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Development pathways for reducing inequality and carbon emissions

Draft 2018 White Paper on Science, Technology and Innovation

Recent emergence of CAT5 tropical cyclones in the South Indian Ocean

Potential of marula waste for the production of vinegar

Econometric models to understand unemployment in South Africa

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Cover caption
Tulbaghia violacea (photo: Krzysztof Ziarnek/CC-BY-SA-3.0).
In an article on page 35, Madike and colleagues report on the genotoxicity of aqueous extracts of *Tulbaghia violacea* – a plant commonly known as wild garlic and used in traditional medicine for the treatment of various ailments.

Does more and better research result in greater and effective impact?

Scholars from almost all disciplines play – directly or indirectly – at least two major roles in relation to publishing the results of their research. The first, and most obvious, is that they share their research findings with fellow researchers, to add to and enrich (it is to be hoped) the store of knowledge in their field, and to enable debate around the nature of their findings. The second, while almost as important but less obvious, is that they share their findings and the implications of their findings with the public at large, including policy- and decision-makers.

Writing in the *Scholarly Kitchen* late last year, David Crotty[1] pointed out that 'Publishing is a service business, and over time, offering that service to the broader community has become one of the main ways that [can generate funding]'. A recent article published in the *South African Journal of Science* shows clearly how important both roles are in adding to knowledge, informing the pubic of important issues – and generating considerable debate. Within 2 weeks of its publication, Jennifer Fitchett's[2] article on CAT5 tropical storms in the South Indian Ocean received 450 views on the journal website and reached an audience of over 800 on Facebook and 3500 on Twitter; the article was also reported on by seven major print and online newspapers. So, as well as being read (and debated) by scientists in the fields of climatology and climate change, the paper has been accessible to the wider public. Most of the broader audience agree with the conclusions of the paper, some (inevitably) disagree, but the issue is that, whether through the journal website or a media report, a wider community of readers has been able to access the findings of the paper and give consideration to their implications.

Assessing the extent to which scholarly publishing in South Africa is developing and changing is, therefore, an important role for the Academy of Science of South Africa (ASSAf). The information arising from this role is also an important source for scholars in general (including for their own disciplines), and especially for those who work in the fields of bibliometrics and scientometrics. As a result, ASSAf commissioned a Consensus Report on *Research Publishing in South Africa*[3] which was published in 2006. From the start, the report stated that:

> *The strategic goal that is the point of departure for this ensuing six chapter Report is to help develop and maintain a robust national system of innovation that contributes materially to the sustainable prosperity of all South Africa's people.*[3]

In other words, the work addressed not only the two roles of scholarly publishing with which this Leader opened – but extended the significance of both into the realm of contributing 'materially' (substantively) to the greater social good.

The Introduction made it clear that, amongst other things, 'South Africa occupies the paradoxical position in the arena of research publishing of being a dwarf internationally and a giant on the African continent'.

It went on to report that about 3500 papers with at least one South African author address were indexed by the then Institute for Scientific Information (ISI) in 2000, representing about 0.5% of all papers in the three major databases of that system, covering approximately 5500 selected international journals in science, engineering and medicine, 1800 in the social sciences, and 1200 in the arts and humanities.[3]

A second report by ASSAf titled *Twelve Years Later: Second ASSAf Report on Research Publishing in and from South Africa (2018)*[4] will be released in 2019. Some remarkable changes have taken place in the field of scholarly publishing over those 12 years. A few conditions remain more or less the same – but the fundamental issue of the public good has not changed, other than to be even clearer now. Not unexpectedly, this report is longer and more detailed, and draws on a number of focused research projects in the fields of bibliometrics and scientometrics that have been conducted since 2006. The new report benefits, then, from vastly more data than were available 12 years ago.

Disappointingly, the 2006 assessment that South Africa is 'a giant on the African continent' still holds true. Research output has improved in a number of African countries, but the improvement in South Africa outweighs those changes, with South Africa still producing over 50% of Africa's output (which totals somewhere between 1% and 2% of global research publications depending on how the figures are calculated).

The South African increase is substantial: from 3550 publications noted in the 2006 report to 15 542 for 2014. This growth has moved South Africa from 34th to 28th position in the list of top research producing countries in the world.

The *Twelve Years Later* report provides valuable insights, backed by substantial sets of data, into the changes that have taken place since the publication of the 2006 report, for books and chapters in books, apart from journal articles.

Which brings us back to the beginning. Set against the improvements, however, is the question of the impact that the great improvements in research output have had and are having on the public and on policy- and decision-makers. Does research on innovation lead to greater, and more effective innovation? Or do papers on the likely impacts of climate change or of fracking have an impact on government policies and actions? If not, there are significant audiences still to be reached and convincing cases to be made.

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Radio, like you've never read it before

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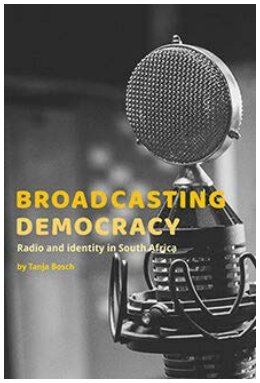
Broadcasting democracy: Radio and identity in South Africa



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The story of radio in South Africa is closely intertwined with the country's struggle history, its political transition and its contemporary societal dynamics. Radio remains the most widespread, affordable and available mass medium in the country and is consumed more than any other mass media product by South Africans. Against this backdrop, University of Cape Town media scholar Tanja Bosch provides an engaging and well-researched account of how different radio formats and stations in South Africa emerged and evolved over recent decades. She chronicles in detail how radio has changed since the fragmentation and state control that characterised the apartheid era to the time that the airwaves were liberalised with the advent of democracy and beyond. Overall, the book is a persuasive account of the broad reach of radio, its transformative potential and its role in shaping cultural identifies in our democracy.

Following the introductory chapter, the next four chapters are devoted to the histories and current challenges facing public service radio, community radio and commercial talk radio. These are followed by case studies of specific radio stations, exploring how and why specific stations continue to be associated with specific racial identities. The chapter on community radio provides a particularly insightful perspective on the unique potential of community radio as a potential 'voice of the voiceless', but also discusses how this potential continues to be limited by the ongoing challenges of financial and operational sustainability. The penultimate chapter focuses on 'radio convergence and the online environment' and highlights how websites, live streaming and social media platforms are changing the face and nature of radio, including a growing number of radio stations that broadcast exclusively online. In the context of thinking about radio as a tool for public engagement, it is noteworthy to see how social networking sites are increasing opportunities for audience growth and interaction, including the growth of citizen journalism. In the concluding chapter – on the future of radio in South Africa – Bosch reflects once more on the complexity of radio consumption in South African society and audiences' strategic choices of the stations to which they listen and their strong affiliations to particular stations, along with its implications for shaping the identities of South Africans. She concludes that this is significant, as 'the lines of race and class that appear in society are mirrored in radio listening and participation'.

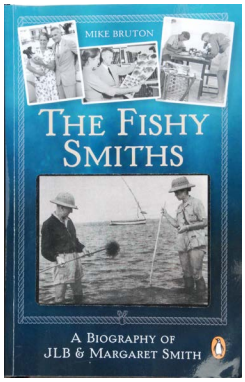
The book was inspired by Bosch's thesis on community radio and public identity, and is largely structured, written and referenced like an academic text. However, in between facts, legal references and theoretical discussions, Bosch weaves the stories of high-profile people and significant events that shaped (and continue to influence) the narrative around radio in South Africa. She provides compelling accounts of controversies, allegations, investigations, corruption and politically motivated editorial decisions. In this way, she brings the history of radio to life and illustrates its ongoing power and centrality in the media landscape. In support of her argument about the central relevance of radio in a democratic society, she provides evidence that radio not only has the widest reach of all mass media channels in South Africa, but that its popularity and penetration continue to grow.

Radio as a tool for democracy and a space for societal engagement is a central theme throughout the book. Bosch argues that radio stations – each with its own unique culture and characteristics – actually represent autonomous systems of cultural activity in our society. Her reflections on radio audiences as active consumers of radio, and people's motivations to tune into (or even call into) a particular radio station, are enlightening. Bosch concludes that 'radio plays a key role in shaping the identities of South Africans, and serves as a vehicle for them to "try on" and "perform" these various identities'.

Reading this book reminds one of how far we have come in terms of transforming mass media in South Africa, but also highlights that we still have much work to do in terms of realising the potential of radio as a collective voice for people who need to be heard and as a space for constructive engagement and identity building.

Tanja Bosch is an associate professor and media studies scholar at the Centre for Film and Media Studies at the University of Cape Town who did her doctoral research on community radio in South Africa. Her in-depth knowledge of the South African mass media environment, as well as her lived experience of radio as a producer, news reader and station manager, are clearly evident in the text. The text is highly accessible and should be a valuable resource for mass media scholars and also appeal to a wider readership.

BOOK TITLE:
The Fishy Smiths: A biography of JLB & Margaret Smith



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A tale of unusual dedication: The lives of JLB and Margaret Smith

Southern Africa is home to almost 10% of the world's marine fishes, drawn from three major biogeographic zones (Indo-Pacific, Atlantic and Antarctic). Our modern understanding of this remarkable diversity is due in no small part to the dedication and hard work of James Leonard Brierley ('JLB') Smith, and his wife Margaret Smith, whose lives were dedicated to laying the foundation of ichthyology in South Africa. JLB Smith began his career in science as a chemistry lecturer. He was married for 14 years to his first wife Henrietta (née Pienaar) with whom he had three children. Following their divorce, he married one of his chemistry students, Mary Margaret Macdonald; together they forged remarkable careers in ichthyology.

In *The Fishy Smiths*, Mike Bruton documents the lives of these two extraordinary scientists. The Smiths led fascinating lives and lived at a time when the biological world around them was largely unexplored. Three themes in particular provide a framework around which this book is structured. The first is the discovery of a living coelacanth in 1939, and the 13-year quest that led to the discovery of a second specimen in 1952. These discoveries were of immense scientific importance, and they changed the course of ichthyology in South Africa. The second was the publication in 1949 of *The Sea Fishes of Southern Africa*, which provided scientists and the South African public with a comprehensive account of the fish fauna of the region. The third was the publication of a popular account of the story of the coelacanth, entitled *Old Fourlegs*, which Mike Bruton has called (arguably quite correctly) 'the best fish book in the world'.

The Coelacanth saga (Smith apparently always used a capital C when referring to this fish) is well known, as many books have covered the story of its discovery. The salient points are covered again, in some detail, in *The Fishy Smiths*. They include the dramatic discovery of the first specimen by the young curator of the East London Museum (Marjorie Courtenay-Latimer); the long search that led to the discovery of a second specimen in the Comores; and the daring dash in a South African Air Force Dakota (later dubbed 'the flying fishcart') to retrieve it. JLB Smith was the sole author of the subsequent publication of the discovery in *Nature*, and, remarkably, the paper contained not a single reference to any other work in the field. In fact, the only person that JLB included as a co-author in any of his 213 ichthyological publications was his wife Margaret. He was a loner.

The publication of Austin Roberts' now famous book *The Birds of South Africa* led to the idea of a similar book on sea fishes. *The Sea Fishes of Southern Africa* turned out to be an enormous undertaking. Many fish-collecting expeditions had to be undertaken to the remote coasts of eastern Africa, where transport, food and water could only be obtained with difficulty, and conditions were downright dangerous. The Smiths faced marauding man-eating lions, venomous snakes, venomous and poisonous fish, sharks, strong currents and rough seas, and exposure to a host of diseases including bilharzia, hookworm, typhus, malaria, blackwater fever and fungoid infections. They spent all their waking hours collecting, preserving and cataloguing fish specimens for later description and illustration. They used any and all means available to collect fish, including dynamiting the reefs. On a trip to Aldabra, for example, they collected 10 000 fish specimens in just 3 days using explosives, something akin to mass slaughter that would be unthinkable today. The book had to be adequately illustrated, and the brunt of this work fell to Margaret. The first edition of *The Sea Fishes* contains over 900 colour illustrations of fish species, 685 of them by Margaret Smith. Each painting took between 8 and 60 hours to complete to the required standard. It is estimated that 30 000 hours of work by several people were crowded into 3.5 years to produce this book. *The Sea Fishes* was an instant success, regarded by many as the best illustrated natural history book yet published anywhere in the world.

Old Fourlegs is JLB Smith's personal account of the discovery of the Coelacanth, written for a broad audience. He was persuaded to write it by his wife following an incident in which he nearly drowned – she was of the opinion that only he could tell the story properly, and that he had better do it soon. We are told that 'he wrote the book, in longhand with a pencil and notebook, in three 10-day spells while floating on the Knysna Lagoon in his boat, accompanied by his dog, Marlin; these were apparently the only circumstances that allowed him to write undisturbed'. The detail in the book is testimony to his powers of recall. It rapidly became an international bestseller, and put South African science on the map to the same extent as when Chris Barnard performed the world's first heart transplant.

JLB Smith was a complex character, viewed by people either as very kind and helpful, or as rude and self-centred. Apparently, if you demonstrated an interest and worked hard, you would fall into the first category, but this was a man with an incredible work ethic, who did not suffer fools gladly, and who would ignore you if you did not live up to his high expectations. He was something of an introvert, but at the same time an excellent teacher and communicator. Because he was both a serious scientist and an avid angler, he was able to write for a broader public, adding to the appeal of his books. He suffered from poor health all of his adult life, as a result of having contracted tropical diseases while in the military. When he married Margaret in 1938, his doctors did not expect him to live longer than another 5 years, yet, by adopting an austere lifestyle that included regular rigorous exercise and a frugal diet, he lived for another 30 years. Not wanting to become a burden to people, he took his own life shortly after his 70th birthday.

Margaret Smith provided an immense amount of support for JLB throughout their 30-year marriage. She helped him with tasks for which he did not always have the strength, followed his austere lifestyle, protected him from disturbance by many people who sought his advice, and accompanied him on all of his collecting expeditions. She cut her hair short and wore it in a unassuming bun, dressed simply, and wore no makeup. JLB named

several fish species after his wife, and in one description he noted: 'This exceptionally beautiful creature is named as a small tribute to my wife, whose contribution to all phases of our work is probably greater than my own'. Following JLB's death, Margaret underwent a metamorphosis, abandoning much of the sombre lifestyle she had followed up to then, and becoming much more outgoing. She also set about cementing her late husband's legacy, establishing the JLB Smith Institute of Ichthyology and becoming its first director (despite having no formal qualification in the field).

The Fishy Smiths is a highly informative book, packed with detail about the lives of two South Africans who left an enviable legacy in science. It covers the lives of others, too, with chapters on Marjorie Courtenay-Latimer, and JLB and Margaret's son William Smith, who was also an outstanding teacher. For those bibliophiles with an interest in books on natural history, *The Fishy Smiths* also contains a wealth of information about, and illustrations of, the books published by the Smiths, those written by other authors from the JLB Smith Institute, and those written about the Coelacanth. This book is about a unique couple whose talents and shortfalls complemented each other perfectly. They formed a formidable and inspiring partnership that changed the course of ichthyology in Africa and beyond. *The Fishy Smiths* is highly recommended reading for scientists, naturalists, anglers and historians.

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Reflections on demonstrating development-oriented innovations in South Africa

Innovation demonstrations are an important means of first-time testing and fine-tuning innovations outside of the laboratory. Through demonstrations, scientists shift the focus from research and innovation quality and novelty, towards issues of acceptability, usability and value-addition for different social groups. It is erroneous to assume that usefulness will follow simply because the technical aspects of the innovation meet scientific standards. South Africa is intent on improving its science, technology and innovation (STI) capabilities, and promoting the use of STI to achieve social development outcomes. Science councils and universities are developing technologies aimed at improving and expanding access to basic municipal services and recent practical work involves demonstrating these among the local poor in rural areas as a means to promote inclusive development.[1] These innovations include water, sanitation and energy technologies. They are often combined with information and communication technologies (ICTs) or require access to ICTs to ensure that they function.

Using provisional results from the monitoring and evaluation of the Innovation Partnership for Rural Development Programme (IPRDP), we reflect on some of the challenges observed in relation to implementing the innovation demonstration process. These challenges are drawn from the perspective of the multiple actors involved in the innovation demonstration process using a range of methods. Our observations point to the need for scientists and researchers to seriously consider how we go about demonstrating innovations to local government, ward councillors and household members. A well-considered process of demonstration planning and implementation could reduce some of the challenges outlined here. The demonstration and introduction of new ideas is unlikely to be met with initial overwhelming acceptance. There is always resistance to change; however, such opposition can be mitigated through careful planning and collaboration.

Policy context

In 2011 the Department of Science and Technology (DST) initiated the IPRD working group to enhance the links and foster a culture of knowledge sharing among organisations working in rural areas. The partnership aims to increase the awareness about innovation and its potentials for rural development, thereby creating an enabling environment for innovation dissemination.[1] The historical innovation focus in rural areas has largely been in agriculture, mining, health, education and ICT.[2,3] The shift to basic services is novel. The DST sees itself responsible for brokering long-term networks and bridging the gap among the innovating agencies, such as science councils, universities and private firms, and national departments, local government, non-governmental organisations and communities, to demonstrate the prowess of innovation within a national system of innovation approach.[4] The IPRDP, launched in 2013, was the first rural-focused and large-scale innovation demonstration programme under the auspices of the IPRD.[5] Its aim is to demonstrate eight innovations at 31 field sites, across 23 of the 27 distressed municipalities in South Africa. Distressed municipalities are those identified by the Department of Rural Development and Land Reform as being the poorest in terms of revenue and services.[6] Key state actors in the rural development space include the Department of Rural Development and Land Reform, Department of Cooperative Governance and Traditional Affairs and the South African Local Government Association.

The IPRDP emphasises innovation for inclusive development through a focus on meeting basic service needs of poor settlements and households. Pro-poor approaches to innovation include ideas of participation by and inclusion of the poor in innovation processes[7], echoed in the initial research and innovation agenda proposed in the 1996 White Paper on Science and Technology and reiterated in the 2017 Draft White Paper on Science and Technology.[8,9] However, the notion of inclusiveness is not clearly articulated in the latter document and paradoxically proposes a definition in which active participation is deemed unnecessary, as long as the poor are included as recipients of innovations.[9] Such a definition goes against recent robust definitions that include the poor as active contributors to the innovation process and/or innovators in their own right.[10-13] It also contradicts citizen participation as accentuated in the National Development Plan (NDP).[14,15] Inclusion in the context of inclusive growth and development is about 'social processes and dynamics of change, and not simply distributional outcomes'[15]. The importance of human agency must be emphasised.[16] The poor are not simply observers or passive recipients but are rather the 'shapers' of change through 'bottom-up' participation.[15] The September 2018 Draft White Paper on Science, Technology and Innovation provides little assurance of what inclusiveness means and how it can be practised, although it does mention users and grassroots innovators. It is shrouded in policy ambiguity.

The IPRDP Programme

The preliminary identification of suitable service delivery innovations was based on a call for proposals by the DST. Innovators presented selected proposals to a group of district municipal representatives. Municipal representatives selected the innovations they wanted but quite soon after the presentations some withdrew their interest, often for financial reasons or because they realised the demonstrations did not meet their needs. Most of the technologies presented had been developed under the auspices of the Water Research Commission and the Council for Scientific and Industrial Research, in collaboration with various local universities. These institutions subsequently managed aspects of the demonstrations. Ultimately, the DST, along with South African Local Government Association, Department of Cooperative Governance and Traditional Affairs and the science councils, selected the 23 districts and the technologies. The innovators visited the districts and engaged with officials but left the selection of households and villages to the local municipalities, ward councillors and the community leaders who went about the process in a manner that seemed to benefit allies and others less needy. For example, households with standpipes in the yards

were selected as beneficiaries of the pour-flush latrine that was intended for households with limited access to water so that they would recycle water to flush the toilet.

The eight sanitation, water and energy demonstrations are presented in Table 1. They are characterised as being recently developed/adapted but not yet demonstrated outside the research station/laboratory. The implication is that their compatibility with the social and physical landscape (mainly rural areas) in which they are to be used is untested.

Methodology

Since 2015 we have worked as researchers monitoring and evaluating the design, process, ongoing implementation and impact of the IPRDP in eight districts. The study was approved by the Human Sciences Research Council Ethics Committee (REC 9-20-05-15). Methods included 14 semi-structured interviews with programme planners, project managers, demonstrators and officials. Evaluators reviewed reports related to the programme. Two workshops with innovators (science councils, universities and private firms), state departments and municipal officials elicited accounts of progress and the challenges experienced. During and after these workshops the researchers engaged in consensual discussions with participants. Field visits enabled discussions with beneficiaries at municipal, ward and household level as well as observations of the demonstration process. More than 64 municipal officials were interviewed. For impact evaluation purposes, two rounds of household surveys were conducted: a retrospective baseline survey with 857 households in March 2017 and a follow-up survey with 653 of the original households in March 2018. The surveys were done across 15 settlements, incorporating intervention sites and control sites (where no intervention occurred) as well as beneficiary and non-beneficiary households.

Findings and discussion

Inclusiveness

Reviews of the various demonstration project plans for each innovation indicate that, in most cases, systematic needs assessments were not conducted, local participation was limited and monitoring and evaluation plans were non-existent.[17] The results of the community impact survey, targeted at households who received IPRDP technologies, concur by revealing that there has been little, if any, consultation with community members about their immediate needs in relation to basic services, let alone participation in the design of the technologies. Where needs assessments were undertaken, no clear framework was used, thereby restricting consistency, scope and focus. Accessing the recipients at household and village level was usually left to the local government structures and community leadership. However, these institutions lack the technical knowledge of the technology and the likelihood of its suitability at village and household levels. One should also not presume that these institutions speak on behalf of community members. This approach is a huge departure from ideals of active citizenry promoted by the National Development Plan[14,15], or user inclusion as advocated in inclusive and open innovation scholarship[18], all of which are necessary for democratising innovation-driven development[13].

Suitability

The 2017 baseline survey shows that the IPRDP innovations fit with household service delivery needs – flush latrines, improved sanitation, clean water and energy supply – at a very broad level. Yet at a more site-specific level, the demonstrated technologies do not coincide with local circumstances, including the physical environment and the available infrastructure necessary for these technologies to work effectively. In one or two cases it was found that sites were geologically unsuitable and the proposed demonstrations were relocated – a resource-consuming process. Some energy regulatory requirements were only realised at the time of demonstration, thus causing delays. The failure to conduct robust needs assessments overlooks current solutions used by local people to address their immediate problems or how, as potential users, they are able to aid the design of proposed innovations. It also fails to ensure a fit between the residents and the technologies. In some instances, the pour-flush latrine was provided to households with standpipes in their yards rather than households without water. Some selected households then 'adapted' the system by adding a cistern and connecting a hosepipe to it, which risks destroying the leach pits and causing environmental and health threats. In some instances, the smart geysers could not be coupled to the smart technology because the necessary ICT infrastructure was not available. The point-of-use water filter was readily accepted but took the longest time to demonstrate because of challenges in regard to manufacturing at scale.

A number of challenges prevailed at municipal level. Many municipalities had their own version of CARRS (Corrective Action Request and Report System) and preferred this customised software that catered for their specific requirements rather than a generic system. The integration of

Table 1: Descriptions of the IPRDP Innovations and the level of demonstration

Service sector	Innovation: Technology	Description	Level of use
Sanitation	Pour-flush sanitation	Toilets that make use of two leach pits and about 2 L of greywater for flushing.	Household level
	Integrated Algae Ponding System (IAPS)	A low-cost system that uses fermentation, algae and extra ponds to enhance the natural purification processes that occur in conventional wastewater ponds.	Municipal level
	High Rate Algae Ponding System (HRAPS)	Ponds use improved algae to remove pollutants from waste water at an enormous cost saving compared to the conventional ponding process. Treated effluent can be used for aquaculture and irrigation.	Municipal and village level
Water	Corrective Action Request and Report System (CARRS)	An ICT-based platform used for the reporting and monitoring of water system faults.	Municipal and village level
	Water Safety Planning (WSP) and Wastewater Risk Abatement Planning (W2RAP)	A risk management, planning and reporting system to ensure drinking water quality and manage wastewater treatment.	Municipal level
	Point-of-use Water Filtration System	A water filtration system using a bucket and a special membrane.	Household level
Energy	Smart geysers	Software application linked to hardware on geysers to reduce water leakages and optimise energy consumption.	Household level
	Small-scale hydropower	Technology to generate electricity using stream velocity and floating turbines.	Village level

CARRS and existing municipal systems with expanded functionalities proved problematic. User involvement in the design of CARRS would have been advantageous. A similar problem was encountered with the ponding systems. IAPS (Integrated Algae Ponding System) became very expensive as the construction of more ponds was required. The High Rate Algae Ponding System (HRAPS) team encountered local resistance when they attempted to promote the use of treated effluent for irrigation purposes and the algae for animal feed. While the innovations are commendable, many do not fit with the requirements of the intended users.

Networks and collaboration

Distances affected the establishment of strong national–local networks and lines of communication. Site visits were irregular and this undermined collaboration. There were misunderstandings between the innovators and the beneficiaries about their responsibilities and the overall purpose of the demonstrations. The scientific purpose of the demonstrations was to test and showcase new technologies, deemed as improvements because they were environmentally friendly, cost-effective and efficient. However, municipal officials prioritised their Integrated Development Plan responsibilities, often at odds with new technologies.

Innovating agencies expressed frustration at the general lack of engagement and leadership, low-levels of technical capacity, delays caused by bureaucratic processes and administrative ineptitude at local government level.[6,19,20] Moreover, in these distressed municipalities, a lack of revenue prevents the municipalities from providing basic services.[6]

Elsewhere, one could explore the debate about whether any of these innovations are likely to be adopted unless they are virtually cost free and require little maintenance. However, it is sufficient to say that scientists should ensure that demonstrated innovations are appropriate, useful and add value to the services required in a specific social and physical environment.

Conclusion

So how do we improve our demonstration of innovations to ensure maximum social buy-in and value-additions? For innovations to succeed in contributing to improved service delivery (result in adoption) they must be linked to local priority needs of municipalities, settlements and households. We acknowledge that certain bulk services may require little to no user participation or needs assessments and that user participation in the design of basic services might not be practical in all instances. Nevertheless, when the development of innovations for the benefit of the poor is promoted as inclusive innovation or innovation for inclusive development, thorough user needs assessments and social research are required at the very least. This means that needs assessments, environmental feasibility assessments and the identification of recipients must be comprehensive, structured and undertaken in conjunction with local residents and officials. Strong lines of communication must be opened and sustained with all actors. The innovations demonstrated must be aligned with the local Integrated Development Plan priorities. If Integrated Development Plans follow the same robust inclusive processes proposed for other assessments, then there should be limited conflicts of interest amongst the innovators, officials and residents.

One of the key challenges of the IPRDP was its extensive scale and costs of operation – 31 demonstration sites of various sizes across 23 districts. This scale caused logistical problems and delays, it fragmented rather than strengthened relationships, and was extremely costly. Lack of knowledge about the conditions at many sites meant that innovators had limited understanding of local circumstances. An alternative is to conduct these first-time demonstrations at a much smaller scale and closer to the innovators. This approach would enable regular contact with stakeholders and the development of capacity-building programmes to empower officials to improve their innovative and service delivery performance. Proximity would also facilitate sustained communication. Many peripheral areas around the eight metropolitan municipalities in South Africa provide destinations for demonstrations. They offer similar situations of income and service poverty as those in the IPRDP municipalities. Yet some have the necessary infrastructure to ensure that the technologies can be demonstrated. Proximity and availability of infrastructure enable a more practical, cost-effective and resourceful means of demonstrating and field-testing new innovations. Experience from these 'closer' encounters can then inform the roll out to other more distant areas.

To conclude, better needs assessments that include social scientists, increased participation of the users, smaller demonstration programmes and closer field sites would facilitate improved understanding, better collaboration and communication, and stronger networks, enabling us to ultimately achieve more effective innovation and development rather than less in the long term.

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Using ocean robots on high-resolution profiling to capture the fast-flowing Agulhas Current

The Argo programme was developed to provide near real-time observations of the ocean and contribute significantly to understanding the changes occurring in ocean temperature and salinity in the upper 2000 m. Riser et al.[1] showed that, for profiles sampling both temperature and salinity to 1000 m or deeper, the Argo programme produced, in just under 16 years, three times as many profiles as all other shipboard observations in the past 100 years. Furthermore, Argo observations have occurred globally, albeit with higher resolution in regions where deployment opportunities were more prevalent.

But what happens in particularly turbulent or fast-flowing current regions such as Western Boundary Currents (WBC) and mesoscale eddies? Errors are reported to be high when Argo data are used to plot monthly and seasonal evolution of structures within turbulent WBCs as a result of the lack of spatial resolution of Argo data.[1] In an attempt to improve observations, the Argo Steering Team has suggested additional float resources be assigned to fast-flowing WBC regions.[1] While this addition may be sufficient for regions where deployment opportunities are numerous, in areas such as the Agulhas Current or the Mozambique Channel, where far fewer research cruises are conducted, another option is to set Argo floats to collect data at higher resolutions.

The Agulhas Current propagates along the east coast of South Africa at peak surface speeds of 1.8 m/s (~155 km/day),[2] and is the fastest WBC of the southern hemisphere. The Agulhas Current is considered stable from Durban in the north to Port Alfred in the south (Figure 1), a distance of ~570 km. Furthermore it is unique in that mesoscale eddies contribute to its source from east of Madagascar and the Mozambique Channel, and mesoscale eddies and Agulhas Rings are shed at the Agulhas Current termination as it retroflects back on itself into the Indian Ocean.[3] The Agulhas Current is not accurately resolved in climate models and thus forecasts used for the International Panel for Climate Change and similar misrepresent this feature, which is largely responsible for the transport of heat and salt from the Indian to Atlantic Oceans.[4] Improved resolution in-situ measurements of this WBC and its source regions are thus crucial for an accurate assessment of the contribution of the Agulhas Current and its sources to the transport of heat and salt.

Mesoscale eddies in the Mozambique Channel, originating usually in the narrows to the north of the Channel, extend to the full depth of the water column as found in in-situ measurements.[5,6] Eddies originating from the South-East Madagascar Current form in dipole pairs, around four to six per year[7], with a strong jet found between the two lobes of the dipole propagating southwestwards[7,8]. Halo et al.[9] showed that mesoscale eddies are indeed highly non-linear and capable of transporting material, such as biological organisms, between Madagascar and the African continent. But to what depths does this transport capability extend with particular emphasis on heat and salt input from the Indian Ocean interior into the Agulhas Current, especially given the significant decrease in velocities below 500 m in the limited in-situ data already available? In order to quantify this extent, dedicated research cruises undertaking extensive CTD (conductivity, temperature and depth) surveys across mesoscale eddies would be required –

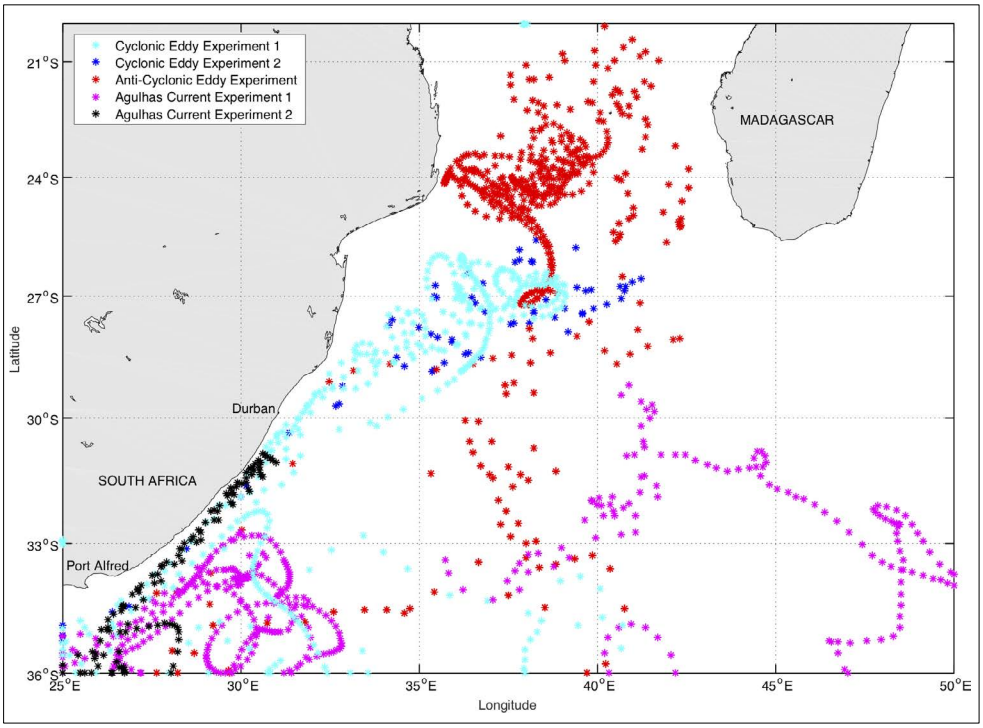

Figure 1: Five high-resolution Argo profile experiments conducted between 2013 to 2017 in the source regions of and the Agulhas Current itself.

an incredibly expensive undertaking. A more affordable solution would be to deploy Argo floats profiling at higher resolution than that of the standard 10-day mission. Understanding what is being contributed to the Agulhas Current from its turbulent sources is imperative in order to validate coupled-climate models for better forecasting capabilities, to accurately assess physical dynamics impacting the coastal regions and critically track the transport of heat and salt, as well as pollutants such as microplastics.

Historically, scientific research cruises have been concentrated on the west and south coasts of South Africa because of the rich fisheries in these regions, whereas the east coast has had limited exposure to long-term studies of its powerful current. Intermittently deployed mooring arrays have been used to acquire data from the Agulhas Current[2,4,10], and opportunistic surveys along the coast have been used to glean additional information whenever possible[11,12]. In contrast, much of the understanding of the northern hemisphere WBCs comes from Argo float data and, when it is possible to deploy fairly regularly, a detailed picture can emerge.[1] For the Agulhas Current, this paucity in in-situ data is further exacerbated by its relatively short length (~ 570 km) and with peak surface speeds of ~155 km/day, an Argo float on the standard profiling of 10 days could miss the Agulhas Current completely in its propagation along the east coast.

With support of Argo teams from the USA, UK and Europe, South African researchers have begun using Argo floats with higher profiling frequencies[13], daily or five-daily as opposed to the standard 10-daily profiling mission, to understand this dynamic WBC and the influence of mesoscale eddies from its source regions, as well as the fate of heat and salt transported by these features. The park and profile depths of these Argo floats were set to be shallower than the standard mission to ensure the floats were maintained within the features. Over the last 5 years, five experiments have been conducted on mesoscale eddies in the southern Mozambique Channel, and along the Agulhas Current (Figure 1). For the entire duration (2000 to 2017) of the Argo programme to date, 136 floats propagated along the east coast of South Africa have acquired 276 profiles within the Agulhas Current (Figure 2). For the 18 floats set to higher sampling frequencies for the five experiments, 199 profiles were collected (Figure 2) – a number more than two thirds higher than that achieved by standard mission floats in close to 17 years, thus dramatically increasing the number of observations in this WBC. For the southern Mozambique Channel, the increase in the number of observations is less obvious (Figure 3a and 3b) given that

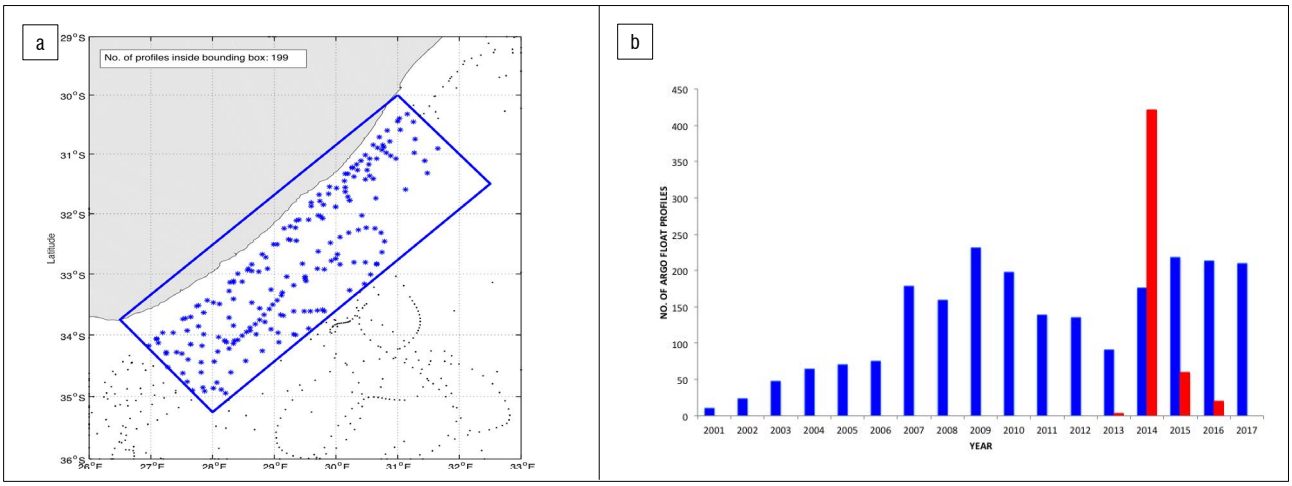

Figure 2: (a) Map of the east coast of South Africa for the 18 high-resolution floats used in the mesoscale eddy and Agulhas Current experiments, with the Agulhas Current region depicted (as per Beal et al.[2]) as a blue rectangle. (b) Histogram depicting, within the Agulhas Current bounding box, the profiles from standard profiling Argo floats (blue) and high-resolution Argo floats (red) per year.

