa, the use of DNA within a forensic context has largely been accepted as the gold standard of evidence for human identification. The value of DNA in forensic science lies both in its objectivity as well as in its highly discriminatory nature, and it currently serves a pivotal role in the courtroom.[1,2] A recent case from the Supreme Court of Appeal, *S v SMM* 2013 (2) SACR 292 (SCA), provides a classic example: the offender who was sentenced to life for the rape of his 13-year-old niece appealed against both his conviction and sentence, but the appeal against conviction was dismissed immediately, as the DNA testimony was sufficient evidence of penetration.[3]

The passing of the *Criminal Law (Forensic Procedures) Amendment Act (2013)* signified the satisfying culmination of a persevering journey by the forensic community in South Africa. The 'DNA Act' amends several other Acts in terms of collecting and retaining bodily samples for forensic identification and intelligence purposes; it also provides regulations with regard to the formation and maintenance of the National Forensic DNA Database of South Africa (NFDD).[4] This very necessary section of legislation serves to fill the gap in terms of allowing current forensic methodologies to be used to their full potential, especially in an era in which the need for applied innovation and technology is so crucial.

DNA profiling is a method used in forensic science to aid identification of potential suspects as well as to link scenes of crime together. It relies on the amplification and subsequent sizing of specific repetitive markers within DNA to generate a DNA profile – essentially a set of numbers which, when statistically analysed, can be highly discriminatory between individuals.[5] Various commercial kits are available. South Africa currently employs the AmpFlSTR Profiler Plus™ PCR kit which analyses 10 markers, including Amelogenin, the sex determining marker, although we are in the process of upgrading to the AmpFlSTR Identifiler Plus™ PCR kit, which analyses 16 markers including Amelogenin.[2,6] Within the forensic biology unit at the South African Police Service, DNA profiling is carried out according to standard operating procedures and quality checks are performed, especially during the interpretation and reporting phases. Once a profile has been generated, interpreted and reported, it is committed to the NFDD through software called STRlab™.

Clause 15E (I) in chapter 5B of the DNA Act, defines a forensic DNA profile as

> *…the results obtained from forensic DNA analysis on bodily samples taken from a person or a crime scene, providing a unique string of alpha numeric characters to provide identity reference: Provided that it does not contain any information on the health or medical condition or any information on the predisposition or physical information of that person other than the sex of that person.*[4]

Clause 15G (5) of the same chapter specifies that the indices on the NFDD

> *…shall not contain the following information derived from a bodily sample which was taken from a person:*
>
> *(a) The appearance of the person, other than indicating the sex;*
>
> *(b) medical information of the person;*
>
> *(c) historical information relating to the person; and*
>
> *(d) behavioural information of the person.*[4]

Therefore, a DNA profile and the NFDD may not contain details regarding the individual's appearance (excepting sex) nor any medical, historical or behavioural information. However, many of the markers initially identified for DNA profiling came from the Cooperative Human Linkage Center (CHLC) (http://www.chlc.org) which forms the basis of genome scans used for genetic linkage studies.[7]

Numerous association studies have been carried out, with one resulting in the exclusion of the HumARA marker in DNA profiling kits because of its direct association with spinal and bulbar muscular dystrophy.[8] Yet other studies have given rise to a set of complex, and at times contradictory, results[9,10], specifically with regard to the TH01 marker[11–15]. Kimpton et al.[16], working with the European DNA Profiling Group, prematurely acknowledged that

> *it is likely that many or possibly most* [forensic markers] *will eventually be shown to be useful in following a genetic disease or other genetic trait within a family and therefore*

> *this possibility must be recognised at the outset of the use of such systems.*[16]