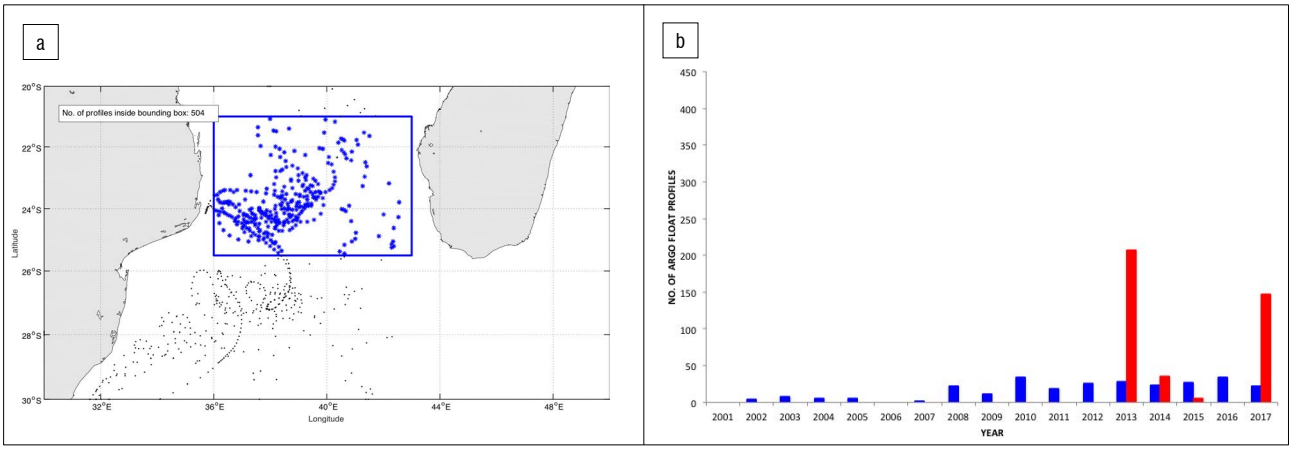

Figure 3: (a) Map of the southern Mozambique Channel for the nine high-resolution floats used in the mesoscale eddy experiments, with the southern Mozambique Channel region depicted as a blue rectangle. (b) Histogram depicting, within the Mozambique Channel bounding box, the profiles from standard profiling Argo floats (blue) and high-resolution Argo floats (red) per year.

fewer high-resolution deployments were undertaken in this region. What is important to note is that, although there are more profiles per year on standard float missions in the southern Mozambique Channel, these floats are not profiling down the Agulhas Current as successfully (Figure 2b), and are thus not capturing the change in dynamics from a turbulent region into the WBC.

With limited opportunities for dedicated research cruises in the Mozambique Channel to collect high-resolution CTD data, multidisciplinary cruises – such as that investigating a young cyclonic eddy spawned off southwest Madagascar in July 2013[14,15] – are crucial to further our understanding of these features. While it was possible to sample only a single high-resolution transect during the cruise[14,15], the deployment of Argo floats with higher profiling frequencies within that same eddy allowed for continuous sampling of water masses, heat, salt and volume transport of the eddy over a period of 4 months as the eddy moved from southwest Madagascar to the Agulhas Current off South Africa (Morris, unpublished data).

Arguably, high-resolution profiling is skewed to time periods when floats are deployed in these turbulent regions (Figures 2b and 3b); however detailed process studies have been made possible[16] and these results will extend our understanding of the role of mesoscale eddies in the upstream dynamics of the Agulhas Current, and the structure and dynamics of the Agulhas Current itself. With the advances in satellite technology, it is now possible to reprogram the float so that once it leaves the high-resolution study region it can be set back to standard Argo profiling, thus extending the battery life of the float. Increased data profiling will increase data transmission costs and put additional strain on Argo data centres to validate data, but these advances should be considered similar to those of Deep-Argo, biogeochemical sensors on Argo floats and the increased float deployments in the equatorial regions. Argo floats were never designed to answer all the physical dynamics questions about the ocean, but given the massive cost of research vessels and dedicated in-situ sampling, obtaining detailed information on particularly turbulent regions to fill in at least some of the gaps should be undertaken in whatever way possible.

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Morphometric comparison of semicircular canals of *Parapapio broomi* and *P. jonesi* from Sterkfontein, South Africa

As an anatomist working on modern baboons at the University of the Witwatersrand, Trevor Jones[1] described a partial cranium of a Plio-Pleistocene baboon (Sts 564) from the Sterkfontein Caves in the Cradle of Humankind. He named it *Parapapio broomi,* a new genus and species in honour of Dr Robert Broom who was based at the Transvaal Museum in Pretoria from 1934 until his death in 1951 (the museum is now referred to as the Ditsong National Museum of Natural History). Jones was a student of Professor Raymond Dart who had encouraged Broom to work at Sterkfontein after this site had yielded fossil baboons similar to those that had been found at Taung[2] – the site from which the holotype specimen of *Australopithecus africanus* was discovered in 1924[3].

It is now recognised that *Parapapio* and hominins are often found together in pene-contemporaneous Plio-Pleistocene deposits in Africa. The first hominin to be found at Sterkfontein (TM 1511, *A. africanus*) was discovered in 1936, soon after the initial discovery of fossil baboons at the site by Trevor Jones and two of Dart's other students from the University of the Witwatersrand.

Parapapio and *A. africanus* represented at Sterkfontein in a unit called Member 4 are considered to be in the order of 2.5 million years old. The earliest reported occurrence of *Parapapio* in southern Africa is based on the discovery of faunal material from Way Point 160 at Bolts Farm in the Cradle of Humankind, dated to between 4.5 and 4 million years ago.[4] As yet, no australopithecines have been found at Way Point 160, but the site has the potential to yield hominin fossils pene-contemporary with *Australopithecus anamensis* from East Africa.

Since 1936 additional primates have been found at Sterkfontein.[5-7] The oldest certain occurrences of *Parapapio* are at Sterkfontein Member 2 and Makapansgat Members 2, 3 and 4.[8] These remains are dated to between 3.5 and 2.5 Ma. Specimens formerly attributed to *Parapapio antiquus* from Taung are now considered to belong to another genus, *Procercocebus antiquus.*[9] Other discoveries of early papionins considered to represent *Parapapio* are from the 'E' Quarry (Varswater Formation) at Langebaanweg and are dated approximately at 5.1 Ma[10], and from Waypoint 160 at Bolt's Farm Cave System[4], but they are too fragmentary or rare for us to be sure of the genus to which they belong[8].

As in the case of hominin taxonomy, the classification of primates attributed to the genus *Parapapio* is fraught with problems. The taxonomy of Plio-Pleistocene *Parapapio* from South African cave sites has been revised and debated inter alia by Freedman[11,12], Freedman and Stenhouse[13], Delson[14], Eisenhart[15], Szalay and Delson[16], Jablonski[17], Heaton[18], Williams et al.[19], Fourie et al.[20], Jablonski and Frost[21], Gilbert[22] and, most recently, by Beaudet[23] and Beaudet et al.[24]; Monson et al.[25] have confirmed that the taxonomy of South African papionins is problematic.

When Jones described Sts 564 as a new genus and species in 1937, he did so with a sample of only one specimen (attributed to *P. broomi*), just as Dart[3] had done in the case of the Taung Child (*A. africanus*). With single specimens it was easy to describe new taxa. Historically, the species diversity of primates in the genus *Parapapio* increased quickly after 1937 to include *P. jonesi* (e.g. Sts 565 from Sterkfontein), *P. whitei* (e.g. Sts 563 from Sterkfontein and MP 221 from Makapansgat) in addition to *P. antiquus* (e.g. TP 8 from Taung). However, some palaeontologists such as Brain[26] have questioned the validity of several species of *Parapapio* occupying similar if not identical habitats at about the same time.

Materials

In this paper we focus our attention on two holotype specimens, not only Sts 564 (*P. broomi*) but also Sts 565 named by Broom[27] as *P. jonesi* in reciprocal honour of Trevor Jones. Both of the fossil baboon specimens come from Sterkfontein, and both are believed to be derived from the same deposit (Member 4) in which *Australopithecus africanus* is represented. The two crania are incomplete and do not have well-preserved dentition, but the semicircular canals are intact.

Method

Virtual 3D reconstruction of the semicircular canals was undertaken on the basis of micro-focus X-ray computed tomography (μXCT) scanning at the South African Nuclear Energy Corporation SOC Ltd (Necsa). Landmark coordinates were obtained after Procrustes superimposition from the two virtual semicircular canals.[23,24] A total of 100 measurements was recorded per specimen. These measurements were subjected to morphometric analyses of the kind described by Thackeray[28] in order to assess probabilities of conspecificity. Dimensions for pairs of specimens were compared using regression equations of the form $y=mx + c$ where m is the slope and c is the intercept, based on measurements of any specimen A (x-axis), and any specimen B of the same species (y-axis), and vice versa.[29]

The log-transformed standard error of the m coefficient (log se_m) is a measure of the degree of similarity between pairs of specimens, and has been shown by Thackeray and Dykes[29] (using cranial data) to have central tendency around a mean value of -1.61 $\pm$ 0.10 for modern conspecific specimens. The mean log se_m value of -1.61 has been considered to be an approximation of a biological species constant, associated with a probabilistic definition of a species, applicable in modern and palaeontological contexts.[28]

The range of difference in log se_m values ('delta log se_m') is obtained from comparisons when specimen A (x-axis) is compared to B (y-axis), and secondly when specimen A (y-axis) is compared to B (x-axis). Delta log se_m is small (circa 0.03) for conspecific comparisons. A high probability of conspecificity can be expected to prevail for pairs of specimens when the mean log se_m is less than or equal to -1.61 and when delta log se_m is less than or equal to 0.03.[29]

Results

Virtual μXCT 3D images of the semicircular canals obtained from Sts 564 and Sts 565 are shown in Figure 1.

When measurements of *P. broomi* (Sts 564 on *x*-axis) are compared to those of *P. jonesi* (Sts 565 on *y*-axis), we obtain a log se_m value of -1.746. For measurements of *P. jonesi* (Sts 565 on *x*-axis) versus those of *P. broomi* (Sts 564 on *y*-axis), a log se_m of -1.714 is obtained. The delta log se_m value is 0.03. For these comparisons of the holotypes of *P. broomi* and *P. jonesi*, the mean log se_m value is -1.73.

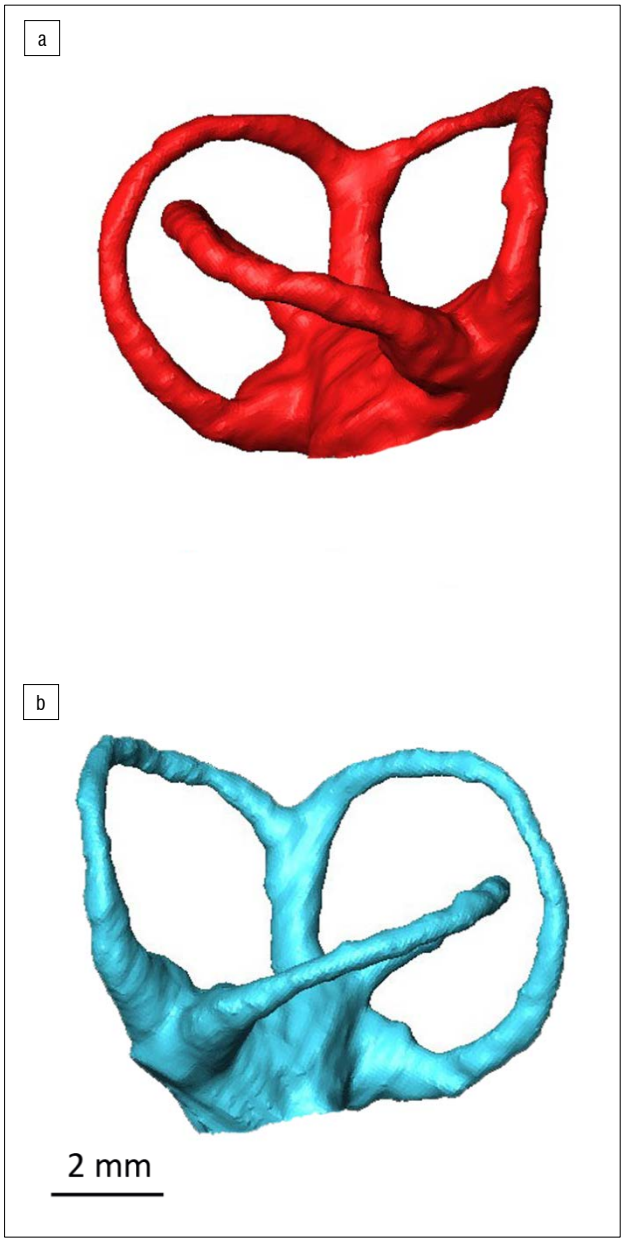

Figure 1: Virtual rendering of the semicircular canals of (a) Sts 565 and (b) Sts 564. Note differences in size but very close similarity in shape, despite the fact that the specimens have been attributed to *Parapapio jonesi* and *P. broomi*. Morphometric analyses indicate a high probability of conspecificity.

Discussion and conclusion

Visual comparison of the virtual rendering of the semicircular canals of Sts 564 and Sts 565 (Figure 1) shows remarkable similarity. In order to assess this similarity quantitatively, dimensions obtained from μXCT scans of these internal anatomical structures, in well-preserved areas of the crania, are particularly valuable.

Unfortunately the edentulous skulls are fragmentary, such that they do not permit detailed analyses of external anatomy of the two specimens. However, morphometric analyses of high-resolution data from μXCT scans of the semicircular canals provide an excellent alternative approach for assessing probabilities of conspecificity. Notably, the delta log se_m value of only 0.03, and the mean log se_m value of -1.73 (less than the mean log se_m of -1.61 and within the lower 95% confidence limit for modern conspecific comparisons), suggest that the holotype specimens of *P. broomi* and *P. jonesi* have a high probability of belonging to the same species. As a hypothesis (H1), we propose that they are conspecific. If correct, the nomen *P. broomi* would have precedence over *P. jonesi*, as the former was described first, by Jones, in 1937. Broom described *P. jonesi* in 1940.

Thackeray and Myer[30] used dental data to question whether specimens attributed to *P. broomi* were those of male individuals, and whether other (generally smaller) specimens attributed to *P. jonesi* were of female individuals. There is no major dietary difference between specimens attributed to either of the taxa, as reflected by stable carbon isotope ratios.[31-33] The isotopic data provide support for the view that a single species is represented by specimens otherwise classified as *P. broomi* or *P. jonesi*. Our morphometric analysis of the type specimens of the two species would seem to confirm this possibility, with the small cranium (Sts 565) possibly being that of a female individual, and the larger specimen (Sts 564) representing a conspecific male specimen of *P. broomi*.

When Trevor Jones first accompanied Robert Broom to Sterkfontein about 80 years ago, Broom picked up the relatively small baboon cranium now catalogued as Sts 565. Almost immediately (after making a cursory examination of the specimen, still encased in breccia), he said something along the following lines: 'Well Jones, thank you for describing a fossil after me. I will return the compliment, and I will name this new baboon after you' (personal communication, Jones to Thackeray, circa 1994). No detailed analyses of the two crania (Sts 564 and Sts 565) had been undertaken at that time. This anecdote reflects the arbitrary manner in which Broom sometimes created new species in the palaeontological record.

It would appear that Broom was being subjective when assessing two specimens of *Parapapio* (Sts 564 and Sts 565) as different species of slightly different size. We have used data from μXCT scans and virtual reconstructions of the semicircular canals of two *Parapapio* crania to test whether they are different at a species level. We conclude that there is a high probability that they are conspecific, based on both log se_m and delta log se_m values. We reiterate the suggestion that the larger of the two (Sts 564) specimens may possibly represent a male individual[30], as the holotype of *P. broomi.* Sts 565 could be referred to the same species, potentially that of a female individual. Here we express these concepts in terms of three hypotheses (H1–H3):

H1: Sts 564 and Sts 565 are conspecific, representing *P. broomi*.

H2: Sts 564 is a male specimen of *P. broomi*.

H3: Sts 565 is a female specimen of *P. broomi*.

The results of our preliminary study of two type specimens, supporting H1, are consistent with the view by Monson et al.[25] indicating that the taxonomic designations of Parapapio and other Plio-Pleistocene Cercopithecidae from South Africa may be 'confounded'. Further analyses, including additional specimens attributed to Parapapio (supplementing our study of Sts 564 and Sts 565, and including specimens attributed to Parapapio cf. jonesi from Ethiopia[34]) are required to address hypotheses of the kind considered in this study.

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The nature of international collaboration in the Benguela upwelling region, 2000–2016

The aim of this piece is to draw attention to the fact that although we, as a country, have participated extensively in collaborative work with neighbouring states in the area of marine science, the number of lingering collaborations is woefully low, at least as measured using collaboratively authored publications as a measure of success in collaboration. And this low level of collaboration is despite significant financial intervention in the first decade of the 21st century. Indeed, the situation is depressing, and from conversations with colleagues, the lack of willingness to be inclusive and generous with authorship leads to mistrust and potentially threatens future relationships. With Operation Phakisa, the South African government is intent on building the blue economy, an economy that can best succeed by working with neighbours. With South Africa currently holding the chair of Indian Ocean Rim Association (IORA) and with the Department of Environmental Affairs Branch Oceans and Coasts investing significantly in research in the Western Indian Ocean, we need to be careful. So this piece is framed with the intention of reminding scientists who are working 'collaboratively', to make good on the fruits of the collaboration.

International collaboration occurs when scientists with different skill sets and/or knowledge/experience from different countries work together on a common subject/problem. International, regional collaborative research within the Benguela Current Large Marine Ecosystem (BCLME) was generously funded between 1997 and 2008, and has been supported subsequently, albeit at a lower level of investment. Collaboratively conceived and executed projects that generate data should result in collaboratively authored publications at project end, conditional upon data quality, subject novelty and time. Starting from a low level then, we would expect to see a progressive increase in collaborative publications pertinent to the BCLME region over the period 1997–2008, reflecting the stimulation and momentum engendered by the injected resources. As funds dwindle, a decline in collaboration might be anticipated that will be followed by a new base built on common curiosities and linkages. Here, we examine the level of collaboration in the scientific publications that emanated from work conducted in the BCLME over the period 2000–2016, with a view to understanding the nature of the collaboration.

The Benguela Current is one of five eastern boundary currents which characteristically flow equatorward along the western seaboards of the major continental land masses. These currents are renowned for their important industrial fisheries that contribute significantly to regional economies and have been subject to considerable study. While teams from across the world try to seek universal truths through comparative approaches[1], much is management orientated, and is conducted 'in-country'[2]. The Benguela Current flows northwards along the west coasts of South Africa, Namibia and southern Angola.[3] Whilst the oceanographic environments off each country differ in details[3], there are strong commonalities between them – not least of which are some mobile, transboundary resources[3]. These resources pose problems for sustainable management. In recognition of these problems, the large marine ecosystem (LME) concept was established[4], the aim of which is to enable the collaborative, ecosystem-based management of resources within transnational areas. The LME relevant to the Benguela Current is the Benguela Current LME (BCLME).

To be successful, nation states within an LME need to work together and coordinate their research and management efforts. In the BCLME region, this research cooperation was initially coordinated through the BENEFIT (BENguela Environment, Fisheries Interaction and Training) programme.[5] Conceived and developed between 1994 and 1996, BENEFIT was launched in 1997 with funding from the governments of South Africa, Namibia and Angola and with donor support primarily coming from NORAD (Norwegian Agency for Development Cooperation) and GTZ (Deutsche Gesellschaft für Technische Zusammenarbei). The programme drew in a number of other international partners including Iceland (through the Icelandic International Development Agency) and France (Institute of Research for Development).

The BCLME programme, which came into effect partway through the life of BENEFIT, started in 2002 with funding from the Global Environment Facility and the United Nations Development Programme, with financial inputs also from regional governments.[6] Whilst many of the goals of the two programmes were similar, the end-point of the BCLME programme was the establishment of the Benguela Current Commission, which would oversee the joint management of transboundary issues. The Benguela Current Commission was set up in 2006, but only became entrenched via the signing of the Benguela Current Convention in 2013.

The BENEFIT and BCLME programmes were founded on two significant pillars. The first focused on research questions common to all of the regional maritime states, and local scientists developed projects around management needs facing at least two of them. Foremost amongst these projects were ones involved with transboundary fish stocks, although many other studies were conducted.[7] The second pillar was capacity development[5,6], and efforts in this regard focused on building human capacity with a lesser emphasis on developing, bettering and maintaining national and regional infrastructure.

Whilst the BENEFIT and BCLME programmes of active research effectively terminated in 2008, a number of other collaborative research programmes were initiated. The National Research Foundation of South Africa has bilateral agreements with the governments of both Namibia and Angola, and projects in the marine sciences have been funded in the last 5 years. The German government funded the GENUS (Geochemistry and Ecology of the Namibian Upwelling System) programme for the period 2009–2015, and NORAD and the Food and Agricultural Organization of the United Nations have continued to sponsor ship's time in the region. And of course, there are a number of regional management bodies, such as the International Commission for South-East Atlantic Fisheries, in which local scientists participate, and through which coordinated and collaborative research could be furthered.

Materials and methods

We acknowledge that the fruits of research collaboration can be measured in many ways: as joint project and cruise reports published in the grey literature; joint presentations at symposia and workshops that never see the light of day beyond the book of abstracts; jointly formulated management decisions and changes to policy; increased technological and academic self-sufficiency and efficiency, etc. We also accept that some products of the same may get published as either books or book chapters. However, we have confined our assessment of collaboration to peer-reviewed scientific journal articles – the golden standard for most practising scientists.

A search for all peer-reviewed scientific journal articles published during the period 2000–2016 was conducted using Google Scholar, with Boolean operators and the keywords "Benguela, Angola, Namibia, South Africa, southern Africa, west coast, W coast, SW coast, Large Marine Ecosystem" and all variants thereof, e.g. "Angola or Namibia and Benguela", or "South Africa and west coast".

Publications were screened for relevance to the marine environment of the BCLME region, regardless of topic or discipline. Papers on taxonomy, biology, climate, geology, oceanography and management, as well as technology were therefore included. The publication details of each paper were captured and the following information culled from the author list and associated affiliations: number of authors, country of origin of the first author and country of origin of co-authors if different from that of the first author. Here, we assume that the first author is the lead author, although we accept this may not always be the case. In cases where authors shared affiliations between institutions owing to short-term secondments or exchanges (e.g. Institute of Research for Development, France and University of Cape Town, South Africa), the country of the home institution only, is considered. Each country was scored only once in a collaborative paper, if represented. The geographic location/focus of each study was assigned as northern Benguela (North of the Lüderitz upwelling cell), southern Benguela (South of the Lüderitz upwelling cell), or the whole BCLME region.

Results

Overview of the data

A total of 808 peer-reviewed journal papers were published on the environment and/or resources of the BCLME region over the period 2000–2016 (Supplementary table 1), averaging 48 annually (Table 1); there was no temporal trend in the data. The majority of papers were published with a focus on the southern Benguela, whilst the fewest were published on the whole of the BCLME (Table 1). There were significant differences in the mean number of countries collaborating together in the different regions ($F=4.37$, d.f.$=48$, $p<0.05$, Table 1), but no temporal change in the mean number of countries participating on papers in the different regions. Scientists from within a single country authored the majority of papers (48%), and colleagues from three or more countries published less than 17%. Regionally, South Africa dominated the single-country papers (57%), Namibia wrote nine (2%), whilst Angola wrote none (Supplementary table 2).

Regional collaboration

Approximately 71% of the papers involved regional authors, but only 12% have involved collaboration between scientists from two or more of the BCLME countries (Figure 1). Although there has been no temporal change in the numbers of publications per partnership (Figure 1), regionally collaborative papers that have been published with a focus on the northern Benguela have increased significantly with time ($R=0.53$, $p<0.05$, Figure 2); there is also some evidence to suggest that BCLME-wide papers too have been increasing post-2007. The level of regional collaboration has been highest in studies with a focus on the northern Benguela, and lowest in studies of the southern Benguela (Table 1).

The majority of the collaborations (88%) have been between two countries, and the dominant partnership has been between South Africa and Namibia (82%) (Figure 1, Supplementary table 3); this pattern of collaboration has not changed through time. Regional scientists have led only 420 (52%) of the collaborative papers produced overall through the period 2000–2016, with South Africa taking the lion's share (376, 90%).

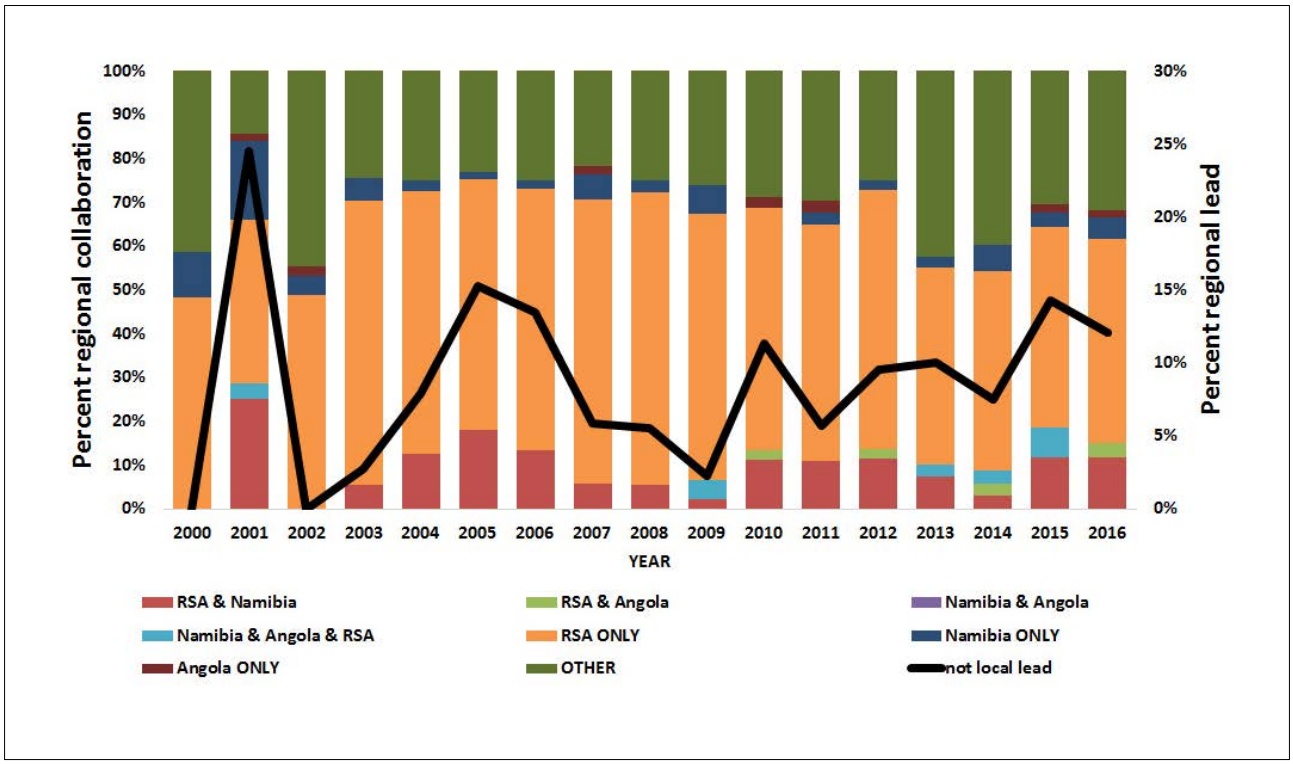

Figure 1: Per cent participation in peer-reviewed journal publications on the resources and/or environment of the Benguela Current Large Marine Ecosystem (BCLME) region during the period 2000–2016 by regional country in isolation, or collaboration. Also shown are the relative contributions that did not include a regional collaborator. Line shows per cent regionally led publications. Numbers of papers published each year from Table 1.

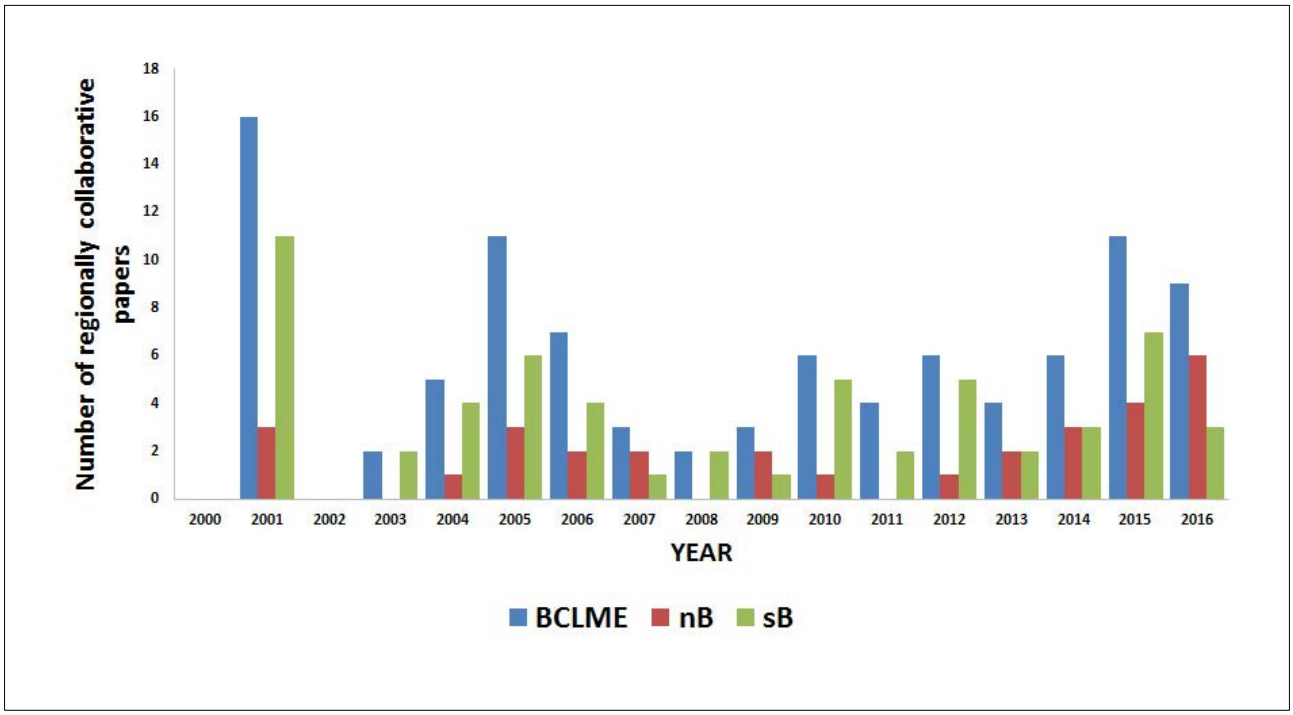

Figure 2: Temporal changes in the numbers of regionally collaborative peer-reviewed journal publications on the resources and/or environment of the Benguela Current Large Marine Ecosystem (BCLME) region over the period 2000–2016, by study focus area: BCLME, regional wide; nB, northern Benguela; sB, southern Benguela.

Table 1: Number of papers (*N*) published on the resources and/or the environment of the Benguela Current Large Marine Ecosystem (BCLME) region over the period 2000–2016. Also shown are the average number of authors per paper and the average number of participating countries per paper. Data subdivided by study focus area: BCLME, region wide; nB, northern Benguela; sB, southern Benguela.

Year	*N*	Authors	Countries	*N*			Countries			Authors		
				BCLME	nB	sB	BCLME	nB	sB	BCLME	nB	sB
2000	29	3.21	1.45	3	16	10	1.33	1.56	1.30	3.67	3.44	2.70
2001	56	3.82	1.95	8	31	17	1.63	2.26	1.53	4.38	4.00	3.24
2002	47	3.62	1.49	15	13	19	1.47	1.38	1.58	3.53	4.46	3.11
2003	37	3.92	1.76	5	11	21	2.20	1.82	1.62	3.80	5.18	3.29
2004	40	3.75	1.78	3	17	20	2.33	1.94	1.55	3.33	3.94	3.65
2005	61	3.51	1.72	13	17	31	2.08	1.88	1.48	3.31	4.35	3.13
2006	52	3.62	1.73	9	15	28	2.22	1.60	1.64	3.89	3.07	3.82
2007	51	3.55	1.55	10	17	24	1.30	1.65	1.58	3.80	3.06	3.79
2008	36	3.94	1.78	7	6	23	1.86	1.67	1.78	5.00	4.17	3.57
2009	46	4.59	1.93	9	11	26	2.44	1.82	1.81	6.89	4.09	4.00
2010	45	4.44	1.82	9	16	20	1.56	1.94	1.85	3.56	4.63	4.70
2011	37	4.49	1.78	4	14	19	1.25	2.00	1.74	2.50	4.36	5.00
2012	44	4.39	1.91	9	12	23	1.67	2.17	1.87	3.22	4.92	4.57
2013	40	4.73	1.63	6	17	17	2.50	1.53	1.41	5.50	4.53	4.65
2014	68	4.15	1.79	13	26	29	2.15	1.69	1.72	4.69	4.00	4.03
2015	59	4.8	1.86	13	19	27	2.31	2.21	1.41	6.00	4.16	4.67
2016	60	4.87	1.8	14	20	26	2.14	1.90	1.54	6.50	4.15	4.54

Approximately 43% of South Africa's publications in the region over the period under study did not involve any collaboration outside the country, and of the balance, only 18% were conducted with Namibia and/or Angola affiliated colleagues (Supplementary table 3). In other words, researchers in South Africa were best at working with themselves and chose to collaborate with non-regional partners on regional science. By contrast, Namibia and Angola depended heavily on collaboration. In the case of Namibia, only 7% of their outputs were generated 'in-country', and of the balance, 70% was conducted with regional collaborators: the comparative figures for Angola were 0% and 71%, respectively.

These figures clearly vary geographically. Few Namibia- and no Angola-based scientists have collaborated with South Africa based scientists on any studies with a focus on the southern Benguela, although South Africa has worked with its northern neighbours on *all* regionally collaborative papers in both the northern Benguela and the BCLME region as a whole. There is an obvious geographical bias to the data: all of the Angolan-led papers have focused on the northern Benguela, as too have 81% of the Namibian-led papers, and 72% of South African led papers have been conducted in the southern Benguela. In terms of actual numbers, however, South Africa has led more papers on the northern Benguela than has Namibia (Supplementary table 3).

International collaboration

A total of 40 non-regional countries have co-authored papers in marine science with a focus on the resources or environment of the BCLME over the period 2000–2016 (Supplementary table 2). Of these, co-authors from Germany, France, the UK and the USA have each contributed to more than 10% of outputs, with Norway participating in ~9% (Supplementary table 2). Notably, Germany has published more articles on the region than Namibia has, and most of the single-country papers produced by scientists from Germany were based on data collected in the northern Benguela (Supplementary table 2). The BCLME region as a whole was the focus of single-country papers from France and the USA, and in both these cases, scientists worked more on the southern Benguela than northern Benguela (Supplementary table 2). Overall, fewer non-regional, single-country studies were conducted in the south than the north (Supplementary table 2). Indeed, when we exclude South Africa's authored or co-authored publications, the majority of the international work has been conducted in the northern Benguela (62%) or has been based on BCLME-wide studies (24%).

The major collaborations between countries publishing on the environment and/or resources of the BCLME region over the period 2000–2016 are shown in Supplementary tables 3 and 4. There are many details in these tables, but the standout features include the facts that the biggest collaborators of German-based scientists were other German-based scientists, the biggest collaborators of French-based scientists were those affiliated to South Africa, and the latter were significant collaborators also with UK-, US- and Norwegian-based scientists. It is noteworthy that after South Africa, Norway was the greatest collaborator with Namibia and Angola (Supplementary table 3). When we consider the level of collaboration by country of the first author, the patterns change only subtly (Supplementary table 4).

Overall, German collaboration with the region was poor: 29% when expressed as a percentage of all Germany's outputs and only 51% when expressed with reference to non-'in-country' papers. By contrast, the comparative figures for Norway were 84% and 91%, respectively, whilst for France, they were 70% and 80%, respectively.

Discussion

A number of factors influence national research productivity, as measured by the publication of peer-reviewed journal articles.[8,9] Given these factors, it is not surprising to note that South Africa published more papers on the resources and/or environment of the BCLME region over the period 2000–2016 than either Namibia or Angola.

The number of publications with a focus on the BCLME as a whole or on the northern Benguela, penned by regional co-authors, has increased since 2007, supporting the idea that with financial intervention, regional research collaboration can be fostered. However, it is not widespread because the number of outputs is low and it would be interesting to examine further the motivations of the authors concerned.

Whilst the southern Benguela focus of South Africa's research may explain why the majority of South African publications excluded Namibian and Angolan co-authors, the disappointing fact remains that South Africa did not, and does not, collaborate extensively with neighbouring LME maritime states. And this despite the fact that the initial Science Plans for the BENEFIT and BCLME programmes were conceived, and co-authored, by scientists from all three countries. Indeed, it would appear that South Africa preferred to collaborate with non-regional partners. By comparison, Namibia and Angola rely heavily on out-country colleagues, reflecting perhaps a lack of other international collaborators, in contrast to South Africa. However, they are not as disappointing as the comparative figures for some of the foreign investors and partners. After all, a part of the BCLME is on the doorstep of South Africa, but is many thousands of nautical miles away for these other nations. Research for foreign nations in the BCLME, unless based on published data or historical samples, requires access to regional waters and therefore government authority.

In South Africa, the letter of permission authorising research by a foreign vessel within 'the EEZ, the Territorial Waters and the Contiguous Zone' does not stipulate formal collaboration. That said, a copy of the cruise report is requested, as too is a set of the duly collected data. Foreign nations often provide opportunities for human capacity development, usually on board the vessel and often using equipment that local scientists otherwise have no, or limited, access to. Whilst this willingness to train can be seen as altruistic (it comes at a cost to the funder and is not a permit condition), it is frequently a prerequisite imposed by the foreign, grant awarding body. In developing countries, human capacity development is always welcome. However, the training provided may not always be appropriate to regional needs, matching, as it invariably does, the expertise available on the vessel. Importantly, however, the IP that has gone into the science of the cruise is almost exclusively foreign: *meaningful*, locally sourced IP is rarely incorporated into either the science agenda or the detailed science plans *from the outset*.

In order to manage the science practice, it is argued that we need to know the worth of individual practitioners. The measurement of individual worth is fraught, but increasingly we are using metrics that variously combine numbers of publications and citations, etc. Disentangling individual worth from multi-author publications can be problematic. As a consequence, many journals now provide detailed guidelines to assist authors in determining who should be included as a co-author and who should simply be acknowledged. Of these guidelines, intellectual inputs around study design and conceptualisation are arguably most significant, although contributions to writing and data analysis are also valued.

Given this, is the lack of regional authorship in foreign-led science publications understandable? We would argue not, although we accept that the generation of new knowledge that can be used to better understand and/or manage our regional environment/resources is good, regardless from where it originates. The too-strict adherence to journal guidelines regarding authorship builds a level of frustration, distrust and resentment amongst local scientists who feel, rightly or wrongly, that they should be party to it, and in the long term, it could threaten the harmony of future research collaborations.

If you cast your mind back to your first peer-reviewed scientific publication, you will remember the excitement. When your work began to get cited, there was a feeling of worth and belonging. Out-of-country regional collaborators that are involved in the meaningful collection of data deserve to be included amongst the authors of collaborative research efforts, if for no other reason than a formal recognition of contribution. There may be very good reasons why collaborators may not have been able to get involved in the writing (language and confidence) or data analysis (lack of capacity), time constraints aside, and an understanding of these is important. The inclusion of collaborators on the author list comes at no reputational cost, yet it builds confidence and a willingness to collaborate in future. Further, we would argue, capacity development aimed at building teams of authors is likely to be more beneficial in the

long term than the acquisition of new skills that go unused. Such would go some way to legitimising collaborative authorship in the minds of the authorship purists.

Many of the issues raised above reflect differences in collaborator capacity, about which much has been written.[8,9] The most successful, meaningful, lasting and inclusive collaborations are built around projects that focus on a common problem, and which are conceived and initiated together.[10] A series of protocols has been developed to assist partners in the development of truly meaningful collaborative projects[11,12], and these protocols are being implanted by a number of funders across the world. It is not our intention here to repeat the recommendations proposed in these aforementioned documents, but we make a plea for regional scientists, and scientists interested in working within the region, to engage with this literature and begin to adopt the principles enshrined within it. Whilst the BENEFIT and BCLME programmes have been rightly hailed as successes[7,13], there is much room for improvement if we are to move forward in a more equitable way, as regional nations.

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Science in the service of society: Is marine and coastal science addressing South Africa's needs?

The modern world is confronted with many and diverse social and environmental challenges of high complexity. In South Africa, rapid and sustainable development is needed to address high levels of poverty and unemployment but this development has to take place in the context of an environment that is already severely impacted by human activities. Sound and relevant scientific input and advice, covering the full scope of each challenge, is essential for effective decisions and actions to address the needs. South Africa has the benefit of strong scientific capacity but the country's National Development Plan reported that national research priorities were not always consistent with South Africa's needs. We investigate the validity of that conclusion in the coastal and marine sciences by examining presentations made at the 2017 South African Marine Science Symposium on the theme of 'Unlocking the ocean's economic potential whilst maintaining social and ecological resilience'. Despite the theme, only 21% of the presentations were judged to be actionable and directly relevant to societal needs, as defined by the criteria used. Less than 7% were evaluated as being interdisciplinary within the natural sciences and approximately 10% were found to include both natural and human sciences. Poor representation by the human sciences was also noteworthy. This preliminary assessment highlights the need for an urgent review of the disciplinary representation and approaches in marine and coastal science in South Africa in the context of the priority practical needs of the country now and into the future.

Significance:

- Despite the urgent need for integrated scientific input and advice to guide responsible and sustainable national development, a preliminary snapshot of marine and coastal science in South Africa demonstrated a low regard for direct relevance and inter- and multidisciplinarity.
- If these general results are verified by a more comprehensive review, urgent realignment of funding and incentives for marine and coastal science, and probably environmental science in general, is likely to be required to ensure science provides a greater service to society, which is the source of much of the country's research funding.

Introduction

The world is facing many near-insurmountable social and environmental challenges that require sound and relevant scientific input and advice if they are to be overcome. In the marine and coastal domains these include ensuring sustainable use of resources and safeguarding biodiversity in the face of widespread poverty, increasing human consumption, climate change, pollution, over-exploitation, infrastructure development and others. At the same time, appreciation of the value of science and therefore support for science globally, including in South Africa, is often fragile.[1] Here we argue that urgent transformation of fundamental attitudes in South African science is required to make it more relevant, appreciated and available for addressing modern-world challenges in the country, in Africa and beyond.

South Africa has a long history of excellence in science and research with many local scientists enjoying international recognition. Research is undertaken and funded by a number of different organisations including government departments, parastatals such as the Council for Scientific and Industrial Research (CSIR), non-governmental organisations and the private sector. We have not investigated the sources and financial contributions of these organisations to research, but the science underpinning South Africa's good reputation does not come without a financial cost. A primary source of funding is the national Department of Science and Technology (DST), which has the mission of 'Increased well-being and prosperity through science, technology and innovation'. The total expenditure of the DST in 2016/2017 was just over ZAR7.38 billion, of which ZAR4.15 billion was spent on 'Research Development and Support', ZAR1.76 billion on 'Socio-Economic Innovation Partnerships' and ZAR1.02 billion on 'Technology Innovation'. Within this total, DST contributed ZAR3.54 billion to the National Research Foundation (NRF), and also contributed funds to the CSIR and other science-related entities.[2] In the same financial year, 2016/2017, the total expenditure of the NRF was ZAR4.51 billion, of which nearly ZAR2.7 billion was for Research and Innovation Support and Advancement and the Technology and Human Resources for Industry Programmes.[3] It must be recognised within the context of this paper that only small fractions of these amounts would have gone into marine and coastal research and that other government departments and state-supported entities also fund such research. The taxpayer and public in general are major contributors to research undertaken and funded by governments and parastatals and it is therefore reasonable to ask if the country is getting a worthwhile return for its investments in science.

It is necessary to consider this question within the local context. South Africa is ranked 119th in terms of its Human Development Index, making it one of the 'medium human development' countries.[4] The Human Development Index incorporates national mean life expectancy (57.7 years) and a mean gross national income per person (USD12 087). However, income per capita is heavily skewed; in 2015 there were over 30 million South Africans living in poverty (on less than ZAR992 per person per month). Unemployment in 2016 stood at nearly 27%.[5]

The needs for economic and social development to overcome these problems are enormous and urgent but they must be remedied in a sustainable way that does not prejudice the resources and environmental potential and opportunities in the future. Science and technology are critical for guiding and informing equitable and sustainable development but

South Africa is not doing very well in this regard either, and in 2015 the country invested only 0.8% of its gross domestic spending on research and development (conducted by all resident companies, research institutes, university and government laboratories, etc.), putting it 37th out of the countries reported on and far behind countries such as Korea (4.2%), Germany (2.9%) and China (2.1%). Malaysia and Brazil spend approximately 1.3% of their GDP on research and development.[6]

Marine and coastal ecosystems and resources provide essential livelihoods and services for hundreds of thousands of people in South Africa. The wholesale value of the marine fisheries sector in South Africa in 2016 was more than ZAR10 billion[7] and about 27 000 people are directly employed in the commercial sector alone[8]. Tourism centred on the oceans and coasts, shipping, offshore oil, gas and mining operations and other sectors provide employment and livelihoods to tens if not hundreds of thousands more. There is also pressure to expand and it has been estimated that South Africa's oceans could contribute as much as R177 billion to the country's gross domestic product and provide between 800 000 and 1 million jobs by 2033.[9]

The need for sustainable development and biodiversity conservation are recognised in South Africa's Constitution, which states that the environment must be protected for the benefit of present and future generations and that development must be ecologically sustainable (Constitution of the Republic of South Africa[10], Chapter 2, paragraph 24). However, the current and historical uses of the marine and coastal zone have put the environment under considerable stress. For example, the 2011 National Biodiversity Assessment[11] concluded that 43% of estuary ecosystems were threatened (39% critically endangered); 58% of coastal and inshore ecosystem types and 41% of offshore marine ecosystem types were considered threatened (24% and 11% critically endangered, respectively).

For resource management and conservation to be more effective and ethical, it must better engage the economic, political and sociocultural dimensions of humans as part of ecosystems.[12,13] Achieving the desired goals requires timely, reliable and relevant scientific information and advice, as emphasised in the National Development Plan (NDP)[14], which also warns that 'Despite an excellent set of science institutions, research priorities are not always consistent with South Africa's competitive advantage or growth strategy.'

What research priorities are required to serve society?

There is no simple way to define the research priorities that would best meet the needs of a developing South Africa, or of the world as a whole. Research needs will depend on the nature, problems and opportunities specific to each case. The approach of science and scientists to setting priorities can be divided into two models.[15] The first is the 'linear model', which emphasises basic research with limited consideration of the potential flow into application for societal benefit. Under the linear model, if potential relevance is a consideration, the scientist will envisage a flow from basic to applied research and then on to application.[15] The second model is the 'stakeholder model' in which the potential users of the research are involved in its design and production and the role of science in decision-making is an important consideration. The linear model can potentially lead to valuable application but we argue that the stakeholder model provides a more participatory and effective approach to ensuring relevance and maximum impact of the science, which are important considerations, especially in a resource- and capacity-limited country like South Africa.

A further aspect that must be considered when assessing the likely impact of science is the extent to which specific research considers or contributes to addressing the full scope of the problem or question. Many of the most intractable challenges that confront us today are complex social-ecological problems such as addressing climate change, the conflicts between development and environmental sustainability, over-exploited fish stocks, competition between different user groups for scarce resources and others. The South African small pelagics fishery serves as an example of the complexity of challenges such as these (Figure 1). Nevertheless, reductionist approaches to science, in which a complex scientific problem is broken down into simpler components, addressed individually, remain the predominant approach to science.[16] Reductionist science unquestionably has its uses but it is increasingly clear that isolated reductionist studies are insufficient for many of today's complex challenges. Karl Popper, a leading philosopher of science in the 20th century, wrote:

> *But this classification and distinction* [into disciplines] *is a comparatively unimportant and superficial affair. We are not students of some subject matter, but students of problems. And problems may cut right across the borders of any subject matter or discipline.*[17]

The response to these awakenings has been a growing demand for and engagement in interdisciplinary and transdisciplinary science.[16,18-21] This growth has been attributed to four drivers: (1) the need to solve societal problems; (2) the intrinsic complexity of social-ecological systems;

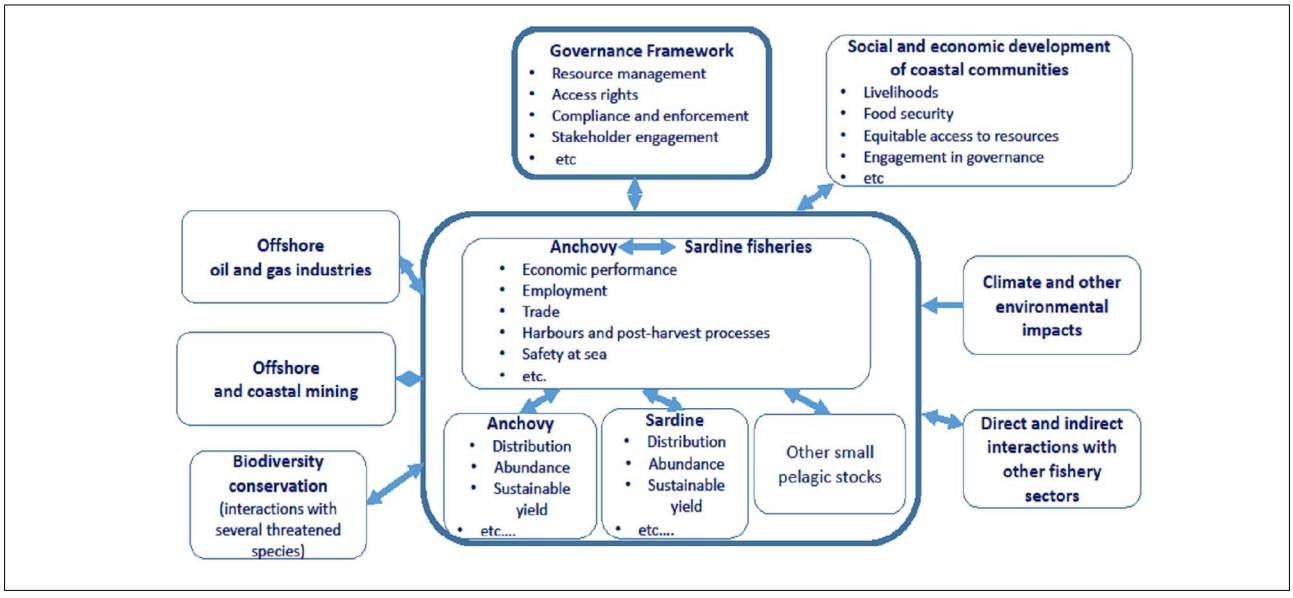

Figure 1: Simplified representation of an example of an integrated social-ecological system that needs to be managed as such: the South African fishery for small pelagic species. The boxes outlined in bold show the components of the core system and external drivers and stakeholders are shown outside the bold boxes.

(3) a desire to investigate issues beyond disciplinary boundaries; and (4) the capabilities of new technologies.[19] The first two are particularly relevant to South Africa while the second two can be seen as factors that should facilitate a shift towards interdisciplinary approaches.

Within this context, we undertook a preliminary assessment, within the field of coastal and marine sciences, of the validity of the concern expressed in the NDP about the disparity between the research priorities required for growth and development in South Africa and those being pursued in practice.

Methods

Scientific research in the marine and coastal environment in South Africa takes place in a number of universities, government departments, specialised research institutes such as the CSIR and the South African National Biodiversity Institute, non-governmental organisations and others. Outputs are published across a wide range of media types. It would be a massive task to survey all the bodies undertaking research and their outputs, and beyond the scope of this study. We therefore took advantage of the 2017 South African Marine Science Symposium (SAMSS) as providing a snapshot of current research in the field. SAMSS is an important biennial event in marine science in the country that aims to bring together local and some international marine and coastal scientists to present their work and exchange ideas. The theme of the 2017 event was 'Embracing the blue. Unlocking the Ocean's economic potential whilst maintaining social and ecological resilience'[22], which would appear to be particularly pertinent to this assessment of the relevance of South Africa's coastal and marine science to meeting social, economic and environmental goals and challenges.

Presentations at the symposium were divided into oral, speed (short oral presentations) and poster presentations. We focused on the oral and speed presentations on the assumption that they would be the more likely to include work from the established scientists and research that was already underway. Abstracts for the 102 oral and 80 speed presentations delivered at the symposium were assessed. The abstracts are available from the Congress Book on the Sancor website[22] and those related to oral and speed presentations can be determined from the programme, which is included in the Book. Alternatively, the PDF documents containing the abstracts already grouped into oral and speed presentation, downloaded from the no-longer available original symposium website (www.samss2017.co.za), are available from us on request. Each abstract was categorised according to the main discipline or theme covered and whether it was multidisciplinary or interdisciplinary in nature.

Disciplines and themes (listed in Table 1) were identified from examination of the abstracts and are intended to provide a general classification giving an indication of the scope of the presentations as a whole and areas of concentration. This approach means that not all disciplines in the natural and human sciences are included in the list. The categories range from conventional disciplines such as zoology and botany to broader categories going beyond traditional disciplinary boundaries, such as conservation of biodiversity and socio-economic development. The boundaries between botany and zoology on the one hand, and ecology on the other, are not always clear. For the purposes of this assessment, only studies that considered the ecology of several species or of systems as a whole and that included more than one natural science discipline (e.g. zoology and oceanography) were classified as ecology. We recognise that other, equally defensible, criteria could be used for this purpose that would produce different breakdowns and potentially higher representation of ecology as a discipline at the symposium.

The definitions of multi- and interdisciplinary research used were[19]:

> *Multidisciplinary: research that involves more than a single discipline in which each discipline makes a separate contribution;*
>
> *Interdisciplinary: research that 'integrates information, data, techniques, tools, perspectives, concepts, and/or theories from two or more disciplines or bodies of specialised knowledge to advance fundamental understanding or to solve problems whose solutions are beyond the scope of a single discipline or field of research practice'.*

The broad interpretation of multidisciplinary used in this assessment (Table 1) means that, for example, ecological research would normally be judged to be multidisciplinary because it involves biology (botany or zoology) as well as, for example, physics, chemistry and/or geology. In contrast, interdisciplinary studies require 'an integration and synthesis of ideas and methods' across two or more disciplines.[19]

Table 1: Guidelines and criteria used in classifying abstracts

Category	Guidelines	Notes and references
Main discipline or theme	Eight categories were applied: zoology; botany; ecology; oceanography; geology/geochemistry/geophysics; conservation of biodiversity; fisheries; socio-economic development (general).	In some cases, abstracts could have been classified under more than one discipline. In such cases the authors selected the option that they considered best fitted the abstract as presented. Further details are provided in the text.
Multidisciplinary	A broad interpretation of the definition was applied and included any study that made use of information from more than one discipline, even if only attempting to advance knowledge in one of them. The results therefore provide a somewhat optimistic result on incidence of multidisciplinary research.	US National Academy of Sciences[19]
Interdisciplinary science: split into either (1) within the natural sciences or (2) including both natural and human sciences	For (1) within the natural sciences, consistency with the US National Academy of Sciences definition[19] and for (2) consistency with the US National Academy of Sciences definition AND encompassing both natural and human sciences.	US National Academy of Sciences[19]. Our purpose with category (2) was to identify research that encompassed social-ecological systems as a whole.
Actionable and relevant to societal needs	(1) Clear and explicit links to practical application and benefits, including indication of the agencies or stakeholders through which this will be done; and/or (2) Abstracts need to demonstrate consistency with the 'stakeholder model' of science.	(2) Pielke[15]. Unsubstantiated and/or vague statements in an abstract that the research will be of benefit were not accepted as sufficient justification.

We did not attempt to distinguish between interdisciplinarity and transdisciplinarity[18] but recognise that both are important.

Finally, we considered whether the abstract fulfilled the criteria for being applied and directly relevant to priority societal needs. Research that fulfils those criteria is described here as being *actionable science*[23,24], which can be defined as:

> *Science that is relevant and/or applicable to government, business, and non-governmental organisational (NGO) audiences, and, in its broadest sense, can inform a larger, interested public. It is scholarship with the potential to inform decisions within government, business, and households; improve the design or implementation of public policies; influence public or private sector strategies; and inform planning and behaviors that affect the environment.*[25]

The term 'actionable science' is introduced and used in this paper in preference to the more general term 'applied science' because the former places particular stress on direct application and support to stakeholders, both of which are needed for growth and sustainable development in South Africa, as argued above. The specific criteria used for categorising the abstracts are provided in Table 1.

Results

Approximately 670 authors were listed in the abstracts for the oral and speed presentations. They included individuals from a number of different countries but the large majority were from South African entities. Without adjusting for duplications where individuals were authors of two or more presentations, and covering all countries represented, approximately 59% of authors gave their primary (first) affiliation as being a university, 18% as a national institution (partly or fully funded by the state), 13% as a government department, 3% as a provincial institution or government department, 1% as an NGO and approximately 6% were unknown.

The presentations were overwhelmingly dominated by the natural sciences: over 40% of the 182 oral and speed presentations were classified as being in the field of zoology, followed by ecology making up 13% of presentations. The relative contributions of zoology and ecology are dependent on the criteria used to distinguish them and, as discussed under Methods, different but equally defensible criteria could produce considerably different results on the split. Nevertheless, whether classified as zoology or ecology, presentations within the general field of zoology were dominant. Conservation of biodiversity was the third most common discipline or theme making up 10% of abstracts (Figure 2). A total of 12 presentations (7%) were classified as being in the field of socio-economic development but not all of those could be described as falling within the human sciences, for example reviews of the role of research programmes or specific disciplines in promoting economic development. Most presentations in the other two functional categories, fisheries and conservation of biodiversity, addressed natural science aspects.

Approximately 35% of the abstracts were judged to be multidisciplinary, using the generous interpretation described in Table 1. These abstracts were all within the natural sciences and no abstracts were identified that could be considered as falling within a conventional human science discipline (e.g. sociology, economics) or that involved two or more discrete human sciences (i.e. multidisciplinary). Most abstracts classified as socio-economic development were classified as being interdisciplinary. Overall, less than 7% of abstracts were evaluated as being interdisciplinary within natural sciences and approximately 10% of the presentations was found to encompass both natural and human sciences in an interdisciplinary manner (Figure 3).

The result that should arguably be of the greatest concern is that only 21% of the presentations, 38 out of 182, were judged to be actionable and directly relevant to societal needs, as defined by the criteria provided in Table 1.

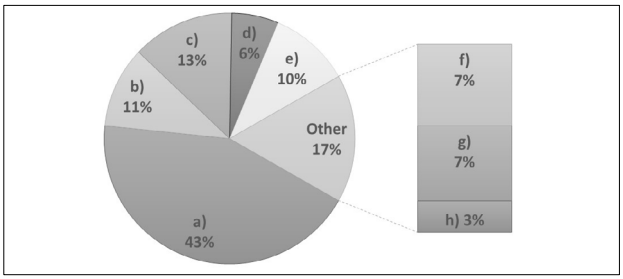

Figure 2: Percentage of presentations (n=182) according to discipline or theme: a) zoology; b) botany; c) ecology; d) oceanography; e) conservation of biodiversity; f) fisheries; g) socio-economic development (general); h) geology/geochemistry/geophysics.

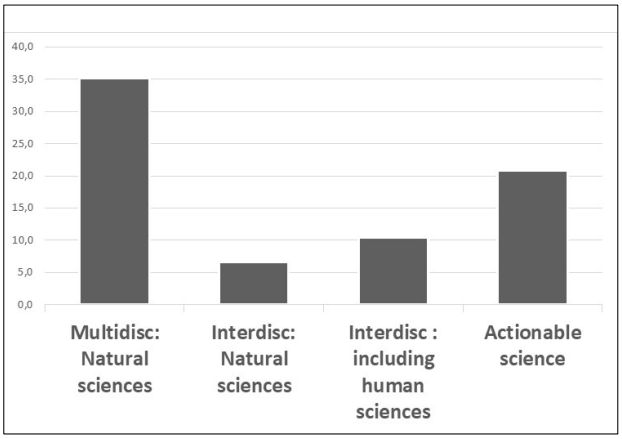

Figure 3: Percentage of presentations (n=182) that were multidisciplinary (Multidisc) or interdisciplinary (Interdisc) and that were assessed to be presenting actionable science.

Discussion

We acknowledge that examination of the oral presentations at a single event provides only a limited and incomplete snapshot of marine and coastal science in the country, but note that SAMSS is the premier national symposium for coastal and marine science in South Africa and can be assumed to have provided a reasonable sample of the leading science in the field across a range of institutions. It can also be argued that the abstracts do not always provide sufficient information for accurate application of the criteria but the abstract is intended to provide a concise overview and we took care to apply the criteria objectively and rigorously. If the research being undertaken was directed at contributing directly to addressing an identified societal need, it is reasonable to assume that this would be referred to in the abstract.

Overall, there will have been an element of subjectivity and potential for error in the categorisations and we consider the results to give only an approximation of the true situation but with the trends being sufficiently marked such that the potential error is unlikely to change the overall picture. The results presented here should therefore be of concern to all scientists, clients of science and funders of science in the country, particularly if one also takes into account the strongly applied, interdisciplinary theme of the 2017 event. If presenters and their co-authors had even noticed this theme, one could have expected the programme to be marked by actionable, interdisciplinary science, which clearly did not happen. Hence, while the banners of application and interdisciplinarity are frequently paraded around to try to accommodate for ongoing trends in science, scholarship and funding globally, true actionable and interdisciplinary research in South Africa appears still to be of limited popularity amongst the marine and coastal scientific community.

Comment must be made on the very poor representation by human sciences in the presentations. It seems clear that SAMSS is largely

perceived to be a natural science symposium and therefore that not much can be concluded from the SAMSS programme about the societal relevance of humanities in marine and coastal research or the engagement of human scientists in interdisciplinary research. One primary cause of the poor representation must be the lower number of human science practitioners in this field in South and southern Africa compared to natural scientists but that is not the only cause. Another important reason, and factor contributing to the lower number of social scientists, is a long-ingrained bias towards the natural sciences that pervades environmental conservation and management in general, including amongst managers of governmental institutions with a mandate for these tasks[21,26], notwithstanding the fact that the scientific advice is sometimes overruled for supposedly social or economic reasons. This bias towards the natural sciences creates substantial barriers in the responsible institutions and practices in marine resource management in South Africa, and globally, to greater involvement of the human sciences. These barriers apply particularly to the social sciences, including human ecology and geography, behavioural psychology and political ecology.

Factors within the human sciences also play a role and, based on our own experiences and interactions with researchers in the humanities, our perception is that there is a bias in South African social science and humanities towards engaging mainly in humanistic (post-modern, reflexivity, critical theory, etc.) academic debates around identity, race and gender. While important in themselves, these issues are of limited direct application to managing and conserving regional marine environment and resources. This raises the question of why so few social science and humanities scholars are studying fishing communities and the ecology of human-environmental interactions when this knowledge is so important for the well-being of both social and natural systems? We argue that an important reason is because contemporary humanities training, which is dominant in both northern and southern hemisphere universities, has a strong anti-science emphasis. Humanities have been challenging northern-dominated conservation models and science in general[27,28], and while such criticism is generally valuable, the growth of other empirical environmental social and behavioural sciences such as human ecology are fundamental to create a better link between the natural and social sciences. It is our view that scholars working in the humanities need to reform their discourse vis-à-vis natural scientists because today many have managed to marginalise their role[29], including by being unable or unwilling to relate to or communicate with natural scientists[30]. Humanities scholars are likely to reject the suggestion that they should change their discourse to match the agendas of natural scientists but this means that, sadly, many humanities scholars are engaged in abstract debates when the South African marine environment is being degraded at an unprecedented rate, contributing to the impoverishment of many of the same subjects that they study and which they want to liberate from poverty.

An additional, likely cause of low engagement of the human sciences in holistic interdisciplinary science and in stakeholder models of applied and actionable science is that the general academic drivers and incentives that lead to low engagement of natural scientists play a role with human scientists too.

This preliminary assessment highlights the need for a review of the disciplinary representation and approaches in marine and coastal science in South Africa in the context of the priority practical needs of the country now and in the future. The primary developments, threats and opportunities for coastal and marine environments and resources and the scientific information and advice most needed to address them should be identified. For example, Operation Phakisa[9] identified seven oceans economy focus areas that included offshore oil and gas, aquaculture, coastal and marine tourism and marine protection services and governance, to which should be added other areas of social and economic importance such as fisheries, conservation and coastal development. What types of scientific support are required to ensure sustainable, responsible and productive development or maintenance of all of these areas and how does that compare to the research status quo?

We recognise that pure science has a place in society[31] but the most pressing and alarming of the results must be the low incidence of presentations assessed to be directly relevant and actionable in addressing societal needs. We agree with the opinion expressed in a 2014 publication by McQuaid[31] that 'South Africa should aspire to being a nation that values science for its own sake' but also with his view that 'society can and should put demands on science' especially given the important and urgent social needs within the country. The key question for all engaged in science in the country, and at least other developing countries, is to find the appropriate balance. The results shown here suggest that society in South Africa has good cause to expect more practical support from science than it is receiving at present.

Similarly, high quality disciplinary science is frequently necessary in provision of scientific guidance to practical questions and problems but is rarely sufficient on its own. Disciplinary science should therefore not be discouraged but much greater emphasis must be placed on development of interest and capacity in interdisciplinary science to enable pressing, complex questions and problems to be addressed in the holistic and integrated way necessary for successful impact.

Overall, the indications from these results are in stark contrast to the missions of the DST: 'To provide leadership, an enabling environment and resources for science, technology and innovation in support of South Africa's development'[2] and the NRF: 'Catalysing knowledge production for societal benefit'[3]. It is a safe assumption that other governmental and parastatal organisations that contribute significantly to marine and coastal research in South Africa, including the Departments of Agriculture, Forestry and Fisheries and of Environmental Affairs, as well as the CSIR, are also mandated to focus on provision of sustainable benefits to society. We did not look at the performances of specific organisations against the criteria but our results demonstrate that, while some actionable science is indeed achieved, in practice much of the marine and coastal science being undertaken in South Africa is not being very effectively targeted at achieving these societally oriented missions.

The reasons behind the weaknesses identified here are complex but we suggest that a fundamental problem must be the incentives that drive scientific careers. One such incentive is the NRF rating process and standards. The NRF's rating criteria (http://www.nrf.ac.za/rating) put emphasis on 'high quality research outputs', which in practice is interpreted primarily as number of papers in the primary scientific literature and citations. We are all B-rated scientists, signifying recognition as 'internationally acclaimed researchers', but are of the firm opinion that these indicators do little to encourage attention to practical implications or interdisciplinary science and probably act more as an incentive for fragmented and 'clean' disciplinary approaches. In our view, the NRF needs to revisit its rating process and other funding instruments to ensure their outputs and outcomes are consistent with its mission and national needs.

The problem is of course much wider than NRF ratings and stems from a long history of reductive thinking and a culture-driven belief that pure science is more worthy than applied (and by implication actionable) science.[16,32] The obvious limitations of this outdated philosophy highlight the need for transformation in science in South Africa and globally so as to recognise and give priority, not just to excellence in science, but to the societal value of actionable science, particularly the science supported and facilitated by the general public through tax and other inputs.

Recommendations

The difficulty of breaking down the prevailing dominance of reductive, disciplinary-based thinking is not limited to South Africa and remains a global problem, but internationally there has been significant progress towards a greater role for holistic, interdisciplinary science in the scientific agenda.[16,19,20,33] For South Africa to ensure that our science is both relevant to the needs of the country and competitive with the latest and best of scientific practices internationally, we recommend:

1. NRF and DST should undertake a first assessment of the current and future needs for scientific research (natural, human and interdisciplinary) to advise and inform the development and use of the social-ecology of the country. This first assessment could be based on already available information, for example, from the

NDP and Operation Phakisa. Here we have addressed only coastal and marine science, but the exercise could usefully be expanded to include environmentally oriented science in general.

2. The first assessment undertaken could subsequently be taken further and finalised through a thorough review conducted in consultation with relevant stakeholder groups including but by no means limited to scientists.
3. Using the first assessment of needs as a starting point, DST, NRF, all tertiary educational and research institutions, and government departments and agencies engaged in environmental governance and research should, through a formalised and peer-reviewed process, urgently review their research and teaching activities and recent outputs in the context of the identified needs.
4. Thereafter, if the results from (3) indicate a substantial disparity between national needs and research activities and outputs, government and the private sector need to ensure that the necessary incentives and pressures are put in place to bring about rapid transition, wherever required, to ensure that resources being put into science are leading to optimal returns for the country as a whole. A simple example of such an incentive would be for government agencies to introduce funded calls for research projects or programmes specifically aimed to address clearly defined and pressing marine and coastal societal needs, and then to ensure that the funded research is adjudicated accordingly.
5. Ensuring the societal relevance of science and research will bring about benefits but must be accompanied by an increase in expenditure on actionable research and development to help to address the multiple and urgent social, economic and environmental challenges that need to be met and to facilitate achieving the goals of, for example, the NDP[14] and Operation Phakisa[9].
6. The changes required will almost certainly include a greater emphasis on interdisciplinary science and integrated, holistic approaches. Urgent priority therefore needs to be given to developing the capacity to meet that need. This requires producing and nurturing qualified practitioners in interdisciplinary science but also ensuring that disciplinary specialists are trained to be able to see beyond the silos of their own disciplines[34], to recognise how their expertise can contribute to wider programmes and to be open to working in interactive ways as members of multidisciplinary teams.
7. It is not within the scope of this article to suggest how to increase the number of qualified interdisciplinary scientists and the awareness of the need for interdisciplinary science in marine and coastal use and management but useful ideas can be found in the report 'Facilitating Interdisciplinary Research'[19] produced by the US National Academy of Sciences.
8. The benefits of the above steps will only be realised if the available and relevant scientific advice is actively solicited, welcomed and used wisely and effectively by the stakeholders, including government. This has not always been the case in the past and, for example, decisions in recent years by the Department of Agriculture, Forestry and Fisheries to exceed scientific recommendations on the total allowable catch of the already seriously depleted West Coast rock lobster *Jasus lalandii* resource[35] give cause for concern. Every effort should be made to ensure that decisions and actions taken by government departments and other stakeholders are based on the available scientific evidence, also taking into account, as appropriate, additional knowledge. This is essential if the Constitutional obligation for ecologically sustainable development is to be realised. In addition, government itself, not only in South Africa but globally, needs to overcome the common tendency to pursue sectoral and vested interests and, instead, to adopt sustainable integrated approaches.[26,36] It is hoped that the 2017 Marine Spatial Planning Bill[37] indicates a movement in this direction for governance of the nation's oceans.

Finally, the quality and reliability of actionable and interdisciplinary science are at least as important as in any other fields of science, and scientists, funders and users of marine and coastal science need to ensure and insist on scientific rigour in design, implementation and interpretation. As in so many other areas, the unique characteristics and diversity of South Africa and its people mean that South African science and scientists could provide innovative leadership in forging new models and paradigms in science for development and sustainability.

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Authors' contributions

K.L.C. was the lead author, and took the lead in all aspects of the study, including conceptualisation, development of the methodology, collation and analysis of data and writing of the initial draft and revisions. W.H.H.S. and S.A. made substantial contributions to conceptualisation, development of the methodology and writing of the initial draft and revisions. W.H.H.S. also contributed substantially to the collation and analysis of the data.

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Growth and yield parameters of three cowpea (*Vigna unguiculata* L. Walp) lines as affected by planting date and zinc application rate

Cowpea is one of the most important food legumes in most African countries. Cowpea is a valuable source of dietary protein for both humans and their livestock. There is limited information available on cowpea production and suitable agronomic practices, such as planting date, to best suit different environmental conditions in South Africa. Therefore, the objective of this study was to evaluate the effect of two locations on cowpea production and the effect of planting date as affected by zinc application rate. Field experiments were conducted at two locations (Bien Donne' and Nietvoorbij) in the Western Cape Province of South Africa, using two planting dates (2 October and 2 November), three cowpea lines (Veg1, M217 and Qukawa) and three zinc (Zn) fertiliser application levels (0 kg/ha, 15 kg/ha and 30 kg/ha) during the 2015 growing season. The experimental design was a randomised complete block with five replicates. The results showed that Veg1 and Qukawa lines performed significantly better in both vegetative and reproductive parameters when compared to M217 at both locations. Application of zinc fertiliser significantly ($p<0.05$) affected seed iron content in Veg1 and M217 at Bien Donne' and seed iron content in M217 and zinc content in Veg1 at Nietvoorbij.

Significance:

- Cowpea lines Veg1 and Qukawa were the best performing lines in all parameters measured, making these two lines suitable for dual purpose cultivation.
- Planting cowpea in November, rather than October, increased the crop production efficiency.
- Cowpea showed a better overall total yield in the sandy soil of Bien Donne' than in the sandy loam clay soil of Nietvoorbij.

Introduction

Cowpea (*Vigna unguiculata* L. Walp) is a significant grain and fodder pulse grown around the world.[1,2] It serves as a dual purpose grain legume crop, providing food for human consumption and fodder for livestock.[3] This crop is successful in most regions because of its ability to survive in low fertile soils[4], and withstand alkaline soils[5]. Cowpea is a staple crop in most African countries.[6] According to Gomez[7], Africa is the leading continent in cowpea production at 68%, followed by Brazil at 17%, Asia at 3%, the USA at 2%, with the remaining 10% produced by the rest of the world. Africa alone accounts for 10 million hectares under cowpea production[8] and the crop is indigenous to Africa[3,9]. Cowpea seed as well as the vegetative parts make a major nutritional contribution to the human diet.[10] The seed contains 25% protein and 64% carbohydrates[11,12], with 27–34% protein in the leaves[13,14]. In South Africa, cowpea is mainly cultivated in the Limpopo, Mpumalanga, North-West and KwaZulu-Natal Provinces.[15] Cultivation of cowpea is mainly to maintain the nitrogen status of soil, thereby reducing the costs of commercial nitrogen fertilisers.[16] According to Bloem et al.[17], biological nitrogen fixation of leguminous crops is an affordable and sustainable biological method to enhance soil fertility that is used by South African farmers to increase crop yield.

Cowpea has been identified as a neglected and underutilised crop species, with further research required in some parts of Africa where there is limited information on its cultivation agronomic practices and seed handling as it is of relatively less commercial interest.[18-20] In South Africa, there is very limited information on the cultivation and agronomy of cowpea because of a lack of interest and funding.[21] Recent results have shown that cowpea is still an underutilised crop.[22] According to Quass[23], no coordinating body exists for cowpea production in South Africa and consequently there are no available data on production. This limitation results in poor supply of good quality seed.[24] To the best of our knowledge, there is no reported information on the cultivation practices of cowpea in the Mediterranean climate of the Western Cape Province of South Africa. In this study, we therefore present the first report on the cultivation of cowpea under two planting dates and at different levels of zinc application in the Cape Winelands region of the Western Cape Province.

The Winelands region contributes to the highest cultivation of grapes which needs high soil fertility. Farmers in the Western Cape Province mostly practice mixed farming which predominantly includes livestock. Integration of cowpea in the vine-based cropping system of the Western Cape can improve nitrogen and carbon supply to the soil with a resultant reduction in the use of chemical fertiliser. The dual purpose cowpea tested in the trial will significantly increase plant-based protein for humans and livestock; and also improve soil fertility for ultimately improved grape production under limited application of mineral fertiliser.

Material and methods

Cowpea lines and study area

Three cowpea lines were used in the study: Veg1, M217 and Qukawa. These lines were obtained from the Genebank of the Vegetable and Ornamental Plant Institute of the Agricultural Research Council, Pretoria, South Africa. Morphological traits of the three lines were recorded according to the International Board for Plant Genetic Resources[25] as presented in Table 1. The field experiment was conducted at the Agricultural Research Council in Stellenbosch, Western Cape. The experiment was done on two Agricultural Research Council research farms – Bien Donne' (33°55'S, 18° 52'E, altitude 139 m) and Nietvoorbij (33°65'S, 18°36'E, altitude 149 m) – during the

Table 1: Qualitative and quantitative traits of the three cowpea lines

Line	Trait														
	GP	GH	LC	FC	NMB	PPP	PA	PL	PS	NPPP	PC	SPP	SC	ST	SS	SW
Veg1	2	3	7	4	4.3	3	3	15.8	3	40.7	1	15.1	3	1	5	11.7
M217	1	2	5	2	4.5	3	5	10.1	5	26.2	2	8.4	1	3	1	14.3
Qukawa	2	5	5	4	4.4	2	3	17.25	3	18.7	3	10.8	2	1	1	14.1

GP, growth pattern: *1, determinate, 2, indeterminate;* ***GH, growth habit****: 1, acute erect (branches form acute angle with main stem), 2, erect (branching angle less acute than above), 3, semi-erect (branches perpendicular to main stem, but do not touch ground), 4, intermediate (most lower branches touch the ground), 5, semi-prostrate (main stem reaches 20 cm or more), 6, prostrate (plants flat on ground),7, climbing;* ***LC, leaf colour****: 3, pale green, 5, intermediate green, 7, dark green;* ***FC, flower colour****: 1, white, 2, yellow, 3, red, 4, purple;* ***NMB, number of main branches****: average of 10 randomly selected plants;* ***PPP, pods per peduncle****, average of mature pods from 10 randomly selected plants: 1=1–2, 2=2–3, 3=3–4;* ***PA, pod attachment****: 3, pendant, 5, 30–90º down from erect, 7, erect;* ***PL, pod length (cm)****: average of 10 mature pods from 10 randomly selected plants;* ***PS, pod shape****: 0, straight, 3, slightly curved, 5, curved, 7, coiled;* ***NPPP, number of pods per plant****: average number of pods from 10 selected plants;* ***PC, pod colour****: 1, pale tan or straw, 2, dark tan, 3, dark brown;* ***SPP, seed per pod****: average of 10 pods;* ***SC, seed colour:*** *1, cream, 2, brown, 3, grey; 4, black or dark purple; 5, other;* ***ST, seed texture****: 1, smooth, 3, smooth to rough, 5, rough, 7, rough to wrinkled, 9, wrinkled;* ***SS, seed shape:*** *1, kidney, 2, ovoid, 3, crowder, 4, globose, 5, rhomboid;* ***SW, seed weight (g)****: weight of 100 seeds per treatment*

2015 summer growing season. The soil at Bien Donne' has a sandy loam texture with a relatively high percentage of sand (77%) and low clay percentage (14.2%). The soil at Nietvoorbij is a sandy clay loam with 69.7% sand and 20.6% clay. The Western Cape Province has a Mediterranean climate and the study area has an annual rainfall of 278 mm, of which approximately 178 mm falls from March to August.[26]

Experimental design and treatment

The trial layout was a randomised complete block design replicated five times with an experimental plot size of 2 m x 1 m. Cowpea seeds were sown at an inter-row spacing of 0.4 m and intra-row spacing of 0.2 m. The experiment had four factors: the two planting dates (2 October and 2 November 2015), two soil types (sandy clay loam and sandy loam soil), three cowpea lines (Veg1, M217 and Qukawa) and three levels of zinc (1= 0% or control, 2 = 50% and 3 = 100%). Soil application of zinc sulfate ($ZnSO_4$) was done at flowering. The trial consisted of nine treatments per location per planting date (Table 2).