Although forensic markers could prove to be linked with genetic disease, such associations are not blatantly obvious upon DNA profile interpretation. What is far more striking is the notion of chromosomal abnormalities. For example, D21S11 on chromosome 21 is an eligible marker which can be used to test for trisomy-21 (Down syndrome)[17,18] and the D21S11 marker is included in the DNA profiling kit used in South Africa. Similarly, D18S51, which is also a forensic marker, can be used to test for trisomy-18 (Edward syndrome).[19] Down and Edward syndromes could also occur via mechanisms other than a third chromosome (trisomy), such as copy number variation or duplication of a part of a chromosome, which could yield varying levels of pathogenicity. DNA profiling, however, is capable of revealing tri-allelic patterns at any of its markers[20–22] and thus could expose potential chromosomal abnormalities during the interpretation of results. Although further testing would be required to confirm Down or Edward syndromes – which is not performed in routine DNA profiling – a tri-allelic pattern at the D21S11 or D18S51 marker would certainly be suggestive of these syndromes. Not only can these DNA profiles reveal potentially medically sensitive information, they can simply be committed to the NFDD via STRlab™.

Although these markers are included in several DNA profiling kits globally, it is not necessarily statutory in other countries that DNA profiles may not contain medically sensitive information, as is the case in South Africa. In the United Kingdom, for example, the D21S11 marker is analysed and Down syndrome may be revealed; however, ethical guidelines exist to regulate the process of entering medically sensitive information onto the database to protect data of this nature.[23,24] Alongside the European Network of Forensic Science Institutes, the National DNA Database Strategy Board and Working Group stipulate guidelines specific to the United Kingdom for submitting DNA profiles onto its National DNA Database. Linked to this, an ethics group was formed in 2007 to independently offer advice on database operations.[25] For example, when the confirmed results of a rare allele or tri-allelic pattern are submitted to the database, the locus is given a failed designation (F, F), ensuring that a potential medical condition is kept confidential. Although this method favours the exclusion of a marker's information which could possibly increase statistical probabilities, it nevertheless guarantees medical confidentiality, even if the tri-allelic pattern was a non-pathogenic mutation or anomaly. Surely a similar policy or set of guidelines should be implemented in South Africa to protect medical confidentiality? If not, does our current DNA profiling system meet the requirements set out by the law?

The very definition of a forensic DNA profile provided in the DNA Act (clause 15E (l)) is refuted by the fact that chromosomal abnormalities can be detected using various DNA profiling kits and thus medical conditions can potentially be exposed. Furthermore, clause 15G (5) is also contested as there is no formal policy regulating the data input to the NFDD. Changing the kit used for DNA profiling is not necessarily the answer to create consistency between DNA profiling methods and the law, because using different markers will not only be a costly and timely expense, but also decrease the potential or statistical significance of matches with individuals who have been profiled on the current system.[26] Furthermore, using different markers could limit the potential of cross-country comparisons which could have a significant impact on loss of evidence as well as costs. Similarly, discounting the clause relating to medically sensitive information not being stored on a database would be in opposition to human rights. Rather, the definition of a DNA profile should be altered and a policy be implemented to regulate the process of entering data on the NFDD. These are concerns which the National Forensic Oversight and Ethics Board (clauses 15V and 15Z) could possibly address during their oversight of the ethical, legal and social implications of the NFDD. In addition, access to the NFDD should also be defined.

While the passing of the DNA Act is a necessary step to fight crime in South Africa, legislation surrounding it should enable the database to operate at its full potential, and as Morris succinctly stated in a recent editorial in this journal, 'not everyone is happy'[27]. We need to acknowledge and accept that forensic DNA markers may be associated with medical conditions, especially chromosomal abnormalities, but this association does not need to detract from the optimal utilisation of the NFDD. A solution in the form of amending the definition of a forensic DNA profile as well as introducing a policy for entry of DNA profiles onto the NFDD would suitably satisfy human rights activists and the forensic community alike. In a nation where crime and recidivism rates are extremely high, the forensic DNA process needs to be a foolproof system, commensurate with international quality standards and compliant with South African law.

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Galls induced by the introduced biological control fly Dasineura rubiformis *on the invasive Australian tree* Acacia mearnsii. *The formation of galls prevents seed production and substantially reduces the invasive potential of the tree (photo: Fiona Impson). Van Wilgen and colleagues review the contributions of the Centre for Invasion Biology in the field of invasion science over the last 10 years on pages 8–19.*

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