Cultivation practices and management

The experimental sites were ploughed, disc-harrowed and levelled into experimental plots. Two seeds were sown per stand using the dibbling method. Plants were later thinned to one plant per stand when the second trifoliate leaves had unfolded. Hand weeding of experimental units was done at 4 weeks after germination and subsequently at 3-week intervals as needed. Cutworm was controlled by applying Cutworm Bait 4 weeks after planting, while aphids were controlled with Kemprin 200 EC sprayed at a rate of 1.0 mL/L water using a backpack sprayer.

Data collection and analysis

Vegetative data were taken from the inner two rows at 2-week intervals. The number of germinated plants was recorded at 7 days after planting and germination (GP) was calculated as a percentage of germinated plants per experimental unit using the formula of Pahla et al.[27]:

GP= no. of g/T x 100,

where g is the number of germinated plants and T is the total number of seeds planted.

The number of leaves borne on each plant at full leaf maturity was counted and the number of branches per plant was obtained by counting the main stem of the sample plants. Plant height (m) was measured from the main stem, from ground level to the tip of the plant using a meter ruler.

Reproductive parameters were collected after harvesting the two middle rows from each experimental unit. Matured pods from sample plants were counted per plant, weighed (g) and measured in metres. Hundred-seed weight (g) was determined by randomly counting 100 seeds from threshed pods per experimental unit using a digital weighing scale.

Table 2: Treatment details and codes

Cowpea line	Name	Zinc level	Application rate
1	Veg1	1	0% Control
1	Veg1	2	50% Zn
1	Veg1	3	100% Zn
2	M217	1	0% Control
2	M217	2	50% Zn
2	M217	3	100% Zn
3	Qukawa	1	0% Control
3	Qukawa	2	50% Zn
3	Qukawa	3	100% Zn

Data on vegetative and reproductive parameters as well as the mineral content of the seed were subjected to an analysis of variance (ANOVA) using SAS.[28] Treatments were tested at a 5% level of significance and differences between treatments were separated using least significant difference and Duncan's Multiple Range Test of the SAS 2012 package.

Results

Vegetative parameters

Cowpea lines had a significant difference ($p<0.05$) in germination percentage. Line 1 showed significantly more ($p<0.05$) germination than Line 2 during the October planting date. Germination percentage was generally higher during the second planting date for both locations (Table 3). Figure 1 shows germination of the three cowpea lines as affected by location.

The number of leaves per plant was not significantly different between cowpea lines and Zn levels at the two locations. Line 1 at Zn level 2 produced the most branches per plant at Bien Donne' (Table 4). Lines 1 and 3 produced taller plants than Line 2 at both locations. The second planting date had a significant effect on all the vegetative parameters measured at Nietvoorbij.

Table 3: Effect of planting date on the germination rate of three cowpea lines at two locations

Cowpea line	Bien Donne'		Nietvoorbij	
	October	November	October	November
1	89[a]	94[a]	81[a]	97[a]
2	75[b]	93[a]	53[b]	93[a]
3	85[ab]	93[a]	79[a]	95[a]
$LSD_{0.05}$	12.25	15.85	15	15.9

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

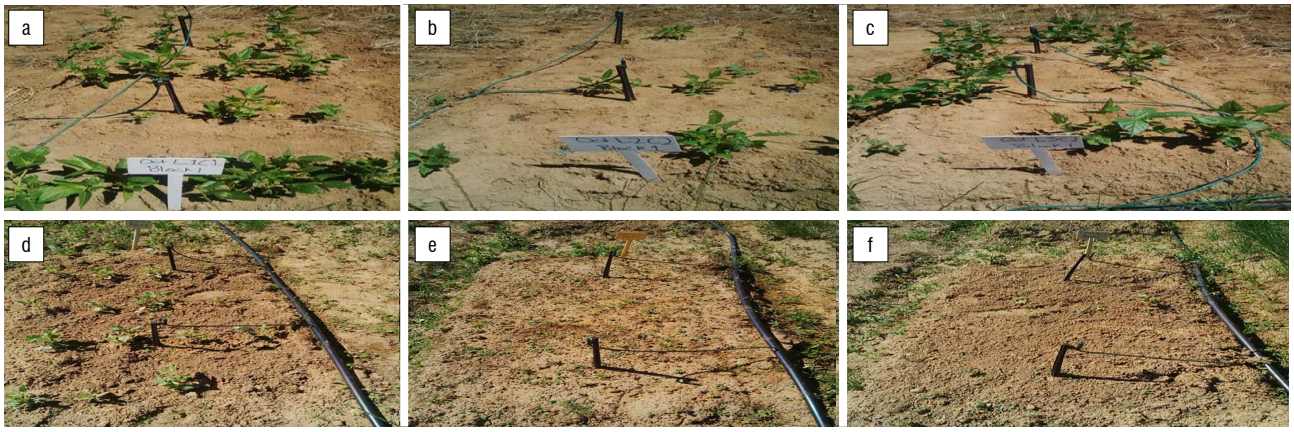

Figure 1: Photograph showing vegetative growth of the three cowpea lines (a,d) Veg1, (b,e) M217 and (c,f) Qukawa at (a–c) Bien Donne' and (d–f) Nietvoorbj at 8 weeks after planting for the first planting date.

Table 4: Effect of cowpea line and zinc application rate on vegetative parameters at two locations

Cowpea line	Zinc level	Bien Donne'			Nietvoorbij		
		Number of leaves	Number of branches	Plant height (cm)	Number of leaves	Number of branches	Plant height (cm)
1	1	65.26[a]	7.06[a]	15.52[a]	59.75[a]	5.17[a]	15.60[a]
1	2	67.37[a]	7.21[a]	14.05[a]	63.26[a]	4.93[a]	14.60[a]
1	3	50.06[a]	6.36[ab]	12.63[a]	48.49[a]	5.06[a]	14.24[a]
2	1	47.19[a]	5.66[ab]	5.10[b]	45.39[a]	3.08[a]	5.26[b]
2	2	54.59[a]	6.20[ab]	5.14[b]	58.38[a]	5.36[a]	5.49[b]
2	3	46.91[a]	4.93[b]	5.47[b]	60.50[a]	4.53[a]	6.25[b]
3	1	56.77[a]	6.90[ab]	15.17[a]	56.09[a]	5.03[a]	15.75[a]
3	2	52.18[a]	6.48[ab]	12.74[a]	56.40[a]	5.30[a]	14.37[a]
3	3	52.36[a]	5.61[ab]	14.17[a]	48.32[a]	3.87[a]	15.16[a]
$LSD_{0.05}$		25.16	2.09	4	25.39	1.64	5.3
Planting date							
October		55.13[a]	8.17[a]	10.09[b]	27.12[b]	3.58[b]	6.82[b]
November		54.36[a]	4.52[b]	12.23[a]	81.71[a]	5.94[a]	17[a]
$LSD_{0.05}$		7.27	0.87	1.68	13.37	1.27	2.28

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Reproductive parameters

Bien Donne'

The effect of cowpea lines on the measured reproductive parameters is presented in Table 5. A non-significant effect within each cowpea line in response to the different Zn levels was observed in most measured reproductive parameters. Line 1 at Zn level 1 produced the most pods but these results were not significantly different to the other lines at the same Zn level. Generally, more pods were produced after the first planting date, thereby increasing the pod weight for all treatments at Bien Donne'.

The results of the analysed seed chemical composition of the three cowpea lines are presented in Table 6. No differences were found in the accumulation of potassium among cowpea lines. The three Zn application levels did not have a significant effect on the seed mineral content within each line. However, a significant decrease in iron content from 88.75 mg/kg to 77.50 mg/kg was observed with the application of Zn in Line 1, representing 12.7% Zn content accumulation. Contradicting results were observed for Line 2 (Table 6). The first planting produced significantly higher seed mineral contents of phosphorus, iron, zinc and calcium.

Nietvoorbij

At Nietvoorbij, Line 1 produced the most harvested pods per plant, and thereby the highest pod weight (Table 7). Lines 1 and 3 obtained the highest number of seeds per pod; a similar trend was observed in pod length with Line 2 obtaining significantly fewer seeds per pod and lower pod weight. The second planting produced significantly more seeds per pod, and greater pod length and 100-seed weight at this location.

The three cowpea lines differed significantly in their measured seed mineral contents, except for nitrogen (Table 8). Variation of seed mineral content was observed between the different cowpea lines but the non-significant response to Zn application was observed for most of the minerals measured. However, application of Zn at Level 3 significantly increased iron in Line 2 compared to application of Zn at Level 2, with iron concentrations of 97.75 mg/kg and 83.50 mg/kg, respectively. A significantly lower Zn content was observed when Zn fertiliser (Level 2) was applied to Line 1. The first planting produced significantly higher phosphorus and sodium contents.

Seed yield

The average seed yield of the three cowpea lines was 60.7 kg/ha and 1184.2 kg/ha at Nietvoorbij and Bien Donne', respectively. The average seed yield per hectare (ha) across the locations is presented in Table 9. At both locations, Lines 1 and 3 performed significantly better than Line 2. At Bien Donne', Line 3 showed a significant 46.6% yield increase compared with Line 2. Remarkably, average seed yield at Bien Donne' was about 58% more than that at Nietvoorbij. The results of the current study generally indicate a very poor performance of Line 2 at Nietvoorbij with up to 87% in seed yield compared with that of Line 1.

Table 5: Influence of zinc application and cowpea line on reproductive parameters at Bien Donne'

Cowpea line	Zinc level	Number of pods/ plant	Total harvested pods	Pod weight (g)	Number of seeds/ pod	Pod length (cm)	100-seed weight (g)
1	1	30.02^{a}	1046.1^{a}	2086.3^{a}	16.53^{ab}	16.35^{b}	11.4^{b}
1	2	34.62^{a}	1027.0^{ab}	2221.5^{a}	16.71^{a}	16.42^{b}	11.5^{b}
1	3	31.61^{a}	995.5^{ab}	2019.3^{a}	15.75^{abc}	16.18^{b}	12.2^{b}
2	1	25.99^{a}	831.9^{abc}	1021.9^{b}	9.26^{d}	11.97^{c}	14^{a}
2	2	30.02^{a}	780.9^{bc}	1104.7^{b}	9.65^{d}	11.78^{c}	13.8^{a}
2	3	32.72^{a}	598.0^{c}	973.8^{b}	9.37^{d}	11.52^{c}	13.4^{a}
3	1	19.64^{a}	854.3^{ab}	2157.5^{a}	15.49^{bc}	17.81^{a}	13.7^{a}
3	2	21.61^{a}	869.6^{ab}	2229.7^{a}	14.92^{c}	17.56^{a}	14^{a}
3	3	20.17^{a}	926.6^{ab}	2368.4^{a}	15.54^{bc}	17.57^{a}	13.4^{a}
$LSD_{0.05}$		15.26	246.59	545.43	51.08	0.57	1.08
Planting date							
October		28.86^{a}	936.32^{a}	1926.8^{a}	13.89^{a}	15.28^{a}	12.6^{b}
November		25.82^{a}	835.10^{b}	1673.4^{b}	13.50^{a}	15.27^{a}	13.49^{a}
$LSD_{0.05}$		4.63	73.82	209.74	0.6	0.33	0.52

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Table 6: Cowpea seed mineral content after zinc application at Bien Donne'

Cowpea line	Zinc level	%			mg/kg				
		N	P	K	Na	Fe	Zn	Ca	Mg
1	1	3.96^{ab}	0.5^{cd}	1.57^{a}	119.25^{ab}	88.75^{a}	35.00^{b}	0.12^{bc}	0.21^{a}
1	2	4.08^{a}	0.49^{d}	1.53^{a}	126.00^{a}	84.25^{ab}	39.00^{ab}	0.11^{cd}	–
1	3	3.96^{ab}	–	1.46^{a}	128.50^{a}	77.50^{bc}	37.25^{b}	0.10^{cd}	0.20^{b}
2	1	3.86^{ab}	0.52^{bcd}	1.47^{a}	107.25^{ab}	67.00^{c}	38.25^{ab}	0.15^{a}	0.18^{c}
2	2	3.78^{b}	0.53^{abc}	1.48^{a}	106.25^{ab}	86.50^{ab}	36.25^{b}	0.14^{ab}	0.20^{b}
2	3	3.88^{ab}	0.53^{ab}	1.49^{a}	77.75^{b}	82.25^{ab}	28.75^{ab}	0.15^{a}	0.19^{bc}
3	1	3.94^{ab}	0.54^{ab}	1.52^{a}	111.25^{ab}	79.25^{ab}	39.00^{ab}	0.10^{d}	0.20^{b}
3	2	4.08^{a}	0.56^{a}	1.57^{a}	107.25^{ab}	85.00^{ab}	42.00^{a}	0.11^{cd}	0.20^{b}
3	3	3.98^{ab}	0.53^{abc}	1.53^{a}	80.75^{b}	80.50^{ab}	38.25^{ab}	0.11^{cd}	0.20^{b}
$LSD_{0.05}$		0.26	0.03	0.13	37.56	10.85	4.12	0.02	0.01
Planting date									
October		3.92^{a}	0.53^{a}	1.52^{a}	118.11^{a}	88.06^{a}	39.56^{a}	0.13^{a}	0.19^{a}
November		3.98^{a}	0.51^{b}	1.50^{a}	96.17^{a}	74.39^{b}	36.83^{b}	0.12^{b}	0.19^{a}
$LSD_{0.05}$		0.15	0.02	0.04	28.19	7.35	2.28	0.01	0.01

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Table 7: Influence of zinc application and cowpea line on reproductive parameters at Nietvoorbij

Cowpea line	Zinc level	Number of pods/ plant	Total harvested pods	Pod weight (g)	Number of seeds/ pod	Pod length (cm)	100-seed weight (g)
1	1	38.31^{a}	542.20^{ab}	1074.2^{ab}	13.78^{a}	16.14^{a}	12.22^{abcd}
1	2	25.47^{abc}	640.57^{a}	1372.5^{a}	13.27^{a}	15.78^{a}	12.11^{abcd}
1	3	33.15^{ab}	647^{a}	1296.7^{a}	13.95^{a}	16.02^{a}	12.5^{abc}
2	1	12.01^{d}	121.50^{d}	121.4^{c}	5.23^{c}	8.24^{c}	9.1^{d}
2	2	17.27^{cd}	121.67^{d}	127.3^{c}	7.87^{b}	11.58^{b}	10.6^{bdc}
2	3	12.29^{d}	180.38^{cd}	180.2^{c}	6.25^{bc}	9.26^{c}	9.4^{cd}
3	1	17.25^{cd}	417.50^{b}	1006.2^{ab}	12.74^{a}	17.23^{a}	14.1^{a}
3	2	21.13^{bcd}	431.80^{b}	1029.5^{ab}	13.65^{a}	17.79^{a}	14.22^{a}
3	3	14.39^{cd}	356.20^{bc}	838.1^{b}	12.24^{a}	16.87^{a}	12.9^{ab}
$LSD_{0.05}$		12.85	195.61	421.79	1.75	2.07	3.3
Planting date							
October		27.61^{a}	405.64^{a}	854.90^{a}	10.56^{b}	13.71^{b}	10.74^{b}
November		15.52^{b}	374.91^{a}	763.16^{a}	11.75^{a}	15.09^{a}	12.98^{a}
$LSD_{0.05}$		5.55	63.67	179.37	0.83	0.9	1.37

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Table 8: Cowpea seed mineral content after zinc application at Nietvoorbij

Cowpea line	Zinc level	%			mg/kg				
		N	P	K	Na	Fe	Zn	Ca	Mg
1	1	3.77^{a}	0.47^{b}	1.55^{ab}	321.5^{abc}	75.50^{c}	62.00^{a}	0.14^{c}	–
1	2	3.77^{a}	0.51^{ab}	1.59^{a}	356.75^{a}	75.50^{c}	57.50^{b}	–	0.20^{a}
1	3	3.88^{a}	0.49^{ab}	1.59^{a}	346.75^{ab}	73.00^{c}	54.50^{bc}	0.13^{c}	0.20^{a}
2	1	3.81^{a}	0.51^{ab}	1.53^{abc}	277.50^{abcd}	92.00^{ab}	50.00^{de}	0.17^{ab}	0.18^{b}
2	2	3.86^{a}	0.52^{a}	1.55^{ab}	287.50^{abc}	83.50^{bc}	49.25^{e}	0.19^{a}	0.19^{b}
2	3	3.79^{a}	0.55^{a}	1.54^{ab}	285.25^{abc}	97.75^{a}	51.25^{cde}	0.18^{a}	0.19^{b}
3	1	3.94^{a}	0.48^{b}	1.45^{c}	210.25^{cd}	77.00^{c}	53.25^{cd}	0.14^{c}	0.19^{b}
3	2	3.97^{a}	0.49^{ab}	1.45^{c}	159.00^{d}	76.00^{c}	54.00^{bc}	0.13^{c}	0.18^{b}
3	3	3.82^{a}	0.51^{ab}	1.48^{bc}	229.00^{bcd}	77.50^{c}	54.25^{bc}	0.15^{bc}	0.19^{b}
$LSD_{0.05}$		0.39	0.07	0.09	120.77	13.45	3.76	0.03	0.01
Planting date									
October		3.85^{a}	0.52^{a}	1.54^{a}	286.56^{a}	80.67^{a}	53^{a}	0.15^{a}	0.19^{a}
November		3.84^{a}	0.50^{b}	1.51^{a}	263.11^{b}	81.06^{a}	53.53^{a}	0.15^{a}	0.19^{a}
$LSD_{0.05}$		0.2	0.01	0.05	13.89	7.49	2.8	0.01	0.003

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Table 9: Average seed yield (kg/ha) across the two locations

Cowpea line	Zn level	Bien Donne'	Nietvoorbij
		Yield (kg/ha)	Yield (kg/ha)
1	1	1043.15^{a}	537.1^{ab}
1	2	1110.75^{a}	686.25^{a}
1	3	1009.65^{a}	648.35^{a}
2	1	510.95^{b}	60.7^{c}
2	2	552.35^{b}	63.65^{c}
2	3	486.9^{b}	90.1^{c}
3	1	1078.75^{a}	503.1^{ab}
3	2	1114.85^{a}	514.75^{ab}
3	3	1184.2^{a}	419.05^{b}
$LSD_{0.05}$		272.72	210.90
Planting date			
October		963.4^{a}	427.45^{a}
November		836.7^{b}	381.58^{a}
$LSD_{0.05}$		104.87	89.69

$LSD_{0.05}$, least significant difference; L1, Veg1; L2, M217; L3, Qukawa; T1, 0% Zn; T2, Zn at 50%; T3, Zn at 100%.

Means with different superscript letters within the same column are significantly different ($p<0.05$).

Discussion

The qualitative and quantitative traits of the cowpea lines studied varied (Table 1); the traits outline the morphology of the three cowpea lines studied. Morphological traits of cowpea lines and the importance of these traits are well documented by Egbadzor et al.[29] Veg1 and Qukawa had the highest mean germination rate, while M217 had the lowest number of germinated plants per experimental unit. The obtained results were similar to those reported by Wada and Abubakar[30] who did a germination test on different cowpea lines and concluded that seed size and viability of seed are the factors that affect germination on different cowpea lines. The results of the study indicate that Veg1 and Qukawa can successfully be sown early (2 October) or late (2 November) in the Western Cape region (Figure 1). Furthermore, M217 will successfully germinate to its highest capacity if sown later (2 November) in the growing season when temperatures are between 10 °C and 30 °C. Germination rate was significantly affected by soil type; in sandy loam soil germination was more efficient than in sandy clay loam soils as a result of the different soil textural percentages at the two locations. Similar results were obtained from a study done by Pahla et al.[27] who found a higher percentage of germination and emergence on sandy loam soils.

Vegetative parameters of the three cowpea lines differed significantly, which could be associated with genotypic make-up, season or location.[31,32] There were no significant differences in the number of leaves per plant observed at Bien Donne' or at Nietvoorbij. Comparable findings on the number of leaves were documented by Olatunji et al.[33] The two farms had soils of different textures. We have shown that plants at Nietvoorbij, which has clay loam soils, had the most branches and greatest plant heights compared with those of Bien Donne'. The results regarding the number of branches are in agreement with those of Shiringani[24].

Veg1 and Qukawa showed the greatest plant heights and M217 was shorter across the two locations. This difference could be associated with the genetic make-up of each line, as the morphological trait of the two lines showed a similar growth pattern. According to Egbadzor et al.[29], plants that are classified as indeterminate are most vigorous. Veg1 had an indeterminate or spreading type plant pattern which concurs with the above statement of Egbadzor et al. According to our results, zinc

fertiliser application at the onset of flowering did not have a significant effect on the vegetative growth of cowpea. These findings are contrary to the results of Elowad and Hall[4], who concluded that early flowering soil application of fertiliser increases the number of branches and pods of cowpea lines. Veg1 and Qukawa were recognised as the best performing lines for cultivation at both locations. Parameters such as the number of pods per plant and number of seeds per pod contributed to the total yield harvested of the two lines. The mean number of pods was in the range of 14–33 per plant. Similar results on 12 genotypes were reported by Peksen and Peksen[34]. Generally, Veg1 was the best performing line across all cowpea lines and M217 was the worst. Shiringani[24] obtained contrary results on the performance of M217 which had the most pods per plant in two locations in that study. At Nietvoorbij, Veg1 had the most pods per plant and no difference was observed between zinc application levels. This insignificant response to zinc application was observed in most of the parameters measured. The inconsistency in response of all lines to zinc application could be associated with the time of application and the ability to absorb and translocate the nutrients to the sink.[35] Rathore et al.[36] stated that the ability of a plant to absorb available zinc in the soil is also influenced by other plant nutrients, which can promote or hinder the plant's ability to absorb and translocate zinc to all parts of the plants. A fascinating finding from our study was that M217 at Bien Donne' obtained the highest 100-seed weight (14 g/100 seed). These weights were significantly higher than those of Veg1 and M217 is regarded as the best performing line. The findings clearly indicate that M217 had the bigger seed size, although it lacked in most of the parameters measured. Bigger seed size is mostly preferred for home consumption.[37] Aliyu and Makinde[38] concluded that seed size was related to the number of days to flowering and pod formation period. These findings are in agreement with our observations in the current study, as line M217 was the first line to flower and bear pods. Zinc fertiliser did not have a significant effect on most of the measured parameters, which could be associated with the time of application and the ability of the plant to absorb the fertiliser.

Conclusion

We evaluated the vegetative and reproductive parameters of three cowpea lines in response to three zinc fertiliser application levels in the Western Cape Boland region. Our results show that Veg1 and Qukawa performed better in the measured parameters than M217. Planting cowpea in November rather than October significantly increased the crops' ability to germinate efficiently, and thereby increased production efficiency. Bien Donne was the best location for the production of cowpea as the total number of harvested seeds was significantly higher for all cowpea lines at Bien Donne' than at Nietvoorbij.

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Authors' contributions

N.M., R.A.M. and F.B.L. conceived and planned the experiments. N.M. carried out the experiments. F.B.L., N.M. and R.A.M. contributed to the interpretation of the results. N.M. took the lead in writing the manuscript. All authors provided critical feedback and helped shape the research, analysis and writing.

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Genotoxicity of aqueous extracts of *Tulbaghia violacea* as determined through an *Allium cepa* assay

Tulbaghia violacea (wild garlic) is commonly used in traditional medicine for the treatment of various ailments including fungal infections, gastrointestinal ailments, asthma, fever, colds and pulmonary tuberculosis. We assessed the potential genotoxic effects of water extracts from the leaves, stems and roots of *T. violacea* using the *Allium cepa* assay. Extracts at concentrations of 100, 250, 500 and 1000 μg/mL were tested on root meristems of *A. cepa*. Ethidium bromide was used as a positive control whereas distilled water acted as a negative control. The results reveal that as the concentrations of the water extracts of *T. violacea* increased, the mitotic indices decreased. Similarly, the percentage of chromosomal aberrations was dependent on the concentration as well as on which part of the plant was used. The six most common chromosome aberrations included laggard chromosomes, chromosome bridges, c-mitosis, sticky chromosomes, formation of binuclei and formation of trinuclei. The presence of micronucleated cells at interphase also increased as the concentration of the water extracts increased. The results confirm that water extracts of *T. violacea* exert significant genotoxic effects at higher concentrations, with the stem extracts being more toxic than the leaf and root extracts at similar concentrations.

Significance:

- Water extracts of *T. violacea* – a plant commonly used in traditional medicine – were found to have significant genotoxic effects at higher concentrations.

Introduction

Recently, there has been a significant increase in the number of herbal medicinal products globally. It is estimated that the world's population will be greater than 7.5 billion in the next 10–15 years, primarily in the southern hemisphere where approximately 80% of the population still relies on a traditional system of medicine based on herbal drugs for primary health care.[1-3] There are over 1.5 million medicinal plants that have been investigated and most of them are reported to contain toxic substances.[4] Therefore, it should be stressed that the use of any plant for medicinal purposes is not guaranteed to be safe.[5] This raises the need for further research on the mode of preparation and toxicology of medicinal plants to gather reliable information on their safety and effective use.[6] *Tulbaghia violacea* Harv., a member of the family Amaryllidaceae (formerly Alliaceae), is commonly known as 'wild garlic or society garlic'.[7-9] The plant is found in the Eastern Cape, KwaZulu-Natal and northern Gauteng in South Africa, and even as far north as Zimbabwe.[10] *Tulbaghia violacea* has traditionally been used extensively in South African traditional medicine for the treatment of HIV/Aids and oral fungal infections. It has also found diverse application in the treatment of gastrointestinal ailments, including as a purgative for treatment of constipation; asthma; fever; colds; and pulmonary tuberculosis[10-13]; and as an anti-helminthic [14]. It has been reported that the odour of *T. violacea* deters moles.[12] Zulu communities in South Africa grow this plant around their homes as it is believed to repel snakes and the bulbs are used to prepare an aphrodisiac.[10-12]

However, like any other drug, extensive consumption of medication prepared from *T. violacea* has been associated with a variety of undesirable symptoms such as abdominal pain, inflammation, gastroenteritis, acute inflammation and sloughing of the intestinal mucosa, cessation of gastrointestinal peristalsis, contraction of the pupils, subdued reactions to stimuli and even fatality.[8,11,15] The aim of this study was to evaluate the genotoxicity of the leaf, stem and root extracts of *T. violacea* by using the *Allium cepa* assay.

Materials and methods

Plant collection

Tulbaghia violacea was collected from different indigenous plant nurseries in the Gauteng Province of South Africa, and grown in a greenhouse at the Vaal University of Technology (Gauteng, South Africa). Identification of this plant was done with the assistance of Professor Stefan Siebert, a botanist at AP Goossen's Herbarium, North-West University, where a unique voucher specimen number ST0008 was deposited.

Preparation of plant extracts

Whole plants of *T. violacea* were uprooted carefully and washed with tap water to remove the soil and debris. The leaves, stems and roots were then separated from each other, cut into small pieces, frozen at -20 °C, lyophilised and eventually pulverised into a fine powder. Crude water extracts from the different parts of the plant were prepared by mixing 10 g of the pulverised plant material with 200 mL distilled water. The mixture was then boiled for 10 min and allowed to cool to room temperature. Thereafter, the mixture was filtered through 0.45 μm Whatman® filter paper. The resultant filtrate was then frozen and lyophilised. A stock solution of each part of the lyophilised crude water extract was prepared at a concentration of 10 mg/mL using distilled water and stored at -20 °C in opaque vessels until they were required. The crude extracts of 10 mg/mL (0.1 g in 10 mL) from the leaves, stems and roots of *T. violacea* were each reconstituted by dissolving in distilled water to concentrations of 100, 250, 500 and 1000 μg/mL.

Pre-treatment

The *Allium cepa* L. (onion) bulbs were grown in distilled water at room temperature for 2–3 days. When the roots were 2–6 mm in length, the bulbs were treated with different concentrations of the crude extracts (100, 250, 500 and 1000 μg/mL; $n=4$ for each) for 24 h. Another set of the onions was placed in ethidium bromide (100, 250, 500 and 1000 μg/mL; $n=4$ for each) to serve as the positive control while a further set ($n=4$) was grown in distilled water to serve as the negative control. The root growth was measured, and the solutions were changed daily. The onion with the poorest growth from every concentration (100, 250, 500 and 1000 μg/mL) and controls (positive and negative) was excluded from the experiment and the remaining three onions were prepared for microscopy.[16,17]

Slide preparation

For each bulb, five root tips at approximate lengths of 10 mm were harvested and fixed in ethanol/glacial acetic acid solution 3:1 (v/v) for 10 min. After fixation, the root tips were washed a few times with distilled water. They were then hydrolysed with 1 N HCl at 60–70 °C for 5 min. The roots were then washed a few times with distilled water. The terminal 1–2 mm of the root tip was cut and placed on a glass slide. The excess liquid was sucked up using blotting paper. A drop of freshly prepared acetocarmine was placed on the root tips and left for 5–10 min at room temperature. Using a glass coverslip, the stained root tips were squashed to form a smear and the excess stain was blotted with paper towel. The sides of the coverslip were sealed with clear fingernail polish. Three slides were prepared per bulb with a total of nine slides per concentration.

Observation of slides

The slides were observed under a light microscope at 200x and 400x magnification. A light microscope (Olympus, Tokyo, Japan) with a digital camera was used to obtain images of the chromosome aberrations. Photomicrographs (10 images per slide) were prepared and a minimum of 1000 cells per slide were analysed (nine slides were observed for each treatment). The mitotic index, presence of micronuclei and chromosome aberrations in mitotic phases were calculated by examining and counting a minimum of 1000 cells per slide (nine slides were observed for each treatment). The experiment was replicated three times with three roots for each replicate. Therefore, nine slides were prepared for each treatment group. The mitotic index, percentage cells with micronuclei and aberrant cells were obtained using Equations 1, 2 and 3, respectively.

$$\text{Mitotic index} = \frac{\text{Number of cells in mitosis}}{\text{Total number of cells}} \times 100 \quad \text{Equation 1}$$

$$\%\ \text{Micronucleus} = \frac{\text{Total number of micronuclei}}{\text{Total number of cells in interphase}} \times 100 \quad \text{Equation 2}$$

$$\%\ \text{Aberrant cells} = \frac{\text{Total number of aberrations}}{\text{Total number of cells}} \times 100 \quad \text{Equation 3}$$

ImageJ analysis

Images obtained from the light microscope were converted to 8-bit greyscale using ImageJ software (version 1.46r, Bethesda, MD, USA). The thresholds of the images were then adjusted to obtain the best fit for different particle aggregates in each cell and the total number of cells was calculated. A total number of nine slides for each concentration of plant extract (100, 250, 500 and 1000 μg/mL) was analysed. From each slide, 10 images were assessed, amounting to a total of 90 images per concentration of plant extract. The mean data for each concentration were used for further analysis.

Data analysis

The mean and standard error of the mean for each of the treatment groups were calculated. Data obtained from the microscopic and ImageJ analyses were analysed using a multiple *t*-test to determine significant differences between treatment groups and the negative control ($p<0.05$).

Results

Root growth, mitotic index and chromosomal aberration analysis

The root length, mitotic indices (MI) and chromosomal aberrations for the various concentrations of the water extracts of the leaves, stems and roots of *T. violacea* on *A. cepa* are shown in Table 1. The results show that as the concentration of the crude extract increased, there was a significant ($p<0.05$) decrease in mean root length, mitotic indices and percentage of aberrant chromosomes. The mitotic index decreased significantly ($p<0.05$) with the leaf extracts at 500 μg/mL and 1000 μg/mL with values of 27.78% and 24.54%, respectively. Leaf extracts at 100 μg/mL and 250 μg/mL produced mitotic indices of 43.71% and 58.66%, respectively. For the stem extracts, the higher concentrations (250 500, 1000 μg/mL) produced a significant reduction in mitotic indices with values of 33.64%, 32.57% and 19.69%, respectively, when compared to the non-significant 40.56% for 100 μg/mL. Similarly, water extracts of the roots at 250, 500 and 1000 μg/mL significantly decreased mitotic indices to 37.24%, 31.08% and 22.59%, respectively, whereas the 100 μg/mL treatment produced no significant change (MI=58.88%). These values were low when compared to the mitotic index for the negative control (distilled water) which was 61.83%. For the positive control (ethidium bromide), all the tested concentrations produced a significant reduction in the mitotic index, with the lowest MI value of 1.48% produced by the highest concentration of 1000 μg/mL. Chromosome aberrations were observed in all stages of mitosis (prophase, metaphase, anaphase and telophase). Figure 1a–l depicts illustrations of normal phases of cell division as well as the six common aberrations observed in the *A. cepa* assay. These aberrations include laggards (Figure 1b), chromosome bridges (Figure 1d), c-mitosis (Figure 1f), sticky chromosomes (Figure 1h), binuclei (Figure 1i) and trinuclei (Figure 1j). The most common chromosomal aberrations were represented by c-mitosis, binuclei formation and sticky chromosomes (Figure 1e–j). The percentage of aberrant cells was 4.72% for the negative control (distilled water), when compared to 21.91% for the highest concentration of 1000 μg/mL for the positive control (ethidium bromide).

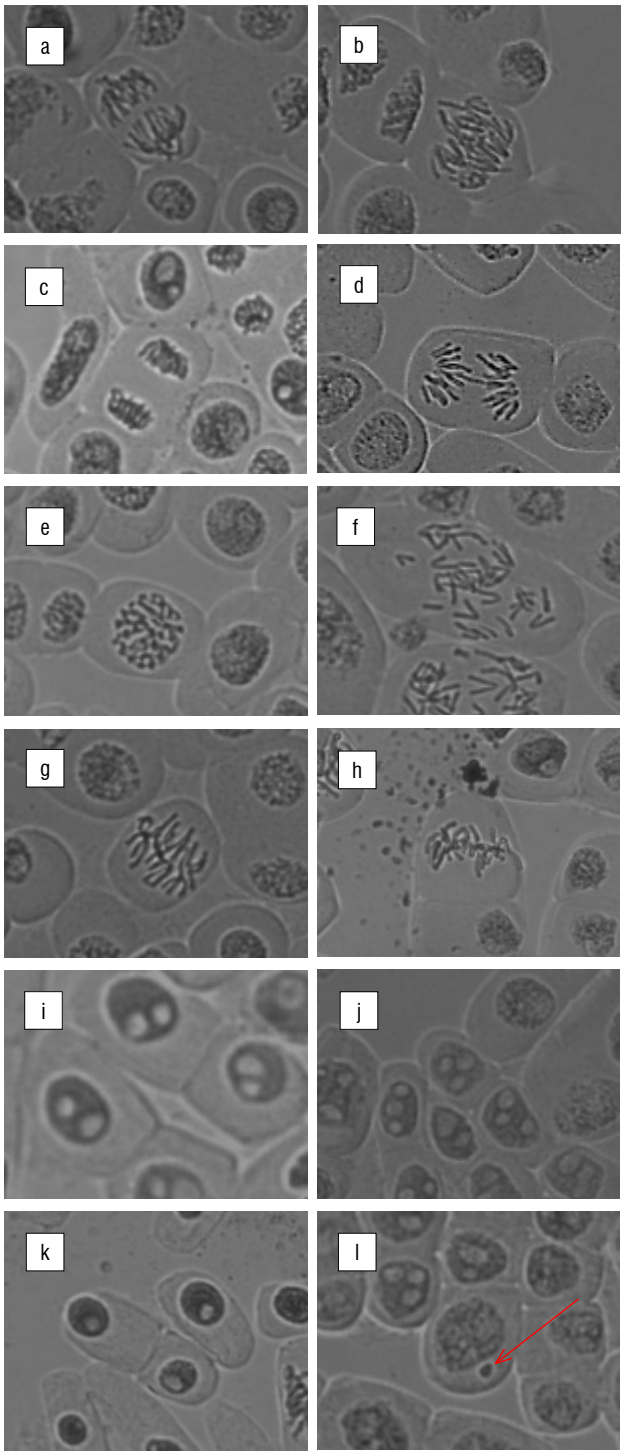
The percentage of micronucleated cells was generally higher at 1000 μg/mL for the stem (3.74%), followed by the root (3.71%) and finally the leaf (3.68%) crude extracts (Table 2).

Discussion

Root length and mitotic indices

A decrease of over 45% in root length indicates the presence of toxic substances[18], which can be regarded to have a sub-lethal effect on plants[19]. In our study, the decrease of over 45% in root length was dependent on the concentration of the extracts and was variable for the different plant organs. For example, inhibition of root growth by the leaf and root extracts occurred at concentrations above 250 μg/mL, whereas that of the stem extracts occurred at concentrations above 100 μg/mL (Table 1). Therefore, although the leaf and root extracts showed potential toxicity at concentrations above 250 μg/mL, the stems may be considered toxic at concentrations above 100 μg/mL.

Similarly, any substance that reduces the mitotic index to below 22% of the negative control is considered to cause lethal effects on test organisms while a reduction below 50% has sub-lethal effects[20] and is called the cytotoxic limit value. We have adopted this system of categorisation in this study. In general, treatment of the *A. cepa* roots with distilled water (negative control) was non-toxic whereas that with ethidium bromide (positive control) was toxic at all tested concentrations with MI values below 22%. Ethidium bromide has been found to be an extremely effective cytoplasmic mutagen which results in the loss or alteration of DNA and RNA.[21] It was found that a low concentration of 100 μg/mL for the leaf extracts produced no toxic effect on the roots as shown by the relatively high mitotic index of 58.66% (Table 1). However, concentrations higher than 100 μg/mL produced a sub-lethal effect as the mitotic indices were below 50% (Table 1). Similar results were obtained



Magnification 400×

Figure 1: Chromosome aberrations observed in *Allium cepa* meristematic cells exposed to water extracts of *Tulbaghia violacea:* (a) normal anaphase, (b) laggard chromosome, (c) normal telophase, (d) chromosome bridge, (e) normal prophase, (f) c-mitosis, (g) metaphase anaphase, (h) sticky chromosomes, (i) binucleus, (j) trinucleus, (k) normal interphase and (l) micronucleus indicated by arrow. The presence of micronuclei (l) was observed in the roots treated with the different extracts of *T. violacea* and most were significantly different ($p<0.05$) when compared with the negative control (Table 2).

for the root extracts (Table 1). For the stem extracts, concentrations of 100, 250 and 500 μg/mL produced a sub-lethal effect on *A. cepa* whereas the 1000 μg/mL concentration produced a lethal effect with an MI value of 19.69%. The lower mitotic indices, especially for the higher concentrations of the crude extracts, may be as a result of the direct genotoxic effects of the extracts. Several factors can decrease the mitotic index, such as obstruction of the onset of prophase, the arrest of one or more mitotic phases, or a slowing of the rate of cell progression through mitosis.[22] Similar reasons may be applicable for the decreased mitotic indices observed in this study. Microscopic analysis revealed a concentration-dependent reduction in mitotic indices (Table 1) with significant differences ($p<0.05$) between the treated groups and the positive control (ethidium bromide) and the negative control (distilled water) value of 61.83%.

Most of the chromosomal aberrations observed were in the metaphase and anaphase stages. This finding is in agreement with the results of Armbruster et al.[23] who treated wheat root tips with the herbicide dithiopyr and with those of Kaymak and Pinar[24] for the herbicide tebuconazole in *A. cepa*. Both studies concluded that structural aberrations of spindle formation may result in cell division disturbances. The most common aberrations that were present in all the tested plant extracts and controls included binucleated cells, sticky chromosomes and c-mitosis, followed in frequency by laggards, chromosomal bridges and trinucleated cells (Figure 1a–j). The occurrence of aberrant cells was concentration and extract dependent, because as the concentration increased, the number of aberrant cells also increased and varied depending on the extract used. Overall, the highest percentages of aberrant cells were observed after treatment with the stem extracts in comparison with treatment with leaf and root extracts. Laggard chromosomes (Figure 1b) are usually a result of the failure of the chromosomes to attach to the spindle fibre and to move to either of the two opposite poles.[25] Chromosome bridges were observed in the anaphase and telophase stages and were more frequent at higher concentrations of *T. violacea* crude extracts, with the highest number of bridges observed after treatment with stem extracts (Figure 1d). The formation of chromosome bridges may be attributed to chromosomal stickiness and the subsequent failure of chromosome separation during anaphase.[26,27] C-mitosis (Figure 1f) results when dissociating disulfide bonds prevent spindle microtubules from assembling[28] and is an indication of a weak toxic effect which may be reversible[18,29]. The number of cells with c-mitosis after treatment with extracts from all plant parts surpassed that of the negative control for all concentrations (100, 250, 500 and 1000 μg/mL) of *T. violacea* treatment, which confirms the mitodepressive effect of *T. violacea* crude extracts on spindle fibres. Sticky chromosomes (Figure 1h) are usually a consequence of a physiological effect resulting from depolymerisation of DNA, partial dissolution of nucleoproteins, breakage and exchanges of the basic folded fibre units of chromatids and the stripping of the protein covering of DNA in chromosomes.[30] Their presence is an indication of a highly toxic and irreversible effect, probably leading to cell death.[31,32] The formation of binucleated or trinucleated (Figure 1i and 1j) cells may be attributed to the inhibition of cytokinesis.[33] It is clear from this study that the crude water extracts from the leaves, stems and roots of *T. violacea* possess chromotoxic and mitodepressive properties. These properties are evident from the reduction in the active mitotic index and manifestation of spindle formation, respectively.[34]

Table 1: Effects of different concentrations of leaf, stem and root extracts of *Tulbaghia violacea* on root length, mitotic indices and chromosomes in *Allium cepa* roots

Treatment concentration (μg/mL)	Phenotypic index			% Chromosomal aberrations ± SEM						% Aberrant cells ± SEM
	Total number of cells ± SEM	Mean root length (mm) ± SEM	Mitotic index ± SEM	Bridges	Stickiness	Laggards	c-mitosis	Binucleus	Trinucleus	
Leaf extracts										
Control	1207 ± 48.53	0.99 ± 0.28	61.83 ± 6.50	1.00 ± 0.19	4.11 ± 0.77	0.33 ± 0.19	4.54 ± 1.35	47.00 ± 4.19	0.33 ± 0.19	4.72 ± 0.49
100	1186 ± 39.94	0.84 ± 0.20	58.66 ± 7.24	1.67 ± 0.58	5.20 ± 1.18	1.11 ± 0.80	5.00 ± 1.07	94.11 ± 9.26*	0.44 ± 0.22	9.07 ± 1.12*
250	1221 ± 39.24	0.58 ± 0.18	43.71 ± 2.93	2.11 ± 1.31	5.33 ± 0.88	1.22 ± 0.73	10.89 ± 5.40	116.44 ± 18.68*	10.56 ± 5.79	12.00 ± 1.68*
500	1118 ± 53.12	0.20 ± 0.19	27.78 ± 6.60*	2.22 ± 1.28	10.00 ± 1.39*	2.33 ± 0.88	11.33 ± 5.84	117.56 ± 24.05*	11.33 ± 4.95*	13.84 ± 1.32*
1000	1263 ± 12.04	0.19 ± 0.02*	24.54 ± 5.44*	5.00 ± 0.38*	10.78 ± 2.72*	2.89 ± 0.68*	13.22 ± 4.83*	163.56 ± 11.86*	11.56 ± 5.36*	16.39 ± 1.87*
Stem extracts										
Control	1207 ± 39.43	0.99 ± 0.28	61.83 ± 6.50	1.00 ± 0.19	4.11 ± 0.77	0.33 ± 0.19	4.54 ± 1.35	47.00 ± 4.19	0.33 ± 0.19	4.72 ± 0.49
100	1116 ± 66.67	0.51 ± 0.13	40.86 ± 9.43	1.89 ± 0.22	6.11 ± 0.29	0.56 ± 0.11	6.56 ± 0.78	99.44 ± 9.14*	0.78 ± 0.29	10.20 ± 1.43*
250	1269 ± 24.36	0.31 ± 0.34	33.64 ± 3.86*	4.44 ± 0.22*	7.00 ± 2.17	3.44 ± 0.73*	8.00 ± 0.69*	129.11 ± 10.20*	7.22 ± 5.92	12.56 ± 1.01*
500	1186 ± 2.83	0.27 ± 0.05	32.57 ± 3.14*	5.11 ± 0.87*	13.44 ± 1.25*	5.00 ± 1.58*	8.79 ± 1.97	159.22 ± 30.20*	9.67 ± 8.53	16.97 ± 2.09*
1000	1303 ± 24.45*	0.06 ± 0.05*	19.69 ± 6.67*	6.89 ± 1.98*	15.56 ± 4.15*	7.00 ± 2.27*	13.00 ± 1.71*	209.44 ± 45.57*	20.44 ± 4.80*	20.91 ± 3.04*
Root extracts										
Control	1207 ± 39.43	0.99 ± 0.28	61.83 ± 6.50	1.00 ± 0.19	4.11 ± 0.77	0.33 ± 0.19	4.54 ± 1.35	47.00 ± 4.19	0.33 ± 0.19	4.72 ± 0.49
100	1263 ± 16.01	0.66 ± 0.67	58.88 ± 5.52	2.56 ± 1.09*	9.22 ± 0.68*	1.78 ± 0.99*	6.56 ± 1.31	94.00 ± 9.26*	0.67 ± 0.33	9.09 ± 1.02*
250	1287 ± 23.93	0.56 ± 0.12	37.24 ± 9.07*	3.33 ± 0.19*	9.78 ± 1.06*	3.78 ± 0.78*	7.44 ± 1.42*	124.11 ± 21.57*	16.66 ± 2.31*	12.83 ± 1.06*
500	1250 ± 22.82	0.37 ± 0.15	31.08 ± 3.14*	3.78 ± 0.29*	10.00 ± 1.61*	4.11 ± 0.78*	8.89 ± 0.99*	137.00 ± 58.28*	20.22 ± 1.16*	14.72 ± 1.82*
1000	1189 ± 24.45	0.09 ± 0.05*	22.59 ± 6.67*	5.44 ± 0.22*	10.33 ± 1.66*	4.33 ± 0.51*	12.67 ± 1.02*	169.89 ± 17.83*	22.44 ± 5.43*	18.93 ± 1.98*
Ethidium bromide										
Control	1207 ± 39.43	0.99 ± 0.28	61.83 ± 6.50	1.00 ± 0.19	4.11 ± 0.77	0.33 ± 0.19	4.54 ± 1.35	47.00 ± 4.19	0.33 ± 0.19	4.72 ± 0.49
100	1229 ± 9.75	0.12 ± 0.07*	8.65 ± 6.48*	1.33 ± 0.00	4.22 ± 1.16	0.78 ± 0.48	8.44 ± 1.25*	155.00 ± 8.51*	1.44 ± 1.50	13.93 ± 1.56*
250	1248 ± 19.49	0.04 ± 0.03*	2.20± 0.14*	2.00 ± 1.26	9.56 ± 2.51*	0.89 ± 0.29	9.33 ± 1.33*	190.89 ± 11.28*	2.56 ± 2.17*	17.04 ± 2.35*
500	1167 ± 47.46	0.05 ± 0.04*	1.60 ± 0.80*	3.00 ± 1.20	10.11 ± 1.76*	1.00 ± 0.17	12.33 ± 2.52*	196.11 ± 14.83*	4.11 ± 10.94	19.42 ± 1.56*
1000	1133 ± 68.38	0.00 ± 0.00*	1.48 ± 0.09*	3.44 ± 0.95*	14.00 ± 2.03*	4.89 ± 0.62*	19.89± 5.02*	202.22 ± 11.77*	4.22 ± 10.93*	21.91 ± 1.45

Values shown are the mean±SEM; n=*3.*

**Represents statistically significant groups compared to the negative control (distilled water) according to a two-sample assuming equal variance* t-*test;* p<*0.05.*

The percentage of aberrant cells (Table 1) was dependent on the concentration of the extract and from which plant part it was derived. The highest proportion (20.91%) of aberrations occurred with the highest concentration of the stem extracts whilst the lowest proportion (16.39%) occurred with the highest concentration (1000 μg/mL) of the leaf extracts. The aberrations as a result of the root extracts were intermediate between those observed for the stem and leaf extracts. In our previous study[35] we found that most of the phytocompounds were present in the leaves of *T. violacea* and recommended use of the leaves as a way of conserving the species. The results of this study suggest that, to prevent genotoxic effects, concentrations lower than 1000 ug/mL should be used for therapeutic purposes. One of the anomalies observed in this study is that the negative control (water) also induced a low number of chromosomal aberrations. There are thousands of cells in the meristematic zone of the roots that are undergoing mitosis at any one time. It is possible that errors in cell division may be expected under these circumstances. The presence of ions in the water may also cause minor chromosomal aberrations.[18] The presence of ions in the negative control was overlooked in this research and should be considered in future research. Nonetheless, there was a significant difference in the number of chromosomal aberrations after treatment with the plant extracts compared to that after treatment with the negative control (distilled water).

The presence of micronuclei-bearing cells (Figure 1l) may be a consequence of clastogenic (chromosome breakage) or aneugenic (chromosome lagging and interference on the spindle behaviour) effects.[36,37] The higher percentage of micronucleated cells after treatment with the stem extracts than that after treatment with the leaf and root extracts (Table 2) confirms that the stem extracts had the greatest genotoxic effect on the cells as also indicated by the number of chromosomal aberrations. The positive control (ethidium

bromide) which was expected to produce the highest percentage of micronucleated cells actually produced the lowest percentage. This result may have been because of more cells in interphase after treatment with the positive control than those observed after treatment with the *T. violacea* plant extracts. This observation may also be attributed to the fact that ethidium bromide prevents subsequent replication of DNA by arresting cell division.[38]

Table 2: Percentage micronuclei in *Allium cepa* after treatment with different concentrations of extracts from different plant organs of *Tulbaghia violacea*

Treatments		
Concentration (μg/mL)	**Mean number of interphase cells examined ± SEM**	**% Micronucleus ± SEM**
Leaf extracts		
100	876 ± 53.34*	1.20 ± 0.30*
250	653 ± 128.32	1.24 ± 0.60
500	577 ± 9.34	1.41 ± 0.27*
1000	464 ± 57.97	3.68* ± 1.42*
Stem extracts		
100	589 ± 80.99*	2.07 ± 0.51*
250	736 ± 75.81*	2.26 ± 0.80*
500	602 ± 34.26	2.86 ± 0.63*
1000	539 ± 115.33	3.74 ± 0.93*
Root extracts		
100	713 ± 39.91*	1.57 ± 0.16*
250	674 ± 111.10	1.66 ±0.08*
500	588 ± 79.76	1.98 ± 1.16
1000	370 ± 39.94	3.71 ± 0.64*
Ethidium bromide		
100	914 ± 29.28*	0.40 ± 0.05
250	914 ± 47.40*	0.41 ± 0.13
500	934 ± 24.64*	0.92 ± 0.68*
1000	939 ± 35.99*	1.11 ± 0.30*
Distilled water		
	464 ± 57.97	0.31 ± 0.08

Values shown are the mean±SEM; n=*3.*

**Represents statistically significant groups compared to the negative control (distilled water) according to a two-sample assuming equal variance* t-*test;* p<*0.05.*

Conclusion

We assessed the potential genotoxic effects of water extracts of the leaves, stems and roots of *T. violacea* using the *A. cepa* assay. Generally, high concentrations of the extracts showed potential genotoxic effects, evidenced by the sub-lethal and lethal effects of the different concentrations of the extracts on the roots, the reduced mitotic indices, the abnormal chromosome behaviour and the presence of micronuclei. Extracts of the stem were generally more toxic than those of the leaves and roots. It can thus be concluded that *T. violacea* plant extracts cause mitodepressive and chromotoxic effects in plant genomes and induce various types of chromosomal aberrations which reveal potential toxicity of the plant, particularly at high concentrations. Although these results provide a good initial indication of the toxicity of *T. violacea* plant parts, a direct link to the toxicological effect of the extracts in humans was not established. There is thus a need to conduct in vivo cytogenetic studies to ascertain the mechanisms behind the in vitro findings of the *A. cepa* assay.

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Authors' contributions

S.T. conceptualised the project and collected the plant; L.N.M. analysed the samples, undertook the data analysis and wrote the manuscript; C.C.S. was responsible for student supervision; M.P. was the project leader and was responsible for data curation and revisions.

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The Pleistocene fauna of the Cape south coast revealed through ichnology at two localities

East of Still Bay on the Cape south coast of South Africa lies a rugged, remote stretch of sea cliffs that expose Late Pleistocene aeolianites. A zone of dense concentration of fossil tracks occurs within this area. Two large rocks, which we call Roberts Rock and Megafauna Rock, were identified ~400 metres apart. These rocks contained a variety of trackways, individual tracks, burrow traces and invertebrate trace fossils on multiple bedding planes. Both rocks were found ex situ, but their context could be determined. Roberts Rock has subsequently slid into the ocean, and Megafauna Rock lies at the base of a coastal cliff. Probable trackmakers include elephant, long-horned buffalo, giant Cape horse, rhinoceros, medium and small artiodactyls, golden mole, birds and invertebrates. Dating studies at an adjacent site, which is comparable to the stratigraphy described here, indicate that both rocks were most likely deposited in Marine Isotope Stage 5e (~128–116 ka). Analysis and description of these tracksites confirms the potential of ichnology to complement the skeletal fossil record and to enhance the understanding of Pleistocene life in southern Africa. The ephemeral nature of such tracksites makes repeated visits to this coastline desirable, both to monitor the fate of known sites and to search for newly exposed trace fossil surfaces.

Significance:

- Roberts Rock and Megafauna Rock are two remarkable fossil tracksites on the Cape south coast, which contain tracks of four members of the Late Pleistocene megafauna. They provide a glimpse of Pleistocene dune life and suggest an area teeming with large mammals.
- These tracks were made on dune surfaces near an interface between the grassland of the Palaeo-Agulhas Plain and the inland Fynbos–Strandveld–Renosterveld. Faunal assemblages from both vegetation zones might therefore be recorded.
- The trace fossil record and body fossil record both have inherent biases, but have the potential to independently provide complementary information on palaeofaunal composition.
- The two rocks have provided the first South African records of fossil elephant tracks (as first described by Dave Roberts and colleagues in 2008), the first rhinoceros track and the first extinct giant Cape horse track, and track evidence of the extinct long-horned buffalo.
- Roberts Rock has slumped into the ocean, and it provides an example of the fate of many exposed tracksites. Conversely, new sites frequently become exposed. This scenario stresses the need for regular ichnological surveys along this track-rich coastline to monitor existing sites and to search for new sites.

Introduction

Late Pleistocene aeolianites, or cemented palaeodunes, are well preserved along the Cape south coast of South Africa. These deposits contain fossil trackways[1-5] preserved fortuitously[6]. An ongoing multidisciplinary project looking at Pleistocene ichnofossils in aeolianites of the Waenhuiskrans Formation, between Witsand in the west and Robberg in the east, a distance of 275 km (Figure 1), was initiated in 2007. To date, more than 100 tracksites have been identified through this project.

Four dominant zones of concentration of tracksites are apparent. One of these zones lies east of Still Bay along a remote, rugged coastline. Here Middle to Late Pleistocene dune cordons of the Waenhuiskrans Formation form coastal cliffs up to 70 m in height, and are overlain by active Holocene dunefields of the Strandveld Formation (Figure 1). These deposits extend for approximately 12 km. This composite dune cordon is separated from older inland lithologies by Rietvlei, an interdune lake.[1,7] Fallen aeolianite blocks lie at the base of the sea cliffs, where they are subjected to gravitational forces and wave and wind erosion. Roberts et al.[1] drew attention to this area, by describing fossil elephant trackways and tracks, and dating them through the early use of optically stimulated luminescence (OSL) in southern Africa. A result of 140±8.3 ka was obtained for the oldest dated layer (below the main elephant track horizon), and 91±4.6 ka for the youngest dated Pleistocene unit. Helm et al. reported on further tracks from this area, including avian tracks[2] and giraffe tracks[3].

One of Roberts' main study sites was a large aeolianite block that had slid down a steep sandy slope from its origin in the cliffs above.[1] It contained a well-preserved, rippled palaeo-surface, 5 m x 3.5 m in size, containing three juvenile elephant trackways and two medium-sized artiodactyl trackways (which Roberts et al.[1] termed 'antelope tracks'). We name this rock 'Roberts Rock'. The instability of the slope and proximity to the ocean made it vulnerable to slumping and to wave action. Multiple visits to the site demonstrated bedding-plane splitting of the block into two halves, with the appearance of further tracks on the newly exposed surfaces. By 2016, Roberts Rock was no longer present, but unexpectedly a large recently fallen aeolianite block lay immediately adjacent to the site, and also contained multiple track-bearing surfaces.

About 420 m to the west of the Roberts Rock site lies another fallen aeolianite block, which was identified in 2016. Multiple large natural mould tracks of variable morphology are evident on its upper surface, which consists of three layers. Large tracks are visible on its sides in cross section and on its underside as natural casts. We name this block 'Megafauna Rock'.

Much of the southern African Late Pleistocene fauna has extant analogues. However, an analysis of Pleistocene tracks requires knowledge of extinct species or subspecies that have been identified through the skeletal fossil record, and openness to interpretation of new track types and the need to analyse tracks systematically, while avoiding assumptions on trackmaker identity based merely on resemblances to the tracks of extant species.

The two rock sites are situated on the edge of the Palaeo-Agulhas Plain[8], towards the centre of the Greater Cape Floristic Region (GCFR). Most of the Palaeo-Agulhas Plain is currently submerged, but was exposed until as recently as the early Holocene.[9] The plain was characterised by fertile soils, extensive C_4 grasslands, rivers, floodplains and wetlands.[8,10] Extant taxa that are not currently present in the GCFR often dominated assemblages on this plain, including large-bodied grazers such as black wildebeest (*Connochaetes gnou*), while extinct grazers included long-horned buffalo (*Syncerus antiquus*), giant Cape horse (*Equus capensis*) and giant hartebeest (*Megalotragus priscus*).[11-14]

Blue antelope (*Hippotragus leucophaeus*) and quagga (the southern race of *Equus quagga*) survived until the 19th century.[8,15] Typical wetland species were present, including southern reedbuck (*Redunca arundinum*) and hippopotamus (*Hippopotamus amphibius*), indicating the presence of floodplains with perennial wetlands.[8] Immediately inland, in stark contrast with the fertile Palaeo-Agulhas Plain, were Fynbos–Strandveld–Renosterveld vegetation types, which were mostly nutrient poor and high in secondary compounds.[8] Herbivores associated with these vegetation types are specialist browsers such as grysbok (*Raphicerus melanotis)* and grey duiker (*Sylvicapra grimmia*).[8] The tracksites we describe were thus adjacent to a diversity of habitats that contained distinct animal assemblages.

The Cape south coast track record may be preservationally biased in that it tends to record the tracks of larger, heavier trackmakers that walked on sand and created larger, deeper tracks that are more readily evident upon re-exposure. However, the skeletal record may also be biased, as it relies mostly on specimens from caves and rock shelters, representing the remains of hunted prey or animals that lived in such features.[3] As with other fossil-bearing regions, the Cape south coast body fossil record and track record have the potential to complement each other, and to independently provide evidence of the Pleistocene fauna. Tracks, furthermore, have the potential to suggest animal behaviour and relative abundance. The relationship between the track record and extant animals and resulting palaeobiological implications has been addressed by Cohen et al.[16]

Methods

A total of 11 survey visits were made to the coastline east of Still Bay between 2007 and 2017. Global Positioning System (GPS) readings were obtained for Roberts Rock and Megafauna Rock using a handheld device. Locality information was reposited with the African Centre for Coastal Palaeoscience. Measurements and photographs were taken of the track-bearing surfaces and the better-preserved tracks. Photogrammetry was performed on tracks at Megafauna Rock using a Canon PowerShot ELFPH 340 HS camera. Point clouds and digital terrain models were compiled using Agisoft Photoscan Professional (v.1.0.4) and colour topographic profiles were created with CloudCompare (v.2.6.3.beta).

Geological outcrops were investigated in the field through comparison and correlation to known documented and dated deposits in the region. Standard field techniques were applied in understanding the context of the ichnofossils to determine the strata from which they were derived. These methods included measurement of the thickness of aeolian foresets, observation of colour, texture and degree of carbonate cementation, and sedimentary characteristics of the clasts.

Results

Roberts Rock

In 2007 Roberts Rock appeared similar to the description published by Roberts et al.[1] It was tilted at an angle of just over 90°, with the track-bearing surface facing the ocean (Figure 2). By 2009 this large rock had split into two approximately equal halves along a bedding plane. The base of the seaward portion had slumped away from its previous location, and its upper edge rested against the base of the landward portion; the track-bearing surface thus was tilted at ~45°. The position of the landward portion had remained relatively unchanged (Figure 3). This created a shaded recess between these two portions (Figure 4). The newly exposed surfaces exhibited numerous small and medium-sized artiodactyl tracks, similar to those described by Roberts et al.[1] as 'antelope tracks'; these tracks are readily identifiable through the presence of two digit impressions separated by an interdigital sulcus which is open anteriorly and posteriorly. Further large tracks similar to those noted as elephant tracks by Roberts et al.[1] on Roberts Rock were evident; these are also morphologically distinctive, with slightly oval pes tracks and relatively circular manus tracks, both of which are often associated with displacement rims.

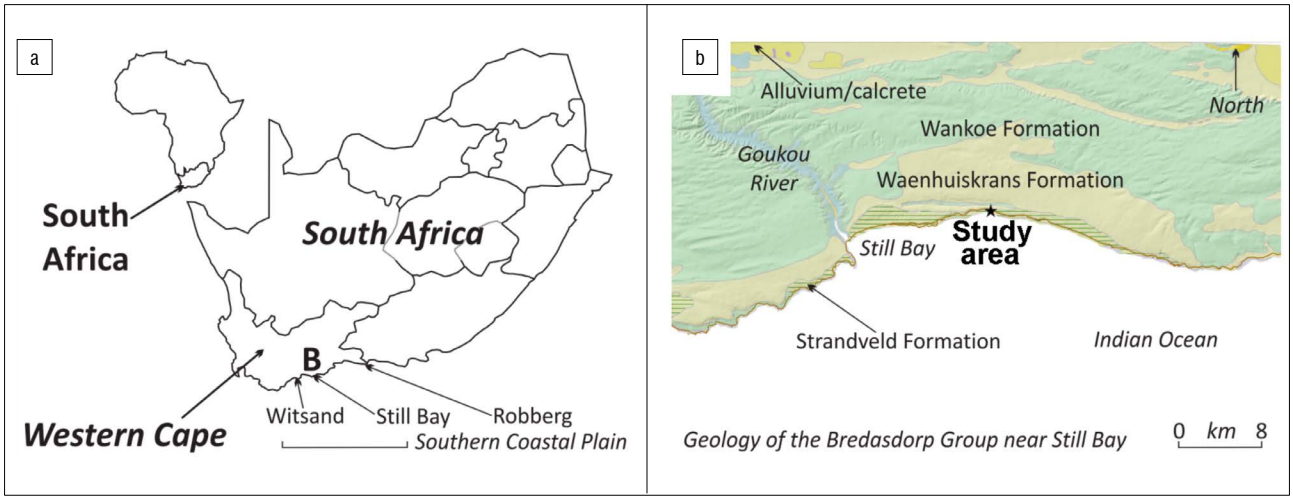


Figure 1: (a) Location of the study area within the Western Cape Province of South Africa. (b) Geological deposits in this region are dominated by strata of the Bredasdorp Group; the coastal deposits constitute outcrops of the Waenhuiskrans Formation, draped by Strandveld Formation unconsolidated sediments.

Figure 2: Roberts Rock in 2007.

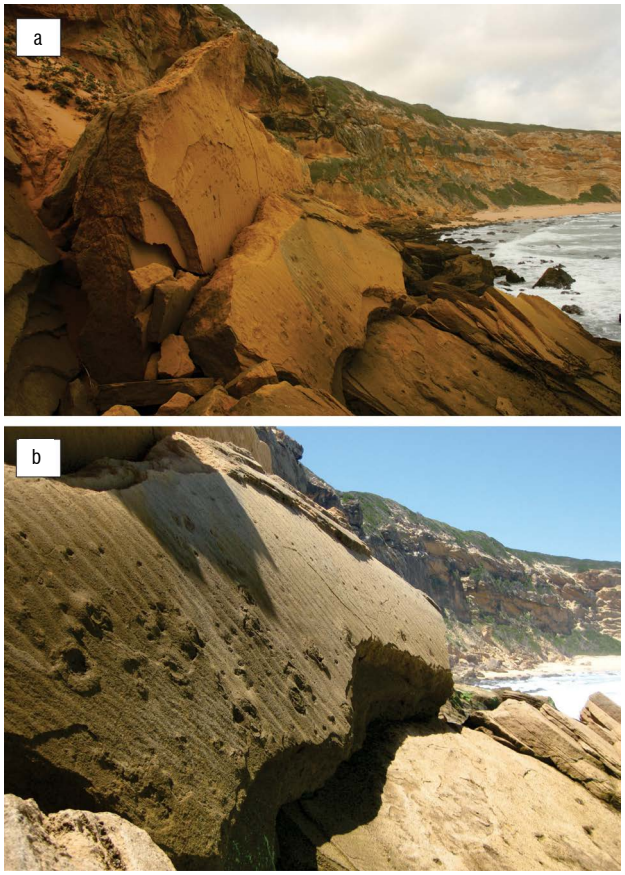


Figure 3: (a) Roberts Rock in 2009, after its separation. (b) The seaward portion of Roberts Rock in 2009 in good light conditions showing elephant and artiodactyl trackways.

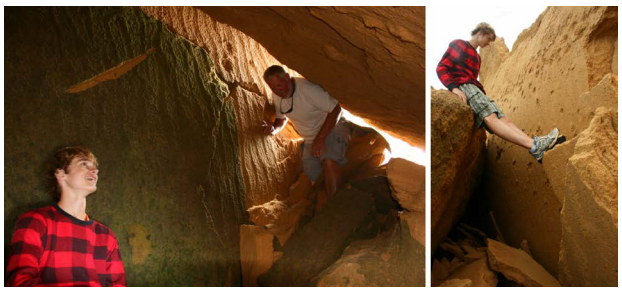


Figure 4: Exploring the gap between the seaward and landward portions of Roberts Rock in 2009. Numerous tracks are evident.

By 2016 Roberts Rock had disappeared into the ocean, and an even larger 12-m long block had slid down the sandy slope, and lay adjacent to the site that Roberts Rock had occupied. The seaward portion of the newly exposed block contained eight exposed surfaces, six of which exhbited tracks or undertracks (Figure 5). Ripple marks were evident on some surfaces.

Figure 5: The newly exposed large rock that is situated adjacent to the Roberts Rock site. (a) Eight bedding planes are exposed. (b) Yellow arrows indicate probable golden mole burrow traces; black arrows indicate avian tracks; white arrows indicate elephant tracks.

Elephant and artiodactyl tracks, similar to those described above, were present. Linear traces resembling burrows, up to 10 cm in diameter, were evident. Two small tridactyl trackways were evident, with relatively narrow digit impressions. Because of the instability of the vertically orientated bedding planes and associated access challenges, measurements were not obtained for these two trackways. Numerous smaller trace fossil features were noted. Vestiges of the track surfaces of Roberts Rock were evident among rocks of the intertidal area.

The aeolianites which make up Roberts Rock and the rock which lay adjacent to the site it had occupied are derived from the same geological unit in the sequence. The aeolianite is of calcarenite composition and is medium-grained, moderately sorted sand, interspersed with shell fragments and sparse heavy mineral grains. These stratified deposits comprise low angle planar cross bed foresets which dip up to 20°.

Megafauna Rock

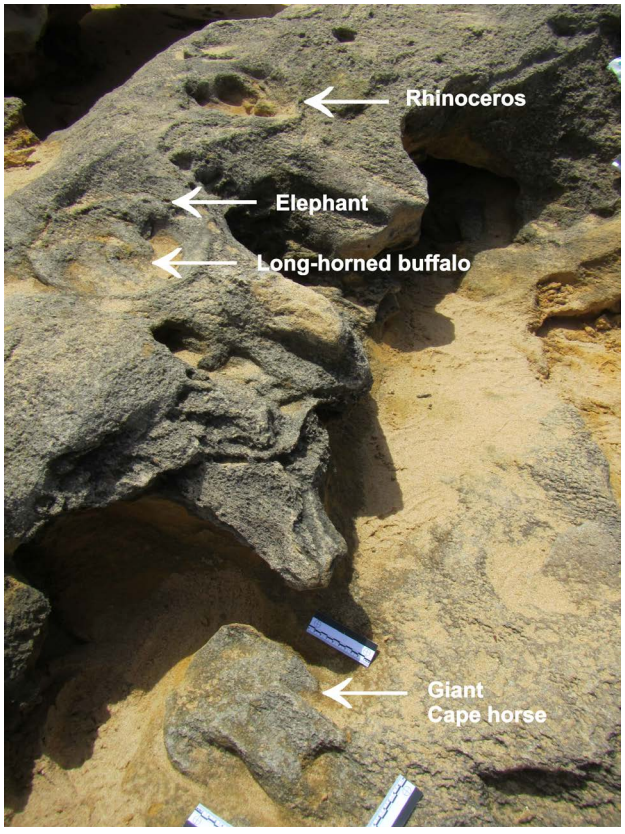
Megafauna Rock was not identified during visits to the area before 2016. The most likely explanation is that it was present but not noticed, as from a distance it does not exhibit features to suggest that it displays fossil tracks. It lies at the upper end of a small beach. The bedding plane from which it has originated can be identified less than 10 m above

its present position. Although derived from the same geological unit as Roberts Rock, Megafauna Rock is from a massive, well-cemented part of the succession. The beds range in thickness from 10 cm to 40 cm and dip shallowly.

Megafauna Rock measures 5 m x 5 m and is over 2.5 m high (Figure 6). On its upper natural-mould surface, which contains three levels, four large track morphologies are evident (Figure 7). Most common are the round or oval depressions. Length and width dimensions of two such tracks are respectively 34 cm x 31 cm and 31 cm x 29.5 cm.

Some of these tracks contain a layer of infill, and impressed into one such infill layer is a large artiodactyl track (Figure 8), with two characteristic digit impressions separated by an interdigital sulcus that is open anteriorly and posteriorly. Track length (13.5 cm) is less than track width (16 cm).

Figure 6: Megafauna Rock.



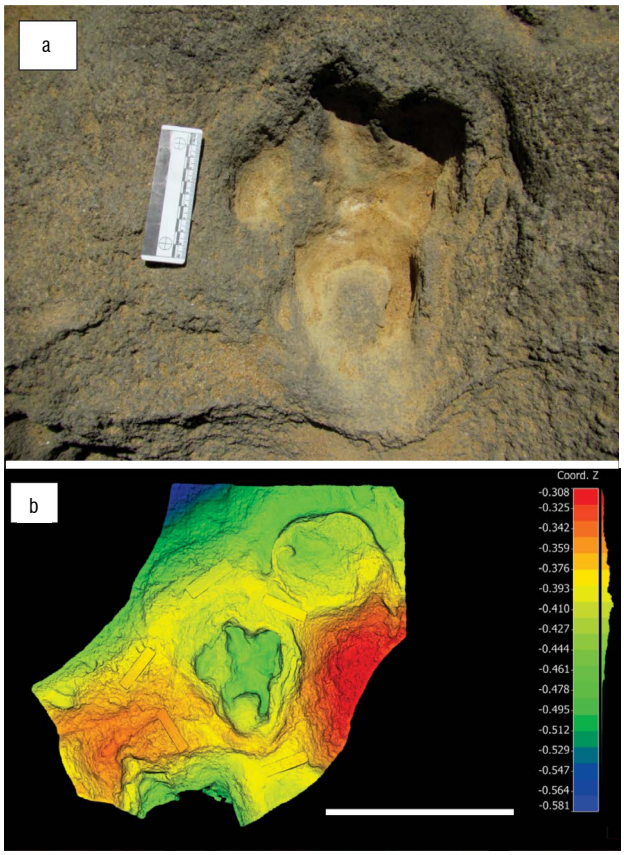
Scale bar = 10 cm

Figure 7: Upper surface of Megafauna Rock; arrows indicate tracks.

A single large tridactyl track with rounded digit impressions (Figure 9) occurs on the same level (length = 24 cm, width = 20 cm, depth = 5.5 cm).

Scale bar = 10 cm

Figure 8: Large artiodactyl track, probably made by long-horned buffalo, impressed upon infill layer of large elephant track on Megafauna Rock.

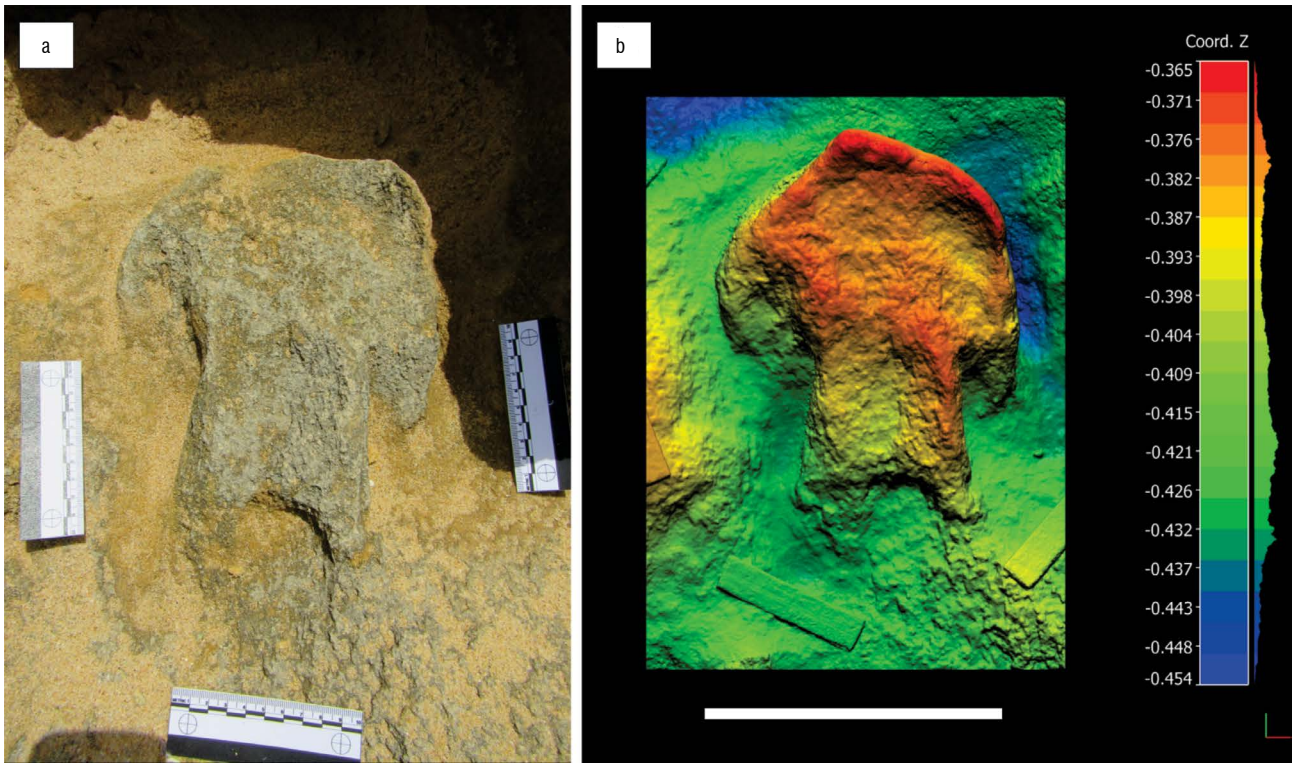


(a) Scale bar = 10 cm; (b) length of white horizontal scale bar = 0.4 m

Figure 9: (a) Large, three-toed, probable rhinoceros track on Megafauna Rock. (b) Photogrammetry colour mesh: probable rhinoceros track (centre) and at least one elephant track (upper right). 3D model was generated with Agisoft Photoscan Professional (v. 1.0.4) using 33 images from a Canon PowerShot ELFPH 340 HS (focal length 4.5 mm; resolution 4608 x 3456; pixel size of 1.33853 x 1.33853 um). Photos were taken an average of 0.42 m from the surface. The surface model error is 0.144403 pix. The final images presented here were rendered using CloudCompare (v.2.6.3.beta). Vertical scale bar is in metres.

One level below these tracks is a raised, symmetrical feature (Figure 10). Maximum length = 27 cm, and maximum width = 20 cm. There is no evidence of a cloven hoof anteriorly, and a 'frog' is probably evident posteriorly.

The sides of Megafauna Rock display large tracks in cross section. What is visible of its underside contains numerous large natural casts.



(a) Scale bar = 10 cm; (b) length of white horizontal scale bar = 0.2 m

Figure 10: (a) Probable *Equus capensis* track on Megafauna Rock. (b) Photogrammetry colour mesh: probable *Equus capensis* track on Megafauna Rock. 3D model was generated with Agisoft Photoscan Professional (v. 1.0.4) using 32 images from a Canon PowerShot ELFPH 340 HS (focal length 4.5 mm; resolution 4608 x 3456; pixel size of 1.33853 x 1.33853 μm). Photos were taken an average of 0.4 m from the surface. The surface model error is 0.138061 pix. The final images presented here were rendered using CloudCompare (v.2.6.3.beta). Vertical scale bar is in metres.

Discussion

Inferred chronology and significance of the Last Interglacial

Based on stratigraphic correlation to the dated layers of Roberts et al.[1], we suggest that Megafauna Rock most likely dates to Marine Isotope Stage (MIS) 5e. The geological stratum in which it occurs is the same unit described by Helm et al.[3] in which giraffe tracks were described. MIS 5e extended from ~128 ka to 116 ka[17] with a peak sea-level highstand at 126±7.1 ka[18], and was associated with a relative sea-level range of 6.6–8 m higher than present on the Cape south coast[19]. This was a time associated with polar temperatures ~3–5 °C warmer than at present[20] and a global mean temperature 1.5 °C higher than at present[21,22]. With the effects of the present interglacial, the study of sea-level indicators from MIS 5e is fundamental to achieving a sense of palaeoclimatic and palaeoenvironmental regimes as suitable analogues. Accurate dating of Megafauna Rock through OSL, and resulting estimates of the extent of the exposed Palaeo-Agulhas Plain and the distance to the coastline at the time the tracks were registered, may enable more robust palaeoenvironmental conclusions to be drawn.

Avian tracks

We ascribe an avian origin to the two short tridactyl trackways with relatively narrow digit morphology on the rock that lies adjacent to the Roberts Rock site. We do not consider these to be distinctive enough to allow for further speculation on trackmaker identity. However, they add to the archive of fossil avian tracks in southern Africa. We have identified 14 such tracksites, representing at least six morphologies, in Pleistocene aeolianites on the Cape south coast, of which 8 are in the area east of Still Bay.[2,4] One of these sites is close to Megafauna Rock, and contains two of the longest known fossil avian trackways in the world.[2] Prior to our studies there was only one published reference to an avian fossil trackway in South Africa.[23]

Elephant tracks

The occurrence of elephant tracks at both Roberts Rock and Megafauna Rock is not surprising. Roberts' initial description[1] of Roberts Rock placed it at the western edge of a 300 m, laterally persistent, low-angled, laminated facies containing numerous elephant tracks; bioturbation was noted, with tracks evident in successive bedding planes over a vertical extent of 4 m.

The slightly oval pes and more rounded manus tracks are distinctive, and there is no plausible trackmaker other than the African elephant (*Loxodonta africana*).[24-27] There is no fossil evidence to suggest that earlier elephant species such as *Loxodonta atlantica* survived later than 400 ka.[14] We have now identified fossil elephant tracks at many sites along the Cape south coast, including Dana Bay, Goukamma (six sites)[4] and Brenton-on-Sea[5]. One cross-sectional Goukamma site exhibits tracks in a section up to 26 m in thickness.[4] While the elephant tracks at Roberts Rock and Megafauna Rock represent some of the southernmost evidence of elephants in the world[1], submarine studies may expand the range further south onto the Palaeo-Agulhas Plain.[28]

The Cape south coast sites are collectively the only known Pleistocene elephant tracksites in southern Africa, and there is a single documented occurrence of a Pleistocene elephant tusk in an intertidal platform in aeolianite near Durban.[29] Pliocene elephant tracks have been reported from Laetoli in Tanzania.[30] Pleistocene elephant tracks were reported

from near Ileret in Kenya[31], and Holocene elephant tracks have been reported from Namibia[32,33].

The African elephant is highly adaptable, and ranged across Africa in numbers of more than 20 million before European colonisation, after which their numbers decreased to an estimated 400 000 today.[34,35] A remnant population survives near the Cape south coast in the Southern Afrotemperate Forest around Knysna, which was once connected with the rest of the southern African population.[36] Evidence suggests that elephants used a variety of habitats and migrated extensively in the GCFR, even crossing mountain passes into the Karoo, eastern Cape thicket and beyond.[37,38] Based on dentition and modern diets, African elephants are considered mixed feeders, favouring woody browse during the dry season and C_4 grasses during the wet season.[39,40] Evidence suggests that their diets contained a higher degree of C_4 grasses in the Pleistocene.[40] The grassy plains, meandering rivers and seasonally waterlogged floodplains of the Palaeo-Agulhas Plain[10] would potentially have been an important seasonal resource for elephants, driving a seasonal migration[15,29] between the grazing resources in the wet season and the forests in the southern Cape, river drainage thickets of the Karoo hinterland, or thicket areas of the eastern Cape in the dry season.

Artiodactyl tracks

Artiodactyl tracks are the most common ichnofossils noted in Late Pleistocene aeolianites on the Cape south coast through the course of our project. Often such tracks cannot be identified to genus level, and can simply be described as 'large artiodactyl', 'medium artiodactyl' or 'small artiodactyl', as on Roberts Rock where small and medium artiodactyl tracks predominated. However, tracks of buffalo species are an exception, being distinctive in size (slightly larger than eland or kudu, smaller than giraffe). Two buffalo species are known from the GCFR: the extant Cape buffalo (*Syncerus caffer*) and the extinct long-horned buffalo (*Syncerus antiquus*). In analysing fossil artiodactyl tracks of this size, we note two morphologies: tracks that are longer than they are wide, consistent with tracks of the extant *Syncerus caffer*, and tracks that are wider than they are long, as noted first in a long trackway at Goukamma[4]; there are no extant artiodactyl tracks in southern Africa that exhibit such dimensions.[24-27] The artiodactyl track on Megafauna Rock is much wider than it is long (Figure 8).

In contending that *Syncerus antiquus* is the most plausible trackmaker, we note the observations of Lockley[41] that wider, longer and often more curved horns are associated with wider, more curved tracks, and that *Syncerus antiquus* had extremely long, laterally extending horns. Cattle farmers in southern Africa indicate that they can distinguish tracks of short-horned cattle from those of Nguni cattle which have horns of medium length, the latter being proportionately wider (Smit N 2016, oral communication, October 16). The track on Megafauna Rock, although single, corroborates the trackway evidence from the Goukamma site regarding track dimensions of this extinct buffalo species.[4] Its occurrence within the infill layer of an elephant track is unusual.

The long-horned buffalo, *S. antiquus,* was common in the GCFR up to the beginning of the present interglacial, becoming locally extinct at ~10–12 ka.[42] Its decline is thought to be related to changing climate and the associated sea-level rise that inundated a large proportion of the Palaeo-Agulhas Plain, resulting in loss of suitable habitat in the early Holocene.[42-44] The smaller Cape buffalo, *S. caffer,* remained fairly common in the southern Cape up to the 18th century, especially from Mossel Bay eastwards.[37,38]

Both *S. antiquus* (~800 kg) and *S. caffer* (~650 kg) are very large ruminants, with the latter already at the extreme of ruminant body size limits.[45] Both species would have required bulk grazing resources in the GCFR which would have provided sufficient energy to sustain them during times of lower availability. Regional migration on the Palaeo-Agulhas Plain between C_4 and C_3 grasslands (e.g. between bimodal and winter rainfall areas) is possible. The C_4 grasslands with wetter habitats on the Palaeo-Agulhas Plain would have played a prominent role in the survival of both species, arguably more so in the case of *S. antiquus*. Klein[43] noted that the hypsodont teeth and long horns of *S. antiquus* indicated a preference for open grasslands. Sinclair[46] noted a preference for riverine grasslands and riverine forest for *S. caffer*. In comparing the habitat requirements of *S. antiquus* and *S. caffer*, Vrba[47] considered *S. caffer* to be less tolerant of very open environments. Peters[48] considered such arguments in analysing the faunal succession at the Ishango site in eastern central Africa, which may have relevance to similar successions on the Cape south coast. Once accurate dating has been performed at Megafauna Rock, and the extent of exposure of the Palaeo-Agulhas Plain at the time the tracks were made can be determined, such considerations may be helpful in palaeoenvironmental interpretation.

Rhinoceros track

The dimensions and morphology of the deep tridactyl impression with rounded digit impressions on Megafauna Rock is suggestive of a rhinoceros trackmaker (Figure 9). This inference is tempered with caution because only one track is evident. However, the presence of other large, well-preserved vertebrate tracks on this surface supports the likelihood this impression is a track rather than a non-biogenic feature. No extant member of the southern African fauna produces three-toed tracks of this size other than rhinoceros, although we acknowledge that in sandy substrates impressions made by the two middle toes of hippopotamus (*Hippopotamus amphibius*) can sometimes appear to fuse, potentially creating a resemblance to a rhinoceros track.[27] We are not able to distinguish whether this track was made by black rhinoceros or white rhinoceros, but the dimensions of this track are smaller than that made by an adult white rhinoceros.[24-27] This is the first documentation of a probable fossil rhinoceros track in southern Africa. Pliocene rhinoceros tracks have been reported at Laetoli in Tanzania.[27]

Black rhinoceros (*Diceros bicornis*) was recorded throughout the GCFR until as recently as the 18th century.[38] White rhinoceros (*Ceratotherium simum*) disappeared from the fossil record in the southwestern Cape ~17 000 years ago.[42] While both species are present in the body fossil record of the GCFR during the Pleistocene[42], *D. bicornis* is encountered more frequently[14]. *D. bicornis* is a browser preferring low-growing woody shrubs, and *C. simum* is a grazer preferring short grass species in the wet season and taller grass species in the dry season.[49] Both species are water dependent.[50] *C. simum* would have tended to inhabit the Palaeo-Agulhas Plain with its C4 dry and short grasslands, and *D. bicornis* would have tended to inhabit Fynbos–Strandveld–Renosterveld areas inland with suitable browse vegetation.

Equid track

The large, symmetrical raised feature on Megafauna Rock (Figure 10) has equid features, and its dimensions are more than double the length and width of tracks of extant zebra species, which are typically ~10 cm in length.[24-27] The morphological features and size suggest a large horse species such as the giant Cape horse (*Equus capensis*) as the trackmaker. While some of the attributes of this track can be attributed to overprinting, the dimensions noted remain substantially larger than those of any extant equid species, and there is no candidate for equid tracks of this size from the body fossil record other than *E. capensis*. We acknowledge that Pleistocene body size may correlate with climate regimes, with carnivore size noted as being larger during glacial phases.[51] However, there is no indication that extant zebra species were similarly affected.

While Roberts et al.[1] noted the presence of equid tracks in aeolianites along the Cape south coast, the track on Megafauna Rock was the first identification of an equid track of this size in southern Africa. Whereas the other tracks on the upper surface of Megafauna Rock are natural mould impressions, this feature is raised. The preservation mechanism can be attributed to compaction of sediment below the track, making it more resistant to erosion than the surrounding matrix.[52] Such a preservation mechanism can be replicated on Cape south coast beaches under suitable conditions: initial compression of surface layers of sand by the trackmaker, followed by wind of sufficient strength removing the softer sand around the track, leaving an elevated 'pedestal track'. Subsequently, fossil equid tracks have been noted at Goukamma[4], Brenton-on-Sea and Robberg. As with the inferred long-horned buffalo

and rhinoceros tracks on Megafauna Rock, the presence of only a single track provides a limited database.

Equus capensis occurrence in the GCFR can be traced to the early Pleistocene[53], but like *S. antiquus* it went locally extinct at ~10–12 ka[42]. The giant Cape horse[54], at ~450 kg, was larger than its close relatives, the Cape mountain zebra (*Equus zebra*, ~234 kg)[50] and the quagga or plains zebra (*Equus quagga,* ~235 kg)[55].

All equids are non-ruminants which are tolerant of poor quality forage, but they require a high rate of intake.[56] *E. quagga* is considered to be a grazer that takes browse occasionally.[57] *E. zebra* is also predominantly a grazer, but takes browse more readily.[58] Extant equids are water dependent and normally stay within 12 km of the nearest water source.[50] *E. quagga* is described as a savanna species which prefers more open areas in woodland habitats.[50] Considering the food and habitat requirements of extant species and the fact that *E. capensis* was a very large animal, the C_4 grasslands of the Palaeo-Agulhas Plain would have been a key resource for this species.

Burrow traces and invertebrate traces

The dimensions of the large burrow traces evident on the large block that lies adjacent to the Roberts Rock site probably make an invertebrate origin unlikely. We considered root casts, as they are found in the region, usually in palaeosols. However, such root casts tend to cross foresets, and tend to taper. While we do not ascribe an origin for these features with certainty, we suggest that they were most likely made by a fossorial species such as a golden mole. Similar, better preserved burrow traces have been found closer to Still Bay, at Goukamma and at Robberg. Early to Middle Tertiary golden mole burrow traces have been described from the Tsondab Sandstone Formation in the Namib Desert.[59] Numerous smaller traces are present consistent with an invertebrate origin. While these burrow traces do not form a current focus of our study, they may form a fruitful subject for future study.

Megafauna Rock – palaeoenvironmental considerations

Megafauna Rock represents an important record from the perspective of understanding faunal distributions in the GCFR. The site location, at what would probably have been a dune setting in an ecotone between the grassland of the Palaeo-Agulhas Plain and the inland Fynbos–Strandveld–Renosterveld, allows for the potential of observing faunal assemblages from both vegetation types. Fossil remains of *S. antiquus* from Late Pleistocene sites are generally associated with bones of typical grazers, including *E. capensis*.[49] The track assemblage on Megafauna Rock thus independently supports the body fossil record. All four species whose tracks are found on Megafauna Rock were water dependent. The concentration of tracks on different bedding planes on one rock (indicating repeated use over time) suggests proximity to a water source. Quick et al.[7] analysed a core sample from Rietvlei, 3 km northwest of Megafauna Rock, with dates extending back to 36 ka. A similar interdune lake could have existed at the time the tracks were registered, as was suggested by Roberts et al.[1]

Areas of concentration

Tracksite zones appear to be concentrated in space and time. An area of concentration east of Still Bay extends laterally parallel to the coast, as well as vertically, implying repeated use of certain areas. Roberts Rock and Megafauna Rock occur within this track-rich zone. In adjacent areas that seem to offer suitable opportunities for track-bearing exposures, none are observed over stretches of more than a kilometre. Proximity to water sources is one possible reason for such zones of concentration. Roberts et al.[1] also suggested the possibility of a seasonal migration trail. Through neoichnological studies, Cohen at al.[12] have suggested how track analysis can be used to estimate population density and recurrent behaviour. The applicability of such suggestions to the tracksites of the Cape south coast, including the sites we describe here, should be considered with caution, as meaningful interpretation would require large sample sizes. Furthermore, the challenges are acknowledged of differentiating between many tracks made by a single individual versus a few tracks made by multiple individuals.

Rate of tracksite exposure and loss

High tides and storm surges impact these coastal cliffs. Cliff collapse and slumping are frequent, as weakly cemented aeolianites readily cleave along bedding planes. Rocks containing track-bearing surfaces may be seen in situ, or ex situ at the base of cliffs, as in the case of Roberts Rock and Megafauna Rock. The rapid changes that occurred in the space of less than a decade at Roberts Rock are testimony to the ephemeral nature and instability of such sites. Repeat visits enabled an observation of the ichnofauna on a succession of surfaces that would not have been apparent from a single visit. It is likely that other sites have been lost to coastal erosion without being recorded. Fortunately, Megafauna Rock appears to be a more stable unit, and it lies above the zone of intertidal erosion. Repeat coastal surveys to document new tracksites and to determine the fate of known sites are desirable.

Conclusions

Roberts Rock and Megafauna Rock form two ichnological highlights of an area rich in trace fossils. Both exhibit impressive track density, and both indicate continued impact on substrates in space and time in definable zones. They provide windows into Late Pleistocene dune life in the southern Cape, and suggest an area teeming with life.

Together they contribute to the understanding of the Late Pleistocene southern Cape megafauna, including the first documentation of elephant tracks, probably the first rhinoceros and giant Cape horse tracks, and ichnological evidence of the long-horned buffalo.

Dating of Megafauna Rock and other tracksites of significance by OSL is anticipated to contribute to further palaeoenvironmental inferences, as the sites would be placed within a temporal framework. The slumping of Roberts Rock into the ocean is a loss to ichnology, mitigated by its replacement by an even larger track-bearing rock. At least it was studied repeatedly during its exposure. As an example of the ephemeral nature of exposed tracksites and the likely exposure of new sites, this case stresses the need for regular ichnological surveys along this track-rich coastline.

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Authors' contributions

C.W.H.: lead author, corresponding author, conceptualisation, data collection, data analysis, writing, project leadership, track analysis. H.C.C.: sample analysis, data analysis, contribution on geological context, field stratigraphy, review of drafts and revisions. J.C.d.V.: data collection, data analysis, discoverer of Megafauna Rock, review of drafts and revisions. M.G.L.: data collection, data analysis, contribution on ichnological content, review of drafts and revisions. R.T.M.: data analysis, photogrammetry, review of drafts and revisions. J.V.: data analysis, contribution on palaeobiology and palaeoenvironment, review of drafts and revisions.

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Palaeotopography of a Palaeolithic landscape at Bestwood 1, South Africa, from ground-penetrating radar and magnetometry

In order to investigate the buried landscape at the Fauresmith locality of Bestwood 1, outside the town of Kathu in the Northern Cape Province, we performed ground-penetrating radar and magnetometry surveys across the sand-filled central portion of the valley. The radar images a strong continuous reflector which we can assign to the boundary between the Kalahari sands and underlying Banded Ironstone Formation gravels. Moreover, the thickness of the sand delineates a buried depression in the centre of the valley with flat plateaus at the sides. Subtracting the sand thickness from the current topography produces a map of a small stream channel in the northern part of the valley. Analysis of the magnetic gradient data allows us to extend this buried channel further to the south. Our geophysical survey provides a valuable contribution towards understanding the context of hominin occupation along the banks of a small stream in the Kathu Complex.

Significance:

- We provide an example of combining two geophysical methods to map overburden thickness, useful for archaeological landscape interpretation.

Introduction

The Kathu Complex is a series of archaeological localities – Kathu Pan, Kathu Townlands and Bestwood – that together represent evidence of extraordinarily intensive occupation through the Earlier Stone Age (Acheulean) and the transitional Earlier Stone Age to Middle Stone Age (Fauresmith).[1-4] The sheer scale of these localities is unusual and poses challenges for both research and conservation.

In the research presented here, ground-penetrating radar (GPR) and magnetic gradiometer surveys were conducted to create a 3D subsurface map of the buried Pleistocene landscape at the site of Bestwood 1. GPR was used to map and define subsurface boundaries while gradiometer data, correlated to depth from GPR data, were used to increase the extent of mapping. The study site, Bestwood 1 (27°42′S 23°03′E, UTM zone 34 S), is situated in a south-facing valley in an isolated hill infilled with Kalahari sands. This hill is located at the western edge of the Kuruman Hills where this formation grades into the southern edge of the Kalahari Basin[3,4] (Figure 1). The sandy base of the valley is mostly level over its entire north–south extent of 2.8 km (Figure 2a). Valley walls slope gently and are composed of Banded Ironstone Formation (BIF) bedrock overlain by scree consisting of flat weathered slabs of BIF that includes large numbers of stone tools. The stone tools found within the exposed scree are heavily weathered. The boundary between the scree deposits on the hill slopes and the sand infill is gradual and sand has infiltrated between the BIF slabs in the lower slopes.

Quarrying for sand and gravel at the southern end of the valley has exposed a stratigraphic sequence of Kalahari sands with a depth of 2–3 m overlying a deep deposit of BIF gravels extending to a depth of at least 15 m. The interface between the two stratigraphic units is sharp although there is some infiltration of sand into the top of the gravel unit and small fragments of BIF in the sands (Figure 2b).

Excavations in two areas 100 m apart in a sand quarry at the south end of the valley have exposed large surfaces (31 m^2 in the eastern Block 1 excavation and 14 m^2 in the western Block 2 excavation) blanketed by artefacts characteristic of the Fauresmith industry (Figure 2c). In both areas the artefacts lie at the interface between the Kalahari sands and underlying gravels. Unlike the artefacts found on the hill slopes, those found in the quarry excavation are in good condition with virtually no weathering. These artefacts show little to no signs of mechanical damage such as rounded or chipped edges and rarely evidence of differential patination on surfaces. The artefacts are found in a single horizon with some artefacts embedded in clays at the top of the underlying gravel horizon (Figure 2b). There is no 'stacking' of objects and artefacts are mostly lying horizontally. Because of the scale of occupation, the Bestwood 1 occupation cannot be considered a clearly bounded archaeological site and is best treated as a palaeotopography of early human occupation. There is no current evidence of areas of high density of artefacts amidst a background of low density, the so-called 'scatter and patches', but rather what emerges is a fairly continuous density of artefacts across the excavated areas (see comparison of excavation areas in Table 1). Given that the entire area of the surveyed valley is about 2.8x0.4 km, and that to date similar densities of artefacts have been found in all areas tested, the potential scale of hominin occupation is massive. The goal of the geophysical survey was to create a 3D map of the contact between the gravels and the overlying sands across the entire valley and thus to determine the morphology of the potential landscape of hominin occupation.

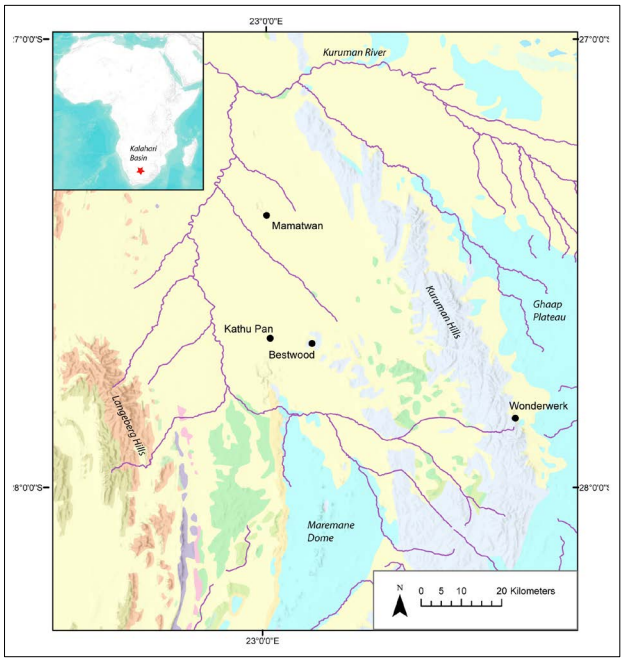

Figure 1: Map showing the geological context of the study area along with the sites mentioned in the text. The banded ironstone (grey) of the Kuruman Hills (Early Proterozoic Transvaal Supergroup) overlies the dolomite (light blue) of the Ghaap Plateau to the east and the Maremane Dome to the west. The Langeberg Hills to the east are outcroppings of quartzite (orange, Late Proterozoic Olifantshoek Supergroup). Between the Langeberg and Kuruman Hills there are exposures of lavas (green, Middle Proterozoic Transvaal Supergroup). The Kuruman Hills are at the southern margin of the Kalahari Basin and the surface deposits to the north are dominated by sands with occasional surface calcretes. The major drainage is the Kuruman River.

Table 1: Comparison of lithic assemblages from excavation areas and test pits. Does not include small flakes and fragments from sieve.

	Block 1	Block 2	GPR 1	GPR 2
	31 m²	14 m²	1 m²	1 m²
Biface and biface fragment†	33	25	1	–
Biface tip	3	1	–	–
Chopper	1	–	–	–
Polyhedron	1	–	–	–
Flake	622	422	14	18
Flake fragment	197	179	5	3
Blade	29	11	1	2
Blade fragment	9	17	1	–
Retouched flake	5	4	1	–
Core	41	34	2	–
Slab	25	6	4	1
Slab fragment	19	–	–	–
Modified slab	22	5	–	–
Modified slab fragment	4	1	–	–

GPR, ground-penetrating radar

†Includes all bifacially worked pieces including handaxes and roughouts/preforms

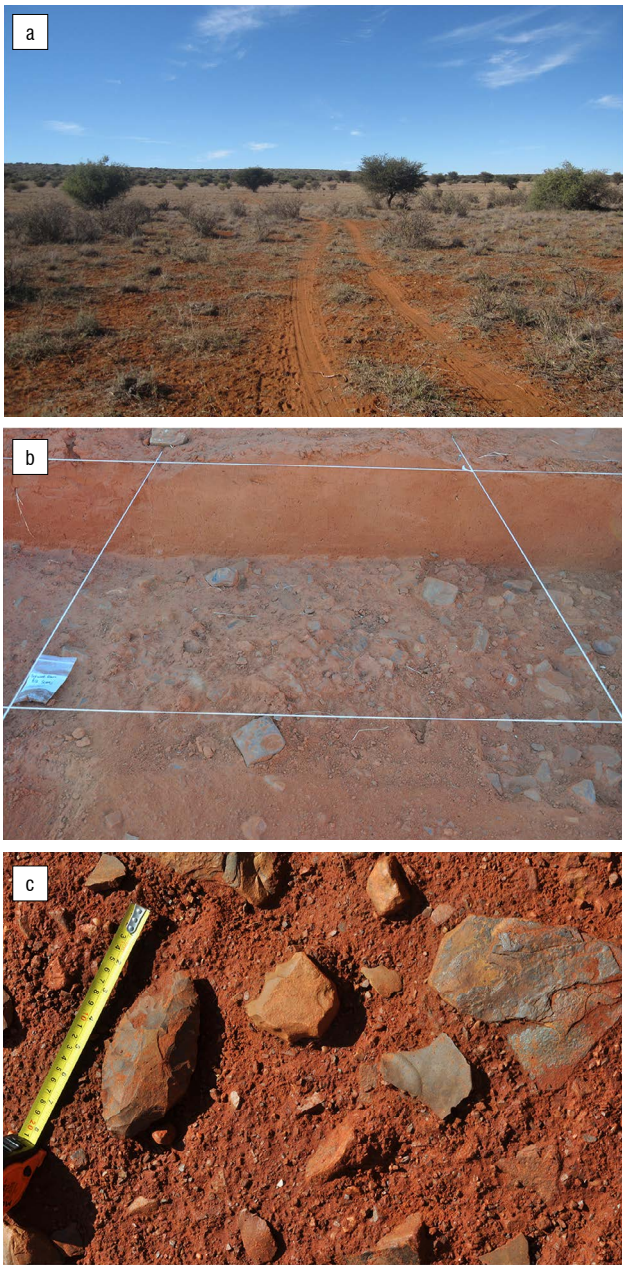

Figure 2: Images of Bestwood 1. (a) View of the valley floor. (b) Stratigraphic profile of Block 2 (Western Block) excavation showing the contact between the gravels and the overlying sands. (c) Block 1 (Eastern Block) excavation showing artefacts, including a hand axe, in situ, at the top of the gravels.

Methodology

Both ground-penetrating radar and magnetometry surveys were undertaken across the sand-filled central portion of the valley. Based on the results of the geophysical survey, two test pits were excavated to determine the accuracy with which the survey identified the boundary between the gravels and the sands and whether the archaeological evidence of hominin occupation extends beyond the area of the sand quarry at the southern end of the valley.

Ground-penetrating radar

The GPR surveys were conducted using a GSSI SIR-3000 connected to a 200-MHz centre frequency antenna with attached survey wheel (Geophysical Survey Systems Inc., Nashua, New Hampshire, USA). Traces were recorded every 50 mm in two-way travel time (TWTT, in nanoseconds) along profiles by moving the GPR antenna in as straight

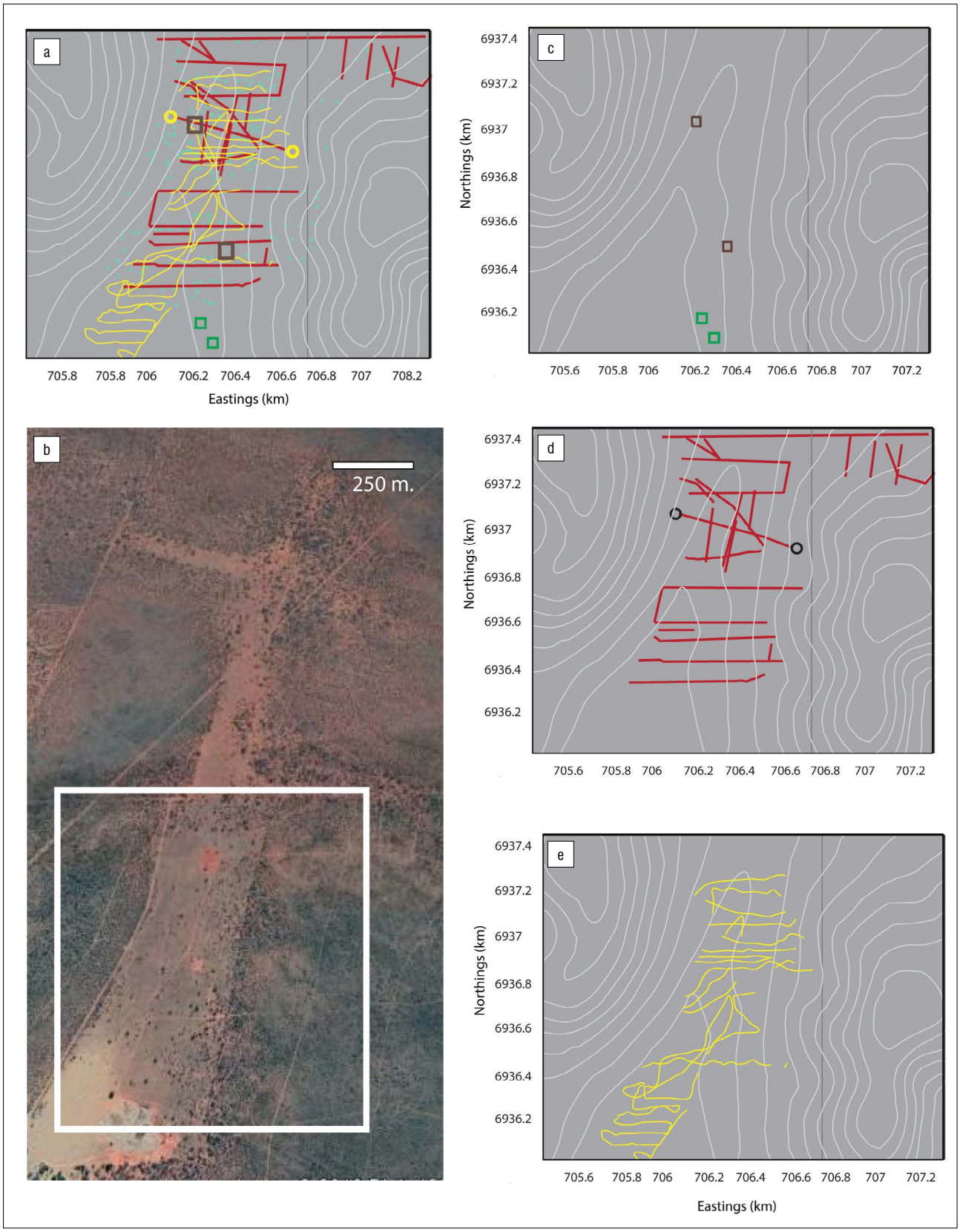

Figure 3: Topographic map of Bestwood 1 with ground-penetrating radar (GPR) and magnetic lines shown along with excavation areas and test pits. (a) GPR shown in red; magnetic lines shown in yellow; grids are marked by brown boxes; the GPR-magnetics correlation line is marked by yellow circles at each end; excavation areas marked in green. Note that one test pit was excavated in each of the grid areas. (b) Satellite image; white box shows the area covered by the topographic map. (c) Grids and excavation areas; (d) GPR lines; and (e) magnetic lines.

a line as was possible. Starting and ending coordinates of each line were recorded using a Garmin eTrex Legend H handheld GPS (Garmin International Inc., Olathe, Kansas, USA). to a stated accuracy of ±4 m. Surveys were conducted both along the length of the valley and across its width and included both sand- and cobble-covered portions of the valley slopes; in addition, we collected data from two 20x20 m grids with 0.5x0.5 m and 0.5x1 m line spacing (Figure 3). All post-collection work including the displaying of radargrams was performed in MATLAB.

Magnetics

Magnetics data were collected using a GSM-19GW proton precession gradiometer (GEM Systems, Markham, Ontario, Canada). Data were collected predominantly on the sand-covered valley floor and the base of slopes (Figure 3). Data locations were determined using the instrument's built-in GPS (location accuracy ±5 m from repeat readings). Magnetic surveys were done independently of the GPR surveys; that is, they are not along exactly the same profiles. Magnetics data were transformed in an attempt to quantify signal variability across the valley for correlation to sand thickness derived from GPR, through two methods: pseudo-amplitude and wavelength.

Pseudo-amplitude

A measurement of the pseudo-amplitude of the gradient signal was determined based on the fact that as distance increases from a magnetic source the amplitude of the magnetic anomaly will decrease.[5] A moving window of 50-m width was used to calculate the range of the data at 10-m intervals. As magnetic gradient strength declines with the fourth power of distance, we applied a transformation of 1 ^ (-1/4) to the moving window outputs to create a depth analogue.

Wavelength

We chose to extract signal wavelength from the gradient data as distance from a magnetic source controls the wavelength of the anomaly. Data were resampled to an equal step distance and an S-transform was applied. The S-transform uses a scalable Gaussian moving window and fast Fourier transform (FFT) to return the data in a distance-wavenumber representation.[6] Wavenumber is then converted to wavelength where wavelength is simply 1/wavenumber and the maximum contributing wavelength to gradient signal at a distance is used for correlation.

Test pit excavation

True sand thickness for the GPR lines was first calculated based on a dielectric range of 3–5 which is appropriate for dry sand.[7] To refine the dielectric range and thus the mapping of the reflector, we excavated one 1x1 m test pit in each of the two radar grids (Figure 3). Locations for test pits were chosen based on relatively low TWTT in nanoseconds. A second goal of these test pits was to test the extent of the distribution of artefacts beyond the archaeological exposures in the sand mine at the southern end of the valley. Pits were excavated by hand and excavation was halted when artefact surface and dense gravel was reached. Artefacts were recovered and large artefact distribution was mapped. We noted no groundwater in the sand, neither in the test pits nor in the sand mine. From that observation we infer that any groundwater would drain into the gravel layer, and that the dielectric constant would not change within the sand layer, thus allowing for straightforward conversion from TWTT to depth.

Results

The GPR transects produced a clear signal of the contact between the Kalahari sands and the underlying gravels. Most radargrams revealed a strong, continuous reflector at depth (Figure 4). In radargrams that cross the valley from slope to slope this reflector is first noticed barely downslope of the transition from scree-dominated ground cover to sand cover. The reflection then increases in depth towards the valley centre to a maximum depth and then decreases in depth towards the other slope, terminating just prior to the sand scree interface. Based on this evidence we interpret the reflector to be the transition between the overlying sand and a continuous layer of underlying gravels.

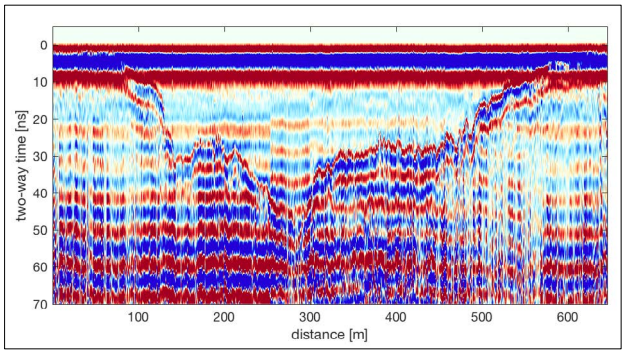

Figure 4: Sample radargram collected across the valley. The reflector reaches the surface near 80 m and 600 m, is at its deepest (~45 ns) near 280 m, and maintains an average two-way travel time of ~30 ns between 150 m and 500 m.

In both test units, similar densities of artefacts to those recovered in the archaeological exposures were found at the interface between the sands and the underlying gravel unit (Table 1). These artefacts are in fresh condition and typologically consistent with the Fauresmith. Depths to the termination of the sand layer were recorded and velocity was calculated to be 15 cm/ns averaged between the two pits which is equivalent to a dielectric constant of 5.

In order to visualise the shape of the reflector (the top of the gravel unit) in three dimensions, a series of manual picks were defined along each radargram. These points define the TWTT to the reflector at a given distance along the profile and the easting and northing coordinates of that point. These points are then combined into a mesh and extrapolated to create a map of the vertical extent of the sand layer in TWTT. Travel times can be converted to depth using

$$v = c/\sqrt{\varepsilon}, \qquad \text{Equation 1}$$

where v is the velocity of the radar wave, c is the speed of light in a vacuum, and ε is the dielectric constant of the medium through which the wave is passing.[8] Depth to a reflection is then one half the travel time multiplied by the velocity in nanoseconds.

The map of TWTT describing sand thickness was converted to a map of the true thickness of sand, or a map to the top of the reflective boundary, using the velocity determined using the dielectric constant of 5 derived from the test excavations (Figure 5). Two main features are revealed in this image. First, there is an elongate portion of higher than average sand thickness which runs north–south through the valley increasing in thickness to the south. Second, this thick sand region is flanked on both sides by sand of moderate thickness which thins the closer the map approaches to the valley slopes.

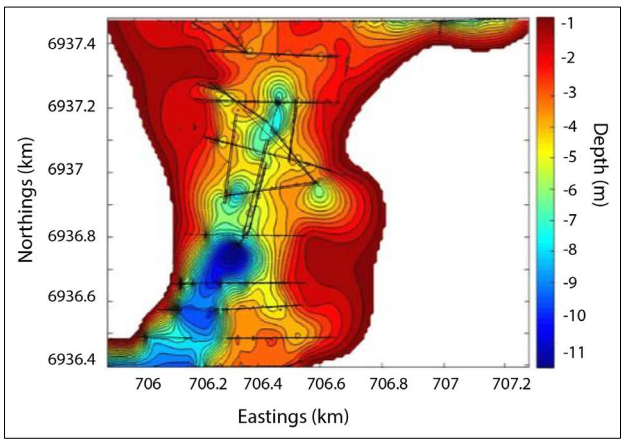

Figure 5: Interpolated map of sand thickness created from ground-penetrating radar data. Radargram positions are shown as black lines.

Relative elevation data were collected using a Leica TC series total station (Geosystems AG, Heerbrugg, Switzerland). Elevations across the valley were similarly gridded to GPR data. We then subtracted the values of sand thickness from those of the elevation data to create a map of what the topography of the valley would have looked like before the sands accumulated (Figure 6). These elevation-corrected data accentuate the features of the sand thickness map. The elongate region of high sand thickness is shown to be a more continuous depression and also takes on an element of sinuosity. Flanking the depression are two wide regions of elevation ranging from -5 m to 0 m. These mid-elevation plateaus terminate near the valley slopes where the elevation gradient increases sharply.

Magnetics

Gradient data show high signal variability over thinner sand and a steadier signal near the centre of the valley (at 150–300 m profile distance) where sand is thicker based on the GPR data (Figure 6). The pseudo-amplitude (PA) data differ from the depth data derived from GPR significantly in that they do not capture the increase in sand thickness from 350 m to 550 m. However, both data sets observe similar looking trends towards their minima: the lowest PA value of approximately -0.31 is at 250 m occurring 50 m sooner than its GPR counterpart (Figure 7) because the origin of the magnetic profile is shifted compared to that of the GPR line.

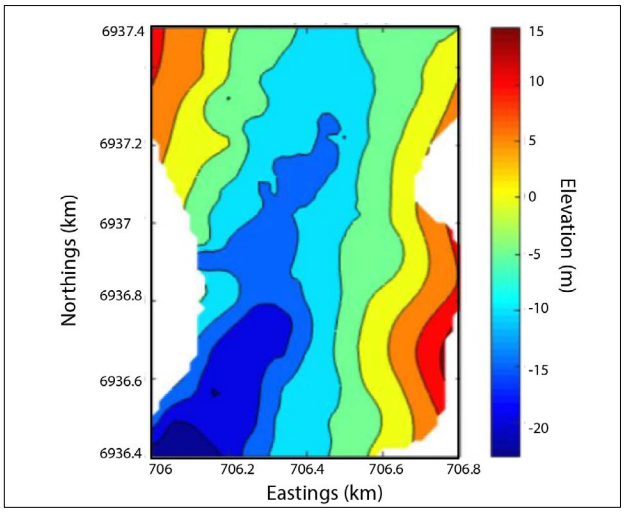

Figure 6: Valley topography revealed after correcting for sand thickness and any topography present on the valley floor.

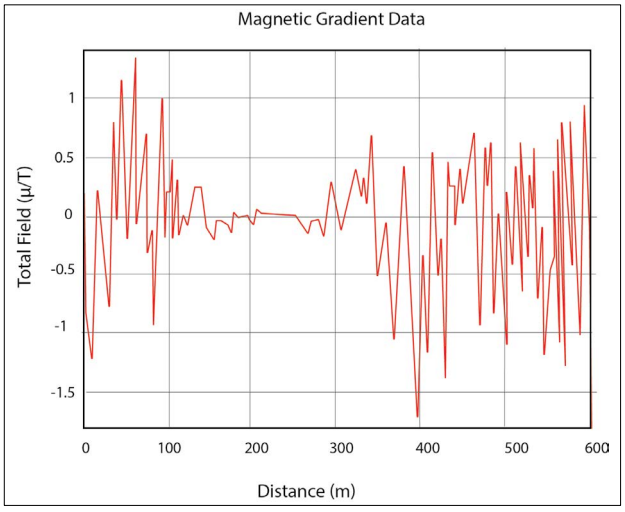

Figure 7: Gradient data collected across the valley width.

The wavelength trend is inverted from the GPR data as expected. While the data capture subtle variations over thinner sand, they also plot in a much blockier manner as an artefact of the fast Fourier transform. At longer wavelengths the S-transform is unable to resolve more than one wavelength value and as such the maximum plots as a solid bar. This results in a correlation which is unable to differentiate between depth values greater than 5 m, as is seen in Figure 8. Despite the similar looking trends between the two PA data sets and sand thickness data derived from GPR, the single line correlation was not as robust as expected. The PA data correlation produced an R^2 value of 0.3 and the wavelength R^2 value was also 0.3.

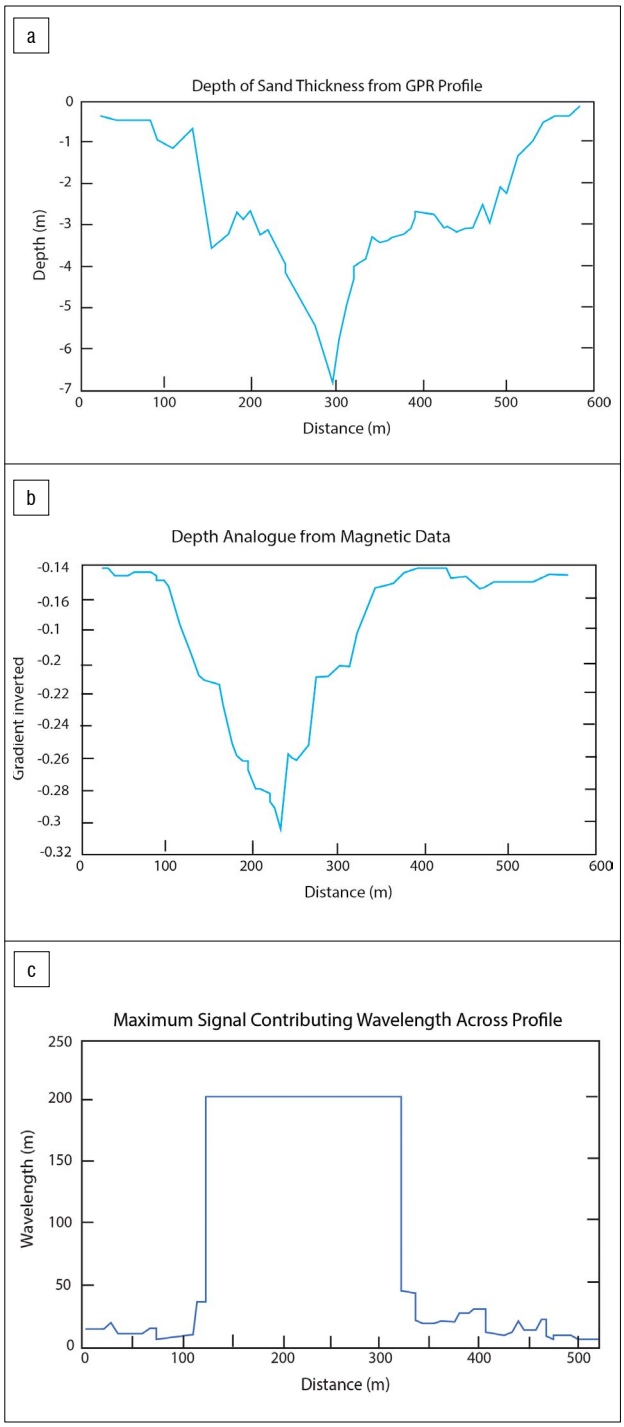

Figure 8: (a) Sand thickness over the distance of the ground-penetrating radar (GPR) profile; (b) pseudo-amplitude values plotted over distance; (c) wavelength contributing most to the gradient signal at a given distance.

Because of the ability of the PA correlation to better predict thicker sand values, this method was chosen for correlation. The PA transformations were applied to every line of magnetics data collected in the valley. These values were then used to form a mesh and extrapolated to the valley scale. This gridded data set was then checked for correlation against the valley scale map of sand thickness from GPR (if we had corresponding lines of both magnetic and GPR data we would have attempted the analysis on these overlapping measurement locations). The resulting plot of this correlation with an R^2 value of 0.6 is shown in Figure 9. The final map of sand thickness (Figure 10) is produced using the linear equation

$$\text{Depth} = 27.16(\text{PA value}) + 1.392 \qquad \text{Equation 2}$$

derived from a line of best fit for the scatterplot of PA and sand thickness data.

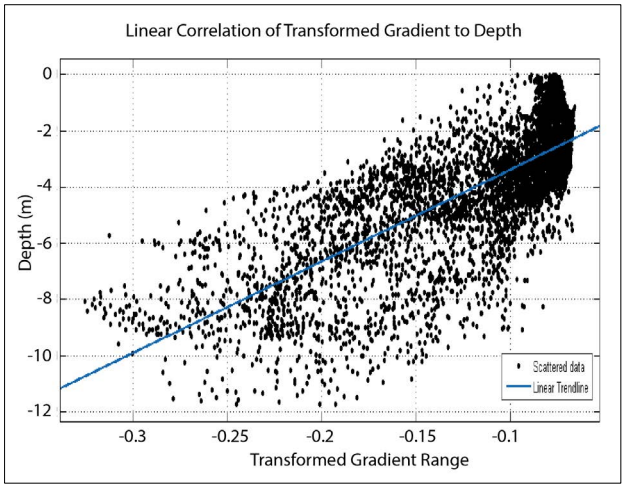

Figure 9: Scatterplot of depth from ground-penetrating radar and pseudo-amplitude transformation of all magnetic lines. The trend line is shown in blue.

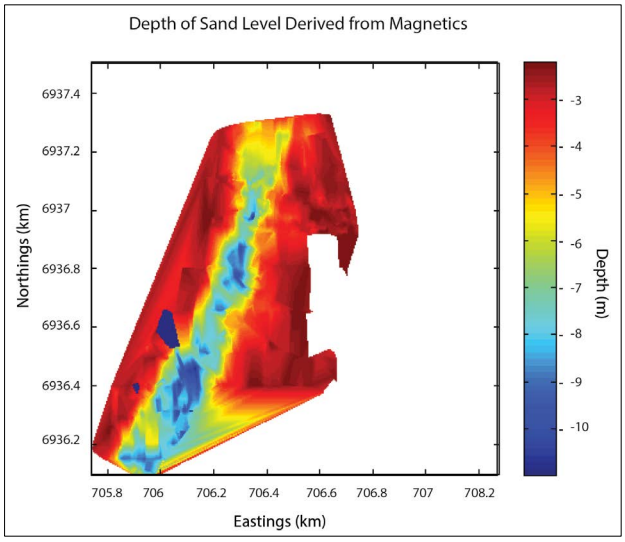

Figure 10: Map of sand thickness derived from gradient data by converting pseudo-amplitude values to depth using Equation 2.

Discussion

Both GPR and magnetics data produced maps of sand thickness that show similar trends in the Bestwood 1 valley. Consistent between two images is the elongate region of thicker sand and the flanking regions on both sides which show little change in elevation.

The palaeotopography map created by subtracting sand thickness from GPR data accentuates these trends. The elongate region characterised by thick sand is shown to be a channelised feature consistent with a river running north to south through the valley and is more sinuous than is seen in the data not corrected for topography. When compared to the eastern side of the valley, individual radargrams show long traverses of fairly flat topography in the subsurface reflector. These, as well as the similar – yet smaller – tracts of relatively even topography, are interpreted as floodplain terrain.

The magnetically derived sand thickness map helps to support these data. With only the palaeotopography map we were unable to define what the subsurface in the southern portion of the valley looked like. The correlation between PA and depth data does not provide a perfect estimate of depth where sand is shallow. As the PA is responding to the variability of the original gradient signal, it can be seen that it is difficult for this method to distinguish thinner sand layers as their variability remains consistently high. Importantly though, the resulting map of sand thickness shows the same channel structure continuing south, indicating that this feature is likely continuous beyond the mapped limits of this project.

As in applications of geophysical surveys in the Wadi Safsaf and Wadi Arid study areas in southern Egypt[8-11] and the Laguna Seca in Portugal[12], the geophysical challenge at Bestwood 1 involves imaging the interface between sands and a substrate of either gravels or bedrock. At Bestwood 1 there is a good match between magnetic data and GPR data. The application of magnetics makes it possible to extend the landscape reconstruction of the palaeolandscape across the whole survey area and reveal a buried palaeofluvial channel.

The geophysical research at Bestwood 1 allows us to situate the extensive hominin occupation along a channel incised in an underlying gravel. This channel would have formed part of the hydrological network that drains into the Orange River to the north. Thus, the context of hominin occupation was proximity to flowing water. However, a number of critical issues remain regarding this occupation. Perhaps the most critical is the duration of occupation. As Stern et al.[13] have pointed out, there is a strong tendency in Palaeolithic archaeology to treat occupations as a 'moment in time' which clearly is inappropriate for landscapes that are palimpsests of activity over very long periods. It is also important to note the role of ants as currently visible agents of bioturbation in the Kalahari sands, which points to the need for caution in assuming that Bestwood 1 is in fact an intact horizon of occupation rather than a 'stone line' of artefacts that have been concentrated at the base of the sands as the result of bioturbation (for discussion of stone lines see Chazan et al.[14]; for the role of ants in bioturbation and transport of artefacts see Rink et al.[15] and Schoville et al.[16]). However, the fact that some artefacts are found embedded in a clay matrix at the top of the gravels argues against such a scenario.

The current working hypothesis is that artefacts accumulated in a rapidly aggrading clay deposit that formed along the banks of the channel. Subsequent bioturbation has broken down this clay deposit creating the impression that the artefacts were deposited directly under the Kalahari sands. The duration of the occupation cannot be ascertained but it is undoubtedly a palimpsest of many visits to the area. Detailed analysis of artefact weathering and micromorphology is critical to developing a thorough understanding of the nature of hominin occupation at Bestwood 1.

Conclusion

We had not planned at the outset of this study to combine magnetic and GPR surveys, and instead ran separate surveys. After noticing that the GPR penetration was not good enough in the southern portion, and that our magnetic data showed strong variations in amplitude from the centre to the sides of the valley, we looked more closely at the magnetic data. A reason the correlation between magnetic pseudo-amplitudes and depth to gravels worked well is that the gravels beneath the sand are highly magnetic and produce strong measurable anomalies. Our study shows that using magnetometry to determine depth of the sand layer is feasible in such a setting; however, most of our results do not rely on this part

of the analysis. For future surveys with a strongly magnetic bottom layer where GPR cannot be used across much of the survey area, we suggest the collection of magnetic data and GPR profiles along the same profiles to obtain the correlation before extending the analysis to other areas. Our method has proven useful at this site and provided an image of a palaeovalley linked to a site of known hominin occupation.

Geophysical research in the Bestwood 1 valley has helped place this extensive hominin occupation in a landscape context. We can now propose a working hypothesis that there was a hominin occupation of many repeated visits to this valley along the banks of a now buried palaeochannel that was part of the Orange River drainage system. This research demonstrates the essential role of subsurface geophysical survey for understanding palaeotopography of hominin adaptation. Ongoing research at the Bestwood 1 site will refine understanding of the tempo and duration of hominin activity that led to the formation of this remarkable locality and the factors that account for the extensive hominin activity in this particular valley. The geophysical survey also provides the basis for designing a sampling strategy to test the extent of the distribution of archaeological occupation that takes into account now buried landscape features. Our results encourage work at multiple spatial scales of analysis including more fine-resolution research currently underway on the distribution of artefacts within the two excavation blocks as well as a large-scale consideration of the evolution of the Orange River drainage.

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Authors' contributions

K.S.P.: Field data collection, data analysis, writing. C.-G.B.: Research design, field data collection, data analysis, writing. S.J.W.: Field data collection. M.C.: Project director, research design, analysis of lithics, writing.

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Perfectionism and motivation in sport: The mediating role of mental toughness

An extensive body of research has been done on the links between perfectionism and motivation, yet the underlying mechanisms linking these psychological characteristics have been underexplored. In this study, we used an integrative modelling approach to examine associations between dimensions of perfectionism (i.e. personal standards [PSP] and concerns over mistakes [CMP]), mental toughness (MT) and motivational orientations (i.e. self-determined motivation [SDM] and non-self-determined motivation [NSDM]). Based on a sample of 318 male (n=218) and female (n=100) tennis players (M_{age}=17.61, SD_{age}=2.41), fit indices derived from structural equation modelling supported a partially mediated model. Residual PSP associated positively with MT (β=0.74) and SDM (β=0.40), and negatively with NSDM (β=-0.22). Conversely, residual CMP associated negatively with MT (β=-0.14) and SDM (β=-0.19), and positively with NSDM (β=0.73). Mental toughness was positively associated with SDM (β=0.28), but was unrelated to NSDM (β=0.07). The relationship between residual PSP and SDM was partially mediated by MT (standardised indirect effect: 95% CI=0.19, 0.46). The findings of this study support research linking dimensions of perfectionism with motivational orientations and offer preliminary evidence on the mediating role of MT in the association between these psychological constructs. With emerging research supporting the capacity to develop MT through targeted interventions, the findings are discussed alongside salient implications.

Significance:

- Mental toughness partially mediated the association between pure personal standards perfectionism and self-determined motivation.
- Particularly among athletes with higher personal standards of perfectionism, more autonomous forms of motivation may be sustained via efforts that seek to develop athletes' mental toughness.

Introduction

Perfectionism is generally regarded as a personality trait that involves establishing and striving for exceptionally high personal performance standards and engaging in critical self-evaluation.[1] Although researchers commonly categorise perfectionism into two superordinate dimensions of perfectionistic strivings (PS) and perfectionistic concerns (PC)[2], there is less consensus about the features that comprise each dimension. Conceptual discrepancies are evident within existing measures of perfectionism, with differences in coverage (i.e. broad versus narrow in scope), orientation (i.e. interpersonal versus intrapersonal dimensions), and the extent to which adaptive and maladaptive aspects of perfectionism are distinguished.[3] Given that socially prescribed features of perfectionism may be internalised and form part of a person's self-imposed perfectionism,[4] we sought optimal parsimony in this study by operationalising perfectionism based solely on intrapersonal dimensions. Along these lines, we drew on the work of others[5,6] and focused on a single feature of each superordinate dimension of perfectionism. Specifically, we refer to the notion of setting and evaluating the self against perfectionistic personal performance standards as personal standards perfectionism (PSP), whereas concerns over mistakes perfectionism (CMP) represents concerns over making mistakes and the evaluative consequences that accompany them.[1]

With conceptual ambiguity surrounding both subordinate and superordinate levels of perfectionism[7], researchers have raised concerns over the effect of statistical partialling on the conceptual meaning of the dimensions of perfectionism[8]. Because PS and PC each involve elements of self-evaluation, statistical approaches (e.g. multiple regression) that control for the overlap between them may change the conclusions that are drawn about the relations PS and PC have with outcome variables of interest.[7] Several studies have found that the typically adaptive relations shown by PS, and the maladaptive relations shown by PC, tend to become stronger when the shared variance between them is partialled out.[8,9] These changes in the predictive validity of PS and PC represent suppression effects – instances in which the relations between predictors and an outcome are altered when they are simultaneously included in a model.[2] Although scholars continue to debate the advantages and disadvantages of partialling PS and PC[2,7,8], there is consensus that researchers should clearly distinguish between findings that pertain to overall (i.e. unpartialled effects) and residual (i.e. partialled effects) PS and PC[7]. In line with recent recommendations[2,8], we refer to unique relations of PSP and CMP that occur as a result of partialling as *residual PSP* and *residual CMP*, respectively.

Perfectionism and motivation

Motivation refers to the underlying causes of human behaviour.[10] While several models of motivation exist, self-determination theory[11] has consistently been applied to the study of perfectionism[12]. Within this framework, motivation is represented by a continuum of motivational subtypes (i.e. intrinsic regulation, integrated regulation, identified regulation, introjected regulation, external regulation and amotivation) that reflect the extent to which basic psychological needs are internalised.[13] The most autonomous forms of motivation (e.g. intrinsic regulation and identified regulation) embody self-determined motivation (SDM), whereas the least autonomous (e.g. external regulation and amotivation) exemplify non-self-determined motivation (NSDM).[6,14]

In their recent review of the literature on perfectionism and motivation, Stoeber et al.[15] concluded that PS are primarily associated with self-determined forms of motivation, whereas PC are largely related to non-self-

determined forms of motivation. These respective associations tend to strengthen when the shared variance between PC and PS is removed. Stoeber and colleagues[15] also noted selected instances in which the effect of partialling resulted in PS associating with less autonomous motivational types (i.e. introjected and external regulation). Although an extensive body of literature exists on the mediating role of motivation in the associations between dimensions of perfectionism and key outcome variables (e.g. burnout), one area that requires further investigation is the mediating mechanism by which perfectionism relates to motivation.

Perfectionism, mental toughness and motivation

Mental toughness (MT) is a psychological construct linked to success (e.g. achievement) in competitive sport[16], with recent evidence supporting the development of MT through both naturally occurring interactions with the environment and targeted interventions[17]. Despite the obvious appeal to athletes searching for a competitive edge, the growing body of research on MT suggests there are several broader reasons for advocating the development of MT among athletes. For example, MT has been found to be associated with adaptive mental health functioning and well-being, including lower reported stress and depression and better sleep quality[18-20], which is encouraging given athletes' risk for experiencing mental health issues[21]. Taken together, these wider implications of MT are important, particularly to personnel (i.e. parents, coaches and practitioners) involved and invested in athletes' personal development and well-being.

In line with recent conceptualisations, we define MT in this study as a psychological resource that enables athletes to initiate and sustain efforts towards goal-directed endeavours.[22,23] We acknowledge that researchers continue to debate the conceptualisation of MT and approaches to measurement.[22,24] For example, while some have produced models and measures that reflect a multidimensional, trait-like construct[25], others have proposed MT to be unidimensional and state-like[22]. Evidence from behavioural genetic research has supported a combination of heritable and non-shared environmental influences, each of which appear to account for approximately half of the variance in MT.[26,27] Additionally, Gucciardi et al.[23] directly examined the dimensionality of MT by comparing a multidimensional, higher-order model encompassing seven dimensions (i.e. self-belief, attention regulation, emotion regulation, success mindset, context knowledge, buoyancy and optimism) of MT to a unidimensional one. They found support for a unidimensional representation of MT, owing to the substantial overlap (i.e. lack of discriminant validity) among the established dimensions of MT.

Drawing on evidence from qualitative research on MT in sport, MT is likely to exhibit unique relations with PS and PC. Across several studies, athletes and key personnel involved with the development of athletes (e.g. coaches) have described MT as consistently striving to achieve one's best, setting and expecting high standards to be met, being committed to performance excellence and attaining success and pushing physical and mental limits to set oneself apart from competitors.[28-30] Furthermore, both athletes[31] and coaches[32] have suggested that athletes' MT development is predicated on high self- and other-initiated expectations (e.g. coach) and encouraging athletes' pursuit of such ideals.

While many of these descriptions of MT are comparable to aspects of PS outlined in the perfectionism in sport literature, research points to an antithetical association between MT and PC. In a study in which athletes were classified into high and low MT-flow groupings, Jackman et al.[30] found evidence of PC, including anxiety about mistakes and concerns over receiving negative feedback, among athletes classified into the low MT-flow group. These findings support previous research emphasising the capacity to reduce negative thoughts, avoid negative reactions to errors that may be detrimental to performance and the ability to rebound adaptively following mistakes[28,33,34] as features of MT.

Findings from a range of studies indicate that mentally tough athletes are autonomously motivated in their work ethic and drive to succeed.[28,29,33] In studies that have identified contrasting poles of MT[34], descriptions of athletes with lower MT include those motivated principally by external sources and those lacking motivation to work hard. Recent quantitative evidence suggests that associations between motivational orientations and MT have varied according to the degree of autonomy each form of motivation represents. For example, at the extreme ends of the motivational continuum, Schaefer et al.[35] found MT to be associated positively with intrinsic regulation, but negatively with amotivation.

The present study

In the current study, we examined associations among dimensions of perfectionism (as measured by PSP and CMP), MT and motivational orientations. Further understanding of these interrelationships is important because MT has been found to be amenable to development[17] and therefore might influence the relationships between dimensions of perfectionism and motivational orientations. For example, MT might offer an explanation for the positive associations between features of PS and self-determined forms of motivational orientations found in previous studies.[8] Using an integrative modelling approach, we explored MT as a potential mediator of associations between dimensions of perfectionism and motivational orientations (see Figure 1). It was expected that (1) residual PSP would be positively and residual CMP negatively associated with MT and, in turn, (2) MT would be positively associated with SDM and negatively associated with NSDM. Considering other mediating mechanisms are likely to be involved in the association between dimensions of perfectionism and motivational orientations, we anticipated finding evidence of partial, rather than full, mediation.

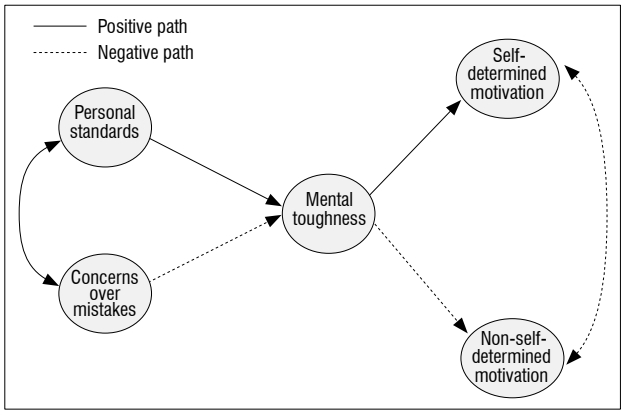


Figure 1: Hypothesised model of the relationships between dimensions of perfectionism, mental toughness and motivational orientations.

Method

Participants

The sample consisted of 318 (male=218, female=100) tennis players aged between 15 and 25 years (M_{age}=17.61, SD_{age}=2.41). All participants were recruited from one of three nationally sanctioned tournaments in South Africa and were competing in either the U16 (n=119), U18 (n=93) or Open (i.e. >18 years; n=106) age categories.

Measures

Perfectionism

PSP and CMP were measured using two subscales from the Sport Multidimensional Perfectionism Scale (Sport-MPS)[36]: personal standards (seven items; 'I have extremely high goals for myself in tennis') and concern over mistakes (eight items; 'Even if I fail slightly in tennis, for me, it is as bad as being a complete failure'). Participants responded to the items using a five-point response scale anchored at 1 (Strongly disagree) and 5 (Strongly agree). Dunn et al.[36] found support for factorial and convergent validity, while findings from several other studies support the construct validity of the Sport-MPS.[5,6] Previously reported internal consistency estimates have ranged from 0.70 to 0.89.[5,6,36]

Mental toughness

Participants completed Gucciardi et al.'s[23] eight-item Mental Toughness Inventory. Items (e.g. 'I believe in my ability to achieve my tennis goals') are rated on a seven-point response scale (1=False, 100% of the time; 7=True, 100% of the time). Associations between scores on the Mental Toughness Inventory, performance outcomes (positive), behavioural intentions (positive) and stress (negative) have been in the expected direction, offering support for the construct validity of the measure.[23,37] Several studies have reported internal consistency estimates >0.80.[23,35,37]

Motivation

Motivational orientations were assessed using selected subscales from the Sport Motivation Scale II (SMS II).[13] These included intrinsic ('…Because it gives me pleasure to learn more about tennis'), integrated ('…Because participating in tennis reflects the essence of whom I am'), external ('…Because people around me reward me when I do') and amotivated ('I don't know anymore; I have the impression that I am incapable of succeeding in tennis') regulation. Similar to Gaudreau and Antl's[14] item-level modelling approach, the two most autonomous (i.e. intrinsic and integrated regulation) and the two least autonomous (i.e. external regulation and amotivated regulation) forms of motivation were used to model SDM and NSDM, respectively. Pairs of items on the intrinsic and integrated motivation subscales (e.g. SDM_1=intrinsic $regulation_1$ + $integrated\ regulation_1$) were aggregated to model SDM, whereas pairs of items on the external and amotivation subscales were summed for NSDM (e.g. $NSDM_1$=$external\ regulation_1$ + $amotivated\ regulation_1$).[14] This resulted in three items for each dimension.

The 12 SMS II items used in this study were rated on a seven-point response scale from 1 (Does not correspond at all) to 7 (Corresponds completely). Anticipated associations with life satisfaction, vitality, task- and ego-oriented goals, and burnout have provided evidence of the construct validity of the instrument. Internal consistency estimates for the SMS II subscales have ranged from 0.70 to 0.83, and test-retest reliability values over a 1-week interval have been between 0.70 and 0.89.[13,38] Although the subscales included in this study were modified before further use, omega point estimates ranged from 0.80 to 0.84 for the subscales of intrinsic, identified, extrinsic and amotivated regulation.

Procedure

The study was granted ethical approval from the Humanities and Social Sciences Research Ethics Committee at the University of KwaZulu-Natal and all procedures adhered to the Declaration of Helsinki principles. At the tennis tournaments from which the participants were recruited, athletes were approached to determine their willingness to participate in the study. Informed consent was obtained from all adult participants. Parental consent was obtained on behalf of all legal minors (i.e. <18 years of age) who indicated their interest in participating. A team of experienced research assistants trained in standardised survey administration procedures administered the questionnaire in an individualised, face-to-face format to each participant, which occurred between participants' matches and at their convenience.

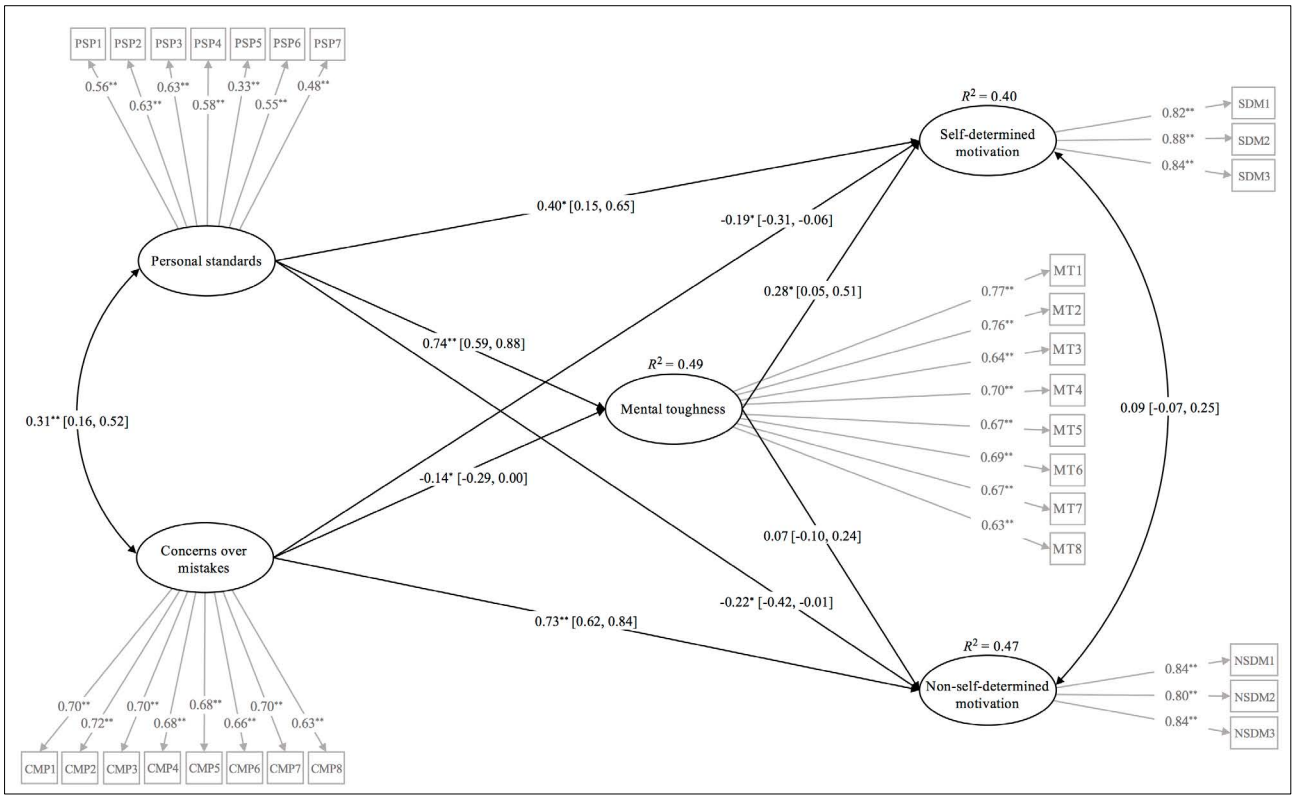
Statistical analyses

Preliminary analyses

All statistical analyses were computed in R.[39] The data set was first screened for missing values, which were replaced using an iterative random forest technique.[40] Standardised values ($\leq \pm 3.29$) and Mardia's multivariate normality test (i.e. $p>0.05$) were used to examine item-level univariate and multivariate normality, respectively.[41] Internal consistency was estimated using omega, which is liberal in its assumption of tau-equivalence.

Primary analyses

Latent structural modelling was performed using maximum likelihood estimation with robust standard errors – a preferred technique when data contain ordinal response categories.[42] Model fit was estimated using χ^2,



*p<0.05, **p<0.001

Figure 2: Final partial mediation model for relations between dimensions of perfectionism, mental toughness and self-determined motivation (standardised coefficients and 95% confidence intervals reported).

along with the robust comparative fit index (CFI), the standardised root mean square residual and the robust root mean square error of approximation. Noting criticisms levelled against the stringent application of fit index criteria[43], we used cut-off values of ≥0.90 for CFI, ≤0.10 for the standardised root mean square residual and ≤0.10 for the root mean square error of approximation[44,45]. A preliminary confirmatory factor analysis was used to determine the appropriateness of the hypothesised measurement model and associations among the latent variables were estimated using Pearson correlations. Preliminary associations among the study variables, age and sex (0=male, 1=female) revealed a single significant association between age and SDM (r=0.13, 95% CI [0.02, 0.24], p=0.016), prompting the inclusion of age as a covariate in each of the structural models. A full mediation model (see Figure 1) was tested first, which was followed by a partial mediation model. Support for the less restrictive, partial mediation model is obtained if there are substantial improvements in model fit.[46] Model comparisons were performed using the scaled difference chi-square test.[47] To establish mediating effects, model parameters were deconstructed into direct and indirect effects. Mediation is most often classified into complementary (partial) mediation (i.e. presence of both a direct and indirect effect, each in the same direction) and indirect-only (full) mediation (i.e. presence of an indirect, but not a direct effect).[48] Indirect effects were estimated using a bias-corrected bootstrapping procedure (10 000 repetitions), with statistical significance interpreted according to 95% bootstrap confidence intervals.

Results

Preliminary analyses

The quantity of missing values was negligible (0.26%) and replaced (proportion falsely classified=0.27) using random forest imputation (10 000 repetitions). The univariate (≤±3.29) and multivariate skewness ($b_{1,p}$=15.09, p=0.407) and kurtosis ($b_{2,p}$=49.43, p=0.726) estimates indicated the data were approximately normal in distribution. Internal consistency estimates were >0.70 for all study variables.

Primary analyses

The measurement model yielded an acceptable level of fit to the data (see Table 1). Standardised item-factor loadings were each statistically significant (p<0.001). Pearson correlations among the study variables are reported in Table 2. MT was positively associated with PSP, CMP and SDM, but was unrelated to NSDM.

Fit indices for the fully and partially mediated structural models are reported in Table 1. Collective evaluation of fit indices for the fully mediated model revealed a weak level of fit, whereas a reasonable level of fit was found for the partially mediated model. The scaled difference chi-square test was statistically significant (p<0.001), favouring the partially mediated model.

The standardised path coefficients for the partially mediated model are reported in Figure 2. Residual PSP was positively associated with MT (p<0.001), whereas residual CMP associated negatively with MT (p=0.047). While residual PSP (p=0.005) and MT (p=0.018) were positively associated with SDM, residual CMP was negatively associated with SDM (p=0.005). Residual PSP associated negatively (p=0.044) and residual CMP positively (p<0.001) with NSDM, although MT was unrelated to NSDM (p=0.427). There was an indirect effect linking residual PSP with SDM (standardised indirect effect: 95% CI=0.19, 0.46), but not NSDM (standardised indirect effect: 95% CI=-0.08, 0.21), via MT. Residual CMP was not associated with SDM (standardised indirect effect: 95% CI=-0.09, 0.01) or NSDM (standardised indirect effect: 95% CI=-0.06, 0.02) via MT.

Table 1: Measurement and structural model fit indices

	Overall fit indices				Comparative fit index
	χ^2 (df)	CFI	RMSEA [90% CI]	SRMR	$\Delta\chi^2$ (df)[c]
1. Measurement model	602.26* (367)	0.928	0.045 [0.039, 0.051]	0.067	-
2. Full mediation[a]	783.51* (397)	0.881	0.055 [0.050, 0.061]	0.107	-
3. Partial mediation[ab]	654.85* (393)	0.919	0.046 [0.040, 0.051]	0.066	150.18* (4)

CFI, comparative fit index; RMSEA, root mean square error of approximation; SRMR, standardised root mean square residual.

*p<0.001

[a]*Models controlled for age.*

[b]*Direct paths added from (1) personal standards perfectionism to self- and non-self-determined motivation and (2) from concerns over mistakes perfectionism to self- and non-self-determined motivation.*

[c]*Scaled difference chi-square test.*[47]

Table 2: Descriptive statistics and bivariate associations among study variables

Variable	(1)	(2)	(3)	(4)	(5)
(1) Personal standards perfectionism	0.73				
(2) Concerns over mistakes perfectionism	0.34** [0.24, 0.43]	0.87			
(3) Mental toughness	0.56** [0.48, 0.63]	0.11* [0.00, 0.22]	0.88		
(4) Self-determined motivation	0.41** [0.32, 0.50]	-0.02 [-0.12, 0.10]	0.48** [0.39, 0.56]	0.88	
(5) Non-self-determined motivation	0.11 [-0.00, 0.21]	0.58** [0.50, 0.65]	0.01 [-0.10, 0.12]	-0.02 [-0.13, 0.09]	0.87
M (SD)	24.29 (4.57)	26.45 (6.60)	39.70 (8.60)	30.24 (7.38)	25.32 (7.73)

Note: 95% confidence intervals presented in brackets; diagonal contains internal consistency estimate.
*p<0.05, **p<0.001

Discussion

In this study, an integrative modelling approach was used to examine associations between perfectionism, MT and motivational orientations. The findings from the multivariate structural modelling analysis indicated that PSP and CMP each have unique relations with MT and motivational orientations. Residual PSP was positively associated, whereas residual CMP was negatively associated, with MT. Residual PSP and MT were both positively associated with SDM, while residual CMP was negatively related to SDM. Support was obtained for a partial mediation effect of MT, as an indirect effect was found linking residual PSP with SDM via MT. Conversely, residual PSP was negatively associated with NSDM, while residual CMP was positively related to NSDM. MT was unrelated to NSDM. Taken together, the findings offered mixed support for the hypotheses.

There are several noteworthy implications based on the findings of this study. The residualised and unresidualised associations between dimensions of perfectionism, MT and motivational orientations are consistent with concerns that have been raised over the effects of partialling on the conclusions that are drawn about perfectionism.[7] For example, compared to the unpartialled effects, when the common variance between PSP and CMP was statistically controlled, the positive association between PSP and MT was strengthened and the association between CMP and MT inverted from positive to negative. Although these findings appear contradictory, when evaluated alongside each other they offer complementary information about the features that are unique and shared among PSP and CMP. That is, if one compares two players, the one with higher CMP and PSP will, on average, report higher MT. However, if one compares two players who have the same PSP scores, the one with higher CMP will, on average, report lower MT.[2] Our findings are also consistent with previous research in that residual PSP yielded more adaptive, while residual CMP obtained more maladaptive, associations with MT, SDM and NSDM than did the unpartialled variables of each perfectionism dimension.[8] Although researchers have yet to agree on the common features that are shared among the general dimensions of PS and PC,[2,7] the present findings are important because they further demonstrate the distinctiveness and overlap between components of perfectionism.

The direction of associations among residual PSP, residual CMP and MT were largely consistent with existing literature on MT in sport. Specifically, MT has often been associated with setting exceedingly challenging performance expectations and maintaining commitment towards reaching such standards.[28,30] These descriptions represent efforts mentally tough athletes direct towards achieving subjective markers of performance and outperforming competitors, which align closely with characterisations of perfectionistic strivings. There is also a self-to-other comparative component to PSP, as athletes who strive for perfection tend to believe they have higher performance standards and achievement goals than their competitors.[36] Likewise, mentally tough athletes are highly competitive, thrive on competitive situations and believe in their ability to outperform their competitors.[28] However, there are potential negative consequences linked to the relentless pursuit of exceedingly high personal standards, particularly when there are barriers impeding the attainment of the performance targets set. Past research has associated MT with overtraining and a willingness to train despite injury or the prospect of incurring a more severe injury,[29] suggesting that an unremitting persistence to achieve could lead to adverse physical or psychological consequences.

The association with residual CMP conforms with the tendency for athletes with higher mental toughness to experience less anxiety about committing errors and negative other-evaluations linked to making mistakes.[30] The positive bivariate relation between CMP and MT, however, may signify the heightened levels of introspection in which mentally tough athletes engage,[49] which may be accompanied by self-criticism when mistakes or underperformance occurs. Although mentally tough athletes may not be impervious to critical self-evaluation, they do appear adept at recovering and sustaining goal-directed efforts by rebounding quickly from mistakes and not dwelling on errors when they occur.[33] This characterisation is likely facilitated by the repertoire of skills (e.g. learned resourcefulness, coping strategies) that enable mentally tough athletes to successfully avoid or minimise the effects of debilitative cognitive-emotional experiences on performance.[50]

Residual PSP associated positively with SDM and negatively with NSDM. In contrast, residual CMP associated negatively with SDM and positively with NSDM. These findings align with those of several studies that have reported more adaptive relations between features of PS (and more maladaptive relations between features of PC) and autonomous forms of motivation.[15,51] While residual PSP has a favourable effect on athletes' self-determined motives, residual CMP is accompanied by less desirable, non-self-determined motives. There was also evidence of an indirect effect linking residual PSP with SDM via MT, providing preliminary support for the partial mediating mechanism of MT. This finding highlights the influence of both residual PSP and MT on the self-determined motivational orientations of athletes. An indication of the unique roles of each construct is captured in the features that distinguish MT from PSP. In particular, a central function of MT is psychological buoyancy[23] – a general term used to describe the ability of mentally tough athletes to remain unaffected by disappointments, respond more adaptively (i.e. cope better) to stress (e.g. underperformance) and bounce back (e.g. regain focus) from setbacks.[28,29,33] Whereas PSP seems fundamental to initiating autonomous forms of motivation that are linked to subjective performance standards, MT may play a more pertinent role in maintaining SDM when athletes face obstacles that impede their ability to achieve the perfectionistic standards which they set.

The findings of this study indicate that MT is unrelated to NSDM, although prior research in this area has been mixed. Some studies have reported positive associations between MT and external regulation[52], whereas others have reported a negligible relationship between the two constructs[35]. Given recent evidence suggesting that expressions of MT may differ across situations,[53] there may be periodic changes in athletes' MT that could affect their motivational orientations. There are also a number of instances in which elite athletes recognised for their MT have experienced phases of disinterest, dejection and a lack of desire to participate in their respective sports.[54] Thus, MT may involve being able to consistently prioritise more (over less) autonomous forms of motivation, as well as the capacity to recover more autonomous forms of motivation.

Practical implications, limitations and future research directions

Based on the findings of this study, we speculate that PSP may be involved in initiating, whereas MT may be central to maintaining, SDM. Efforts directed towards enhancing MT, which have been successful in the past, may have fruitful benefits for maintaining athletes' SDM. In one study, Bell et al.[17] reported improvements in MT following an intervention that coupled progressive exposure to pressurised performance situations with a supportive and encouraging sporting environment. Thus, MT development stemmed from improvements in athletes' capacity to withstand adversity. By creating training environments that mirror high-pressure competitive performance contexts and providing athletes with the necessary psychological skills to deal with such demands, developments in certain aspects of athletes' MT (e.g. self-efficacy) may increase the likelihood that sustained SDM will be exhibited when performance-related challenges (e.g. errors) occur. Such an approach to MT development might be supplemented by cultivating autonomy-supportive environments[31] that encourage athletes to establish sport performance standards that closely align achievement with fulfilment of their athletic potential. Similarly, coaches and practitioners ought to emphasise self-comparative (as opposed to other-comparative) appraisal processes when assisting athletes with setting performance expectations and evaluating performance outcomes,[55] creating sporting climates that focus on demonstrating self-referenced competencies and maximising one's athletic potential.

The present findings should be considered alongside relevant methodological limitations. Firstly, the sample consisted of competitive athletes participating in tennis – an individual, non-contact sport. Consequently, caution should be applied when generalising the findings to other subpopulations of athletes. Secondly, we used a cross-sectional design, and assumptions about causality would need to be clarified

through the use of experimental types of design. Thirdly, selected findings may be indicative of contextual or temporal changes in selected constructs (e.g. MT) that were not directly measured in this study. To explore this further, researchers might consider longitudinal designs with multiple measurement points. Fourthly, all variables were measured using self-report ratings provided by the athletes, which may have resulted in self-report bias and socially desirable responding. Future research could employ a multi-pronged measurement approach, such as the use of other-informant ratings or observations.

Conclusion

This study provides insight into the associations between unique dimensions of perfectionism, MT and motivational orientations in competitive athletes. Residual PSP yielded more adaptive relations with MT and motivational orientations compared with residual CMP. The findings offer preliminary support for MT as a mechanism underlying the link between residual PSP and SDM. As evidence accumulates in support of the developmental aptitude of MT, targeted MT training programmes might provide a useful avenue for maintaining self-determined forms of motivation among athletes with exceptionally high personal performance standards, particularly when there are barriers (e.g. underperformance) to achieving such standards.

Authors' contributions

All authors developed the study concept and contributed to the study design; R.G.C. coordinated data collection, performed the data analyses and drafted the manuscript; L.C., P.C.J. and T.R.D. provided critical revisions to the manuscript. All authors approved the final version of the manuscript for publication.

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Observations from SANSA's geomagnetic network during the Saint Patrick's Day storm of 17–18 March 2015

Geomagnetic storms are space weather events that result in a temporary disturbance of the earth's magnetosphere caused by a solar wind that interacts with the earth's magnetic field. We examined more closely how some southern African magnetic observatories responded to the Saint Patrick's Day storm using local K-indices. We show how this network of observatories may be utilised to model induced electric field, which is useful for the monitoring of geomagnetically induced anomalous currents capable of damaging power distribution infrastructure. We show an example of the correlation between a modelled induced electric field and measured geomagnetically induced currents in southern Africa. The data show that there are differences between global and local indices, which vary with the phases of the storm. We show the latitude dependence of geomagnetic activity and demonstrate that the direction of the variation is different for the X and Y components.

Significance:

- The importance of ground-based data in space weather studies is demonstrated.
- We show how SANSA's geomagnetic network may be utilised to model induced electric field, which is useful for the monitoring of geomagnetically induced anomalous currents capable of damaging power distribution infrastructure.

Introduction

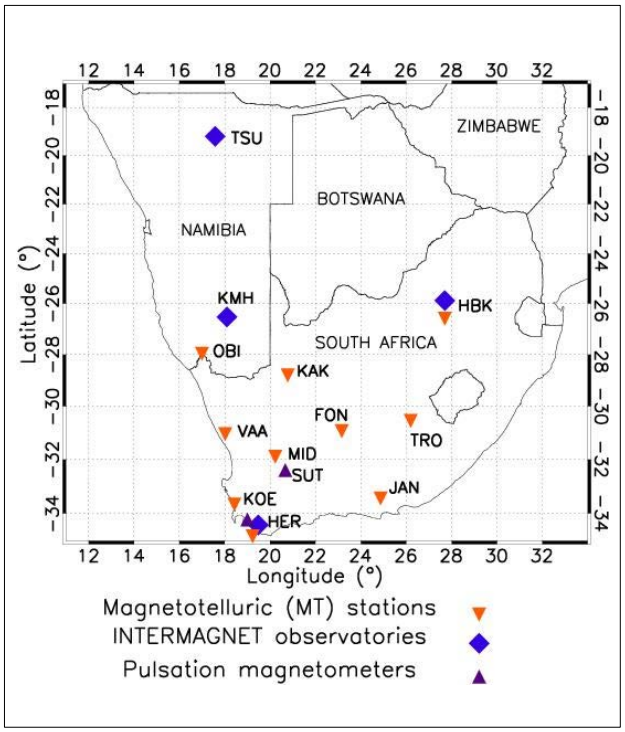
Geomagnetic storms can affect communication satellites, interrupt radio communication by changing the status of the ionosphere, induce low frequency electric currents in long conductors like power lines and disrupt power grids. During a magnetic storm, magnetospheric currents are diverted through the earth's ionosphere causing large disturbances in the geomagnetic field observed on the ground. These rapid fluctuations in the ground magnetic field are also the source of induced electric fields in the earth's surface.[1] Disruptions in sensitive technological systems resulting from geomagnetic-induced currents are mostly reported in higher geomagnetic latitude regions, but geomagnetically induced currents (GICs) large enough to cause transformer failures in power systems have been observed in mid and low latitudes as reported by Gaunt and Coetzee[2]. Ground magnetic observations have contributed immensely to the monitoring of the levels of geomagnetic activity and in studying the impact of geomagnetic storms on earth.[3] The widespread use of indices derived from geomagnetic observatory data indicates the importance of having ground magnetic records, and a well-managed system for disseminating the data.

The measured earth's surface magnetic field shows short time variations that are mostly linked to external currents resulting from geo-effective ejections from the solar corona. The monitoring of this field variability has led to the development of various indices to characterise the geomagnetic conditions in a fairly compact form.[4] The 3-hour range index, K, was introduced by Bartels in 1939.[5] The K-index is computed using data recorded at a particular magnetic observatory. It measures the magnetic variability at this particular station, and is thus a local index. But, it was further decided to have a planetary index of geomagnetic activity; a network of 13 subauroral magnetic observatories was selected to calculate a planetary K-index, Kp.[6] The ring current Dst index was introduced by Sugiura[7] to measure the intensity of the ring current. The Dst index is based on the hourly average variations of the horizontal field component, H, recorded at low-latitude magnetic observatories after removing the average solar quiet variation and the main magnetic field. The observed depression in the H component of the geomagnetic field during magnetic storms is caused by an enhancement in the ring current, which is constituted primarily by energetic ions that flow in the westward direction in the magnetospheric region at an altitude of 4–6 terrestrial radii during the growth of the storm main phase – the period following the sudden storm commencement (SSC) during which the symmetric component of the ring current increases and the north-directed components of the magnetic field on the surface of the earth decrease as reflected in the decrease of the Dst index or its analogue, the SYM-H index.[8]

The South African National Space Agency (SANSA) operates four INTERMAGNET (*Inter*national *R*eal-time *Mag*netic Observatory *Net*work) observatories in southern Africa: Hermanus (HER) and Hartebeesthoek (HBK) in South Africa, and Tsumeb (TSU) and Keetmanshoop (KMH) in Namibia.[9] In addition to these observatories, SANSA operates two induction coil magnetometers for magnetic pulsation data at Hermanus and Sutherland. SANSA operates 10 magnetotelluric stations. The magnetotelluric instrument, a LEMI-417 device (Lviv Center of Institute of Space Research, http://www.isr.lviv.ua/lemi417.htm), of which several are installed in this region, is composed of three magnetic channels to measure the X, Y and Z components of the magnetic field at 1-s intervals, and two electric channels to measure the horizontal components of the electric field at the same location with the same cadence. This network of magnetotelluric stations allows researchers to use measurements of natural geomagnetic and geo-electrical field variations at the earth's surface to model the subsurface electrical conductivity over southern Africa and apply the conductivity to calculate GICs in power grids. The physical locations of these magnetometers and magnetotelluric stations are given in Table 1 and Figure 1.

Table 1: The location of SANSA's geomagnetic network stations over southern Africa

Station	Station code	Geographic coordinates		Geomagnetic latitude (°)	Instruments	Sampling interval
		Latitude (°)	Longitude (°)			
Hermanus	HER	-34.425	19.225	-42.076	DMI FGE Fluxgate Magnetometer LEMI-025 Fluxgate Magnetometer Induction coil magnetometer	1 min 1 s 1 s
Hartebeesthoek	HBK	-25.883	27.707	-35.513	DMI FGE Fluxgate Magnetometer	
Tsumeb	TSU	-19.202	17.584	-30.495		1 min
Keetmanshoop	KMH	-26.541	18.110	-36.246		
Sutherland	SUT	-32.400	20.670	-40.665	LEMI-025 Fluxgate Magnetometer	1 s
					Induction coil magnetometer	1 s
Middelpos	MID	-30.150	18.517	-38.966	LEMI-417M Long-Period Magnetotelluric Magnetometer and electric field monitor	1 s
Vaalputs	VAA	-31.917	20.230	-40.300		
Trompsburg	TRO	-30.017	26.994	-38.924		
Fonteintjie	FON	-30.942	23.158	-39.617		
Jansenville	JAN	-30.081	25.011	-38.965		
Obib	OBI	-28.225	16.775	-37.521		
Kakamas	KAK	-28.760	20.640	-37.931		
Koeberg	KOE	-33.667	18.430	-41.510		
Hermanus	HER	-34.425	19.225	-42.076		
Hartebeesthoek	HBK	-25.883	27.707	-35.513		



TSU, Tsumeb; KMH, Keetmanshoop; HBK, Hartebeesthoek; OBI, Obib; KAK, Kakamas; FON, Fonteintjie; VAA, Vaalputs; TRO, Trompsburg; MID, Middelpos; SUT, Sutherland; KOE, Koeberg; JAN, Jansenville; HER, Hermanus

Figure 1: South African National Space Agency's geomagnetic observation network over southern Africa.

The largest geomagnetic storm of solar cycle 24 was the severe (G4) storm on Saint Patrick's Day on 17 March 2015.[10] The Dst index reached a minimum of -223 nT during this storm.[11] In this paper, we look at how SANSA's magnetic network responded to this magnetic storm using local K-indices and show how magnetotelluric stations can be used for the mapping of electric fields and for studying GICs in power networks in southern Africa. The magnetotelluric data from the Hermanus station as recorded on 17 March 2015 are shown in Figure 2.

K-indices

During a geomagnetic storm, temporal geomagnetic variations are the superposition of the regular daily variation, Sq, and the irregular temporal geomagnetic variations. The former is estimated and removed from the signal and the amplitude range indices are calculated based only on the latter. The K-index measures the level of magnetic disturbance and it is derived from the maximum fluctuations of horizontal components relative to the regular 'quiet-time' variation observed during a 3-hour interval. In this study, the linear-phase robust non-linear smoothing (LRNS) method was used in the processing of the magnetic disturbance.[12] To compare the local K-indices with a global geomagnetic storm index, we used the Kp-index. For comparison purposes, the Halloween storm on 29 October 2003 was considered. Local K-indices are plotted together with the global Kp-index in Figure 3a and 3b. The trend of the magnetic activity shown by all sets of indices is the same, but the difference in measured magnitude disturbance at the magnetic observatories (Figure 4a and 4b) is significant because it indicates a spatial variation which could have led to non-homogeneity in the E-field over the region during some phases of the storm. This difference can be attributed to latitude dependence of geomagnetic activity, as shown in Figure 4a and 4b for the X and Y components of the geomagnetic field respectively. The variation of the field from one station to another is particularly evident during the main phase of this magnetic storm. Note that the direction of the variation is different for the X and Y components: the magnitude of the disturbed magnetic variation in the X component decreases with latitude, while in the Y component it increases with latitude.

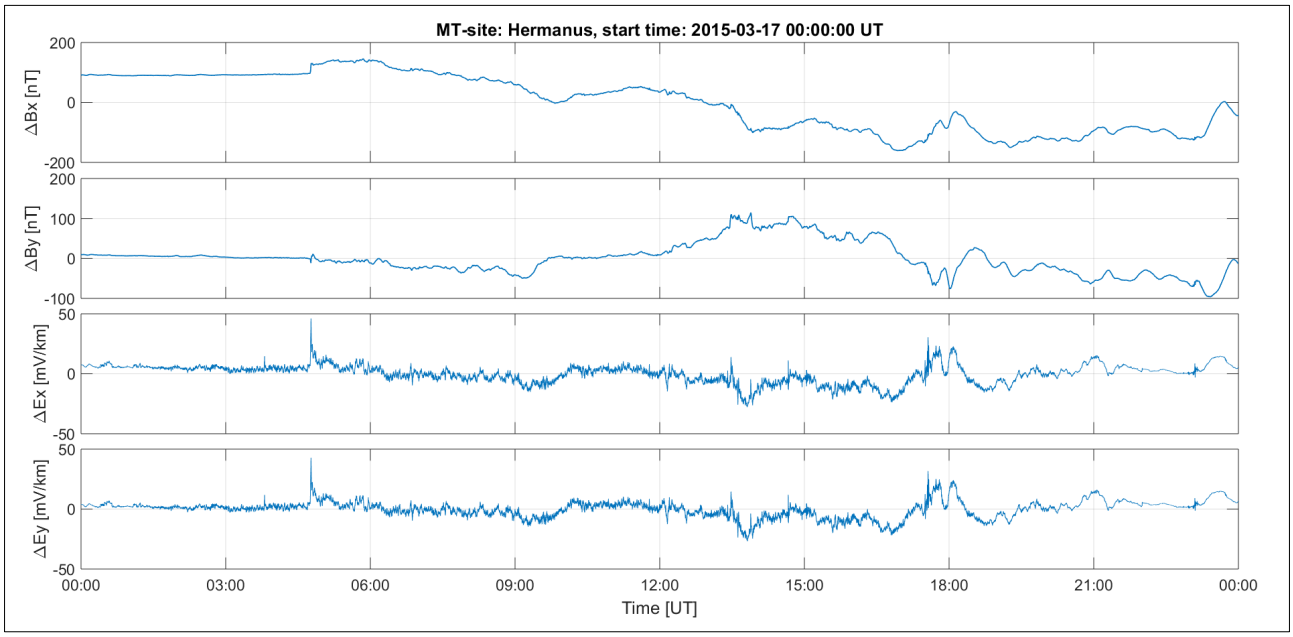


Figure 2: The geomagnetic and geoelectric field recorded by the magnetotelluric (MT) instrument at SANSA Space Science in Hermanus. The data were logged at 1-s intervals, and provide the means to verify models for E-field calculation and also to determine the local surface impedance, which is a key parameter for the estimation of geoelectric fields from magnetometer data, used in the calculation of geomagnetically induced currents.

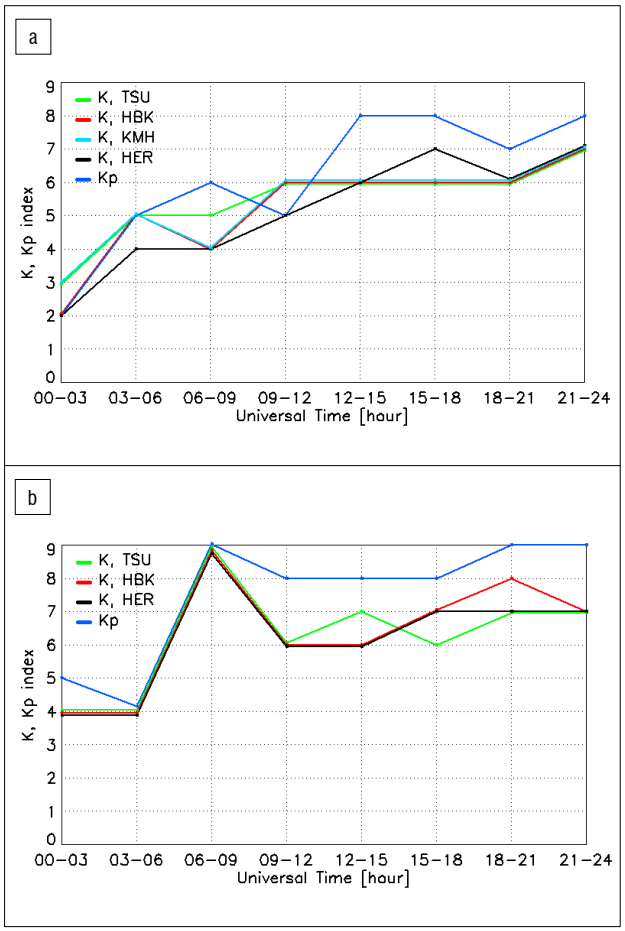


Figure 3: Comparison of geomagnetic local K-index at HER, HBK, TSU, KMH and global Kp-index for (a) Saint Patrick's Day storm on 17 March 2015 and (b) Halloween magnetic storm on 29 October 2003. KMH started operating in 2006 and is therefore not represented in (b).

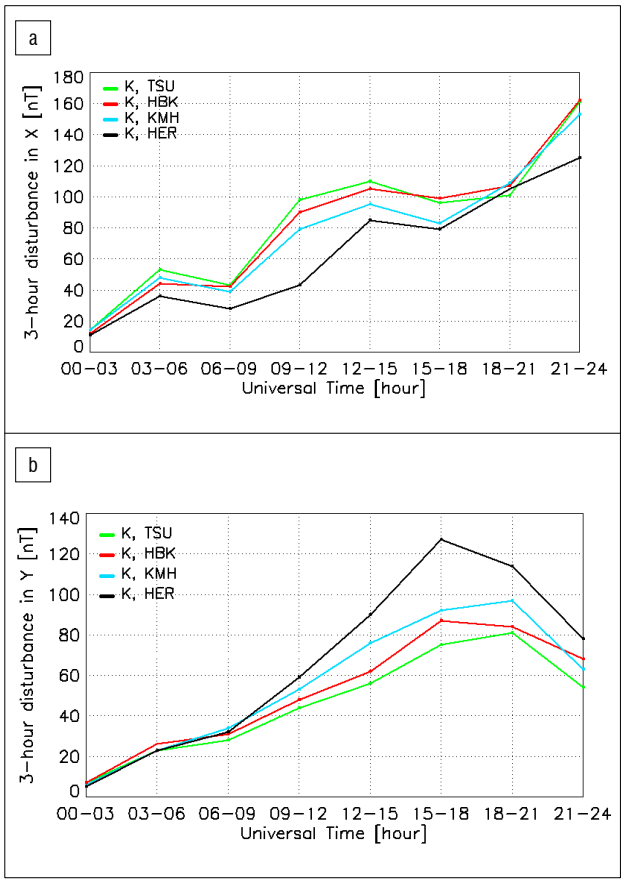


Figure 4: The comparison of 3-h disturbance magnitude values in the (a) X component and (b) Y component at HER, HBK, KMH and TSU on 17 March 2015. These disturbance values were calculated by subtracting the solar quiet-day variation (Sq) from recorded geomagnetic variations and determining the largest range of geomagnetic disturbances during a 3-h UT interval.

The enhancement in the Y-component disturbance is consistent with disturbances as a result of field-aligned currents, which typically manifest in the dusk to pre-midnight sectors at middle latitudes. The decrease/increase in X/Y disturbance with latitude (Figure 4a and 4b) is indicative of the relative contribution of the ring current related disturbance (enhancing X) diminishing at higher latitudes, and the contribution of the field-aligned current related enhancement (to the Y component) increasing with latitude.[13-15]

The availability of several observatories in the region is a significant advantage for the characterisation of the latitude dependence of the components of the geomagnetic field. The difference between local K-indices and the Kp-index, and the fact that the differences are not the same for all storms and K-values, makes it necessary to consider local K-indices in the characterisation of storm intensity. In Figure 3a, during the first 12 h of the geomagnetic storm of 17 March 2015, the local K-values are generally lower than or equal to Kp, while during the last 12 h of the storm, the local K-values are consistently lower than Kp. This same trend was also observed for the storm of 29 October 2003 shown in Figure 3b. The difference between Kp- and local K-indices was also observed at other mid-low latitudes INTERMAGNET observatories, namely Fredericksburg (FRD), Kakioka (KAK) and Cheongyang (CYG). The local K-indices are generally smaller than the global Kp-indices specifically for observed planetary geomagnetic disturbances classified as strong, severe or extreme.[16] The observation that the variation in the geomagnetic fields at HBK and KMH (on the same latitude and both not coastal) as shown in Figure 3 is about the same (at times during the storm HBK values are slightly higher than those at KMH while at other times they are slightly lower) seems to confirm that stations at the same latitude have similar variations in the geomagnetic field.

The comparison of magnetograms at the four INTERMAGNET stations – HER, HBK, TSU and KMH – during the storm of 17 March 2015 is shown in Figure 5. The following discussion of the variation of the geomagnetic field includes the storm-related increase and decrease of horizontal (B_x or north directed and B_y or east directed) and vertical (B_z or downward directed) field components during the storm. The sudden increases in the B_x and B_z components and decrease in the B_y component are observed at all observatories around 04:45 UT. Table 2 shows the increase in the B_x component from 04:45 to 04:47 UT and the highest rate of change in B_x and B_y components in this time interval. This marks a sudden storm commencement at 04:45 UT.[11] The values in Table 2 show that the highest rate of change in horizontal components during the sudden storm commencement occurred at TSU and the lowest at HER, and HER had the lowest sudden magnetic field increase in B_x and the lowest sudden decrease in the B_y component. Figure 6a and 6b show the plots of the rate of change in horizontal components, B_x and B_y, respectively. From Figure 6a it is evident that the maximum rate of change in the B_x component occurred at all four stations during the sudden storm commencement. The largest deviation from the mean over the four stations occurred in the B_z component measured at the Hermanus station, which is closest to the coast. Figure 6b shows that the maximum rate of change in the B_y component occurred in the Hermanus data and was not during the sudden storm commencement but during the main phase of the storm at about 14:00 and 18:00. The peak values in dB_x/dt (20.8 nT/min) were larger than the peak values in dB_y/dt (-11 nT/min), which seems to indicate a dominance of the ring current in causing the geomagnetic disturbance. On the other hand, the increase in the variation of the B_z component of the Hermanus observations relative to the variation of the other observatories (Figure 5), and the increase in the maximum dB_y/dt from Tsumeb to Hermanus (Figure 6b) is consistent with disturbances resulting from field-aligned currents.[13]

Table 2: The sudden magnetic field increase in B_x (ΔB_x) and decrease in B_y (ΔB_y) and its highest rate of change in both components (dB_x/dt and dB_y/dt) from 04:45 to 04:47 UT on 17 March 2015 at four magnetic observatories: HER, HBK, TSU and KMH

Station	Geographic latitude (°)	ΔBx	dBx/dt (nT/min)	Time of dBx/dt (UT, h:min)	ΔBy	dBy/dt (nT/min)	Time of dBy/dt (UT, h:min)
TSU	-19.202	42	20.8	04:46	-16	-9.6	04:45
HBK	-25.883	38	18.8	04:46	-19	-9.6	04:46
KMH	-26.541	40	20.3	04:46	-10	-11.0	04:45
HER	-34.425	30	14.7	04:46	-8	-8.0	04:45

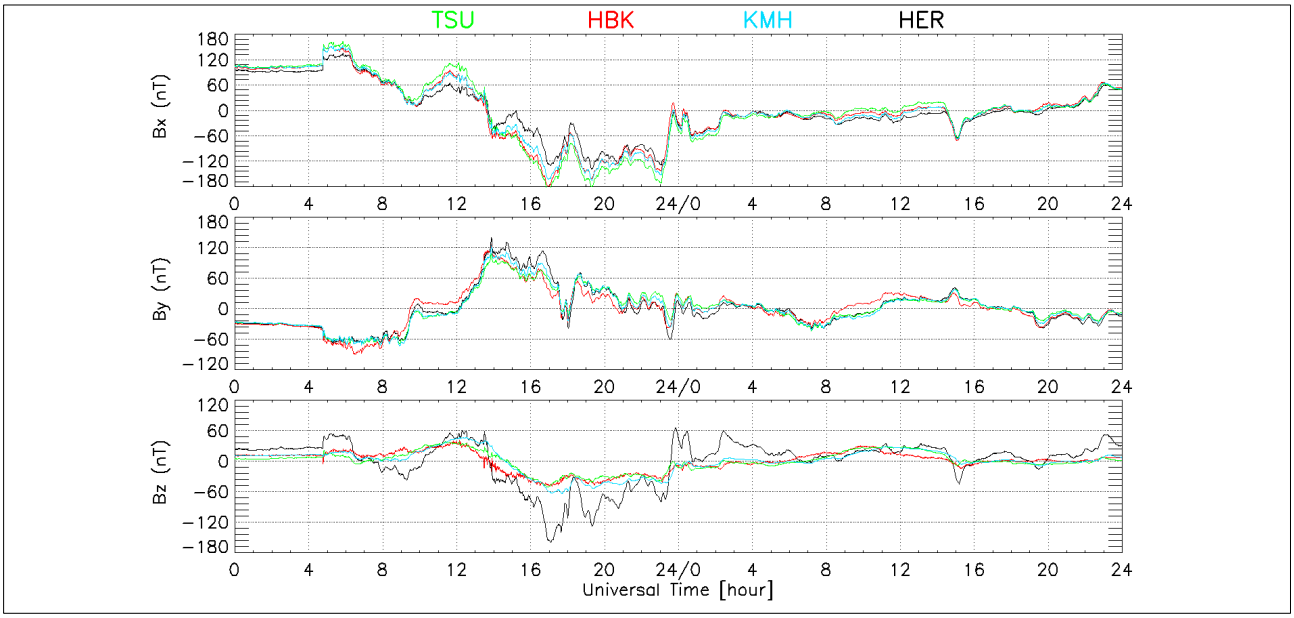


Figure 5: Plots of 1-min data magnetograms recorded during the Saint Patrick's Day storm, 17–18 March 2015, at the four INTERMAGNET observatories (HER, HBK, TSU and KMH) managed by SANSA. The mean value over the 2-day period shown was subtracted from the data at each station before plotting.

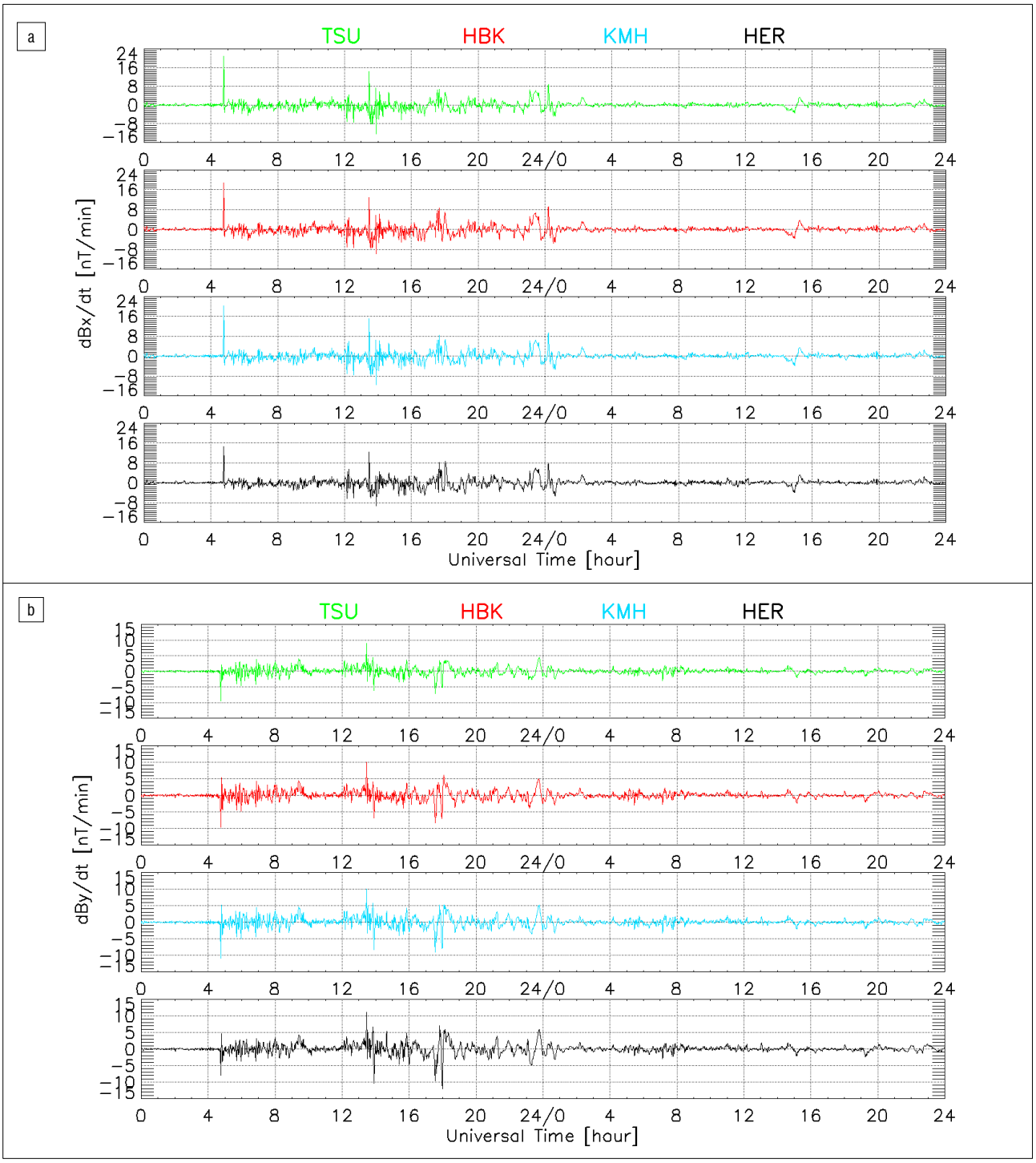


Figure 6: Plots of the rate of change in the (a) B_x component (dB_x/dt) and (b) B_y component (dB_y/dt) derived from the measured data during the Saint Patrick's Day storm, 17–18 March 2015, at each of the four INTERMAGNET observatories in southern Africa

Geomagnetically induced currents

Geomagnetically induced currents (GIC) have been recorded in the South African power distribution network since 2003. During the geomagnetic storm of 29–31 October 2003, there was a significant impact on the transformers in the network, resulting from thermal damage to power transformers.[2] The electric field, which is the primary driver of GIC in the network, has been shown to have a significant spatial variation over southern Africa during a geomagnetic storm, based on the small time differences in the data from different geomagnetic observatories in the region.[17] The electric field along every power line is derived from the interpolation of the rate of change of the horizontal components of the geomagnetic field and the surface impedance as derived from local magnetotelluric measurements.[18] For the E-field results shown in this paper, the surface impedance derived from the magnetotelluric station in Hermanus was used for calculating the E-field over the whole region of interest. The GIC at any particular grounded transformer is determined by the summation of induced currents in the lines connected to the transformer and the alignment of the power lines connected to the transformer with the electric field. Figure 7a shows the horizontal electric field over southern Africa during the peak of the SSC on 17 March 2015 when the peak electric field magnitude |E| reached 92 mV/km and

during the main phase of the storm when |E| reached 53 mV/km. Figure 7b shows the spatial distribution of the horizontal component of the E-field during a time when there was a maximum spatial variation in the direction of the E-field. Figure 7a shows that the variation in magnitude and direction of the E-field is minimal during the period when the E-field was high. On the other hand, Figure 7b shows that both the magnitude and the direction of the E-field exhibit a significant spatial variation during other times of the storm. The spatial variation shown in Figure 6b does not provide strong evidence of either a latitudinal or coastal effect. The coastal effect – namely an increase in the component of the E-field perpendicular to the coast on the landside at locations close to the land–ocean boundary – is a result of the increase in the conductivity of the earth moving from land to sea. This increase is physically a result from charge accumulation at the land–ocean boundary.[19] In Figure 7b there is evidence of both an increase of the E-field towards the ocean along the line from KMH to HER (Figure 7b, left panel) and at another time a decrease in the E-field towards the ocean along the line from KMH to HER (Figure 7b, right panel). This observation is attributed to the fact that a uniform surface impedance was used for the calculation of the E-field at all grid points, including those over the ocean, and that the phase differences in the E-field which give rise to spatial turbulence supersede the latitudinal and coastal effects.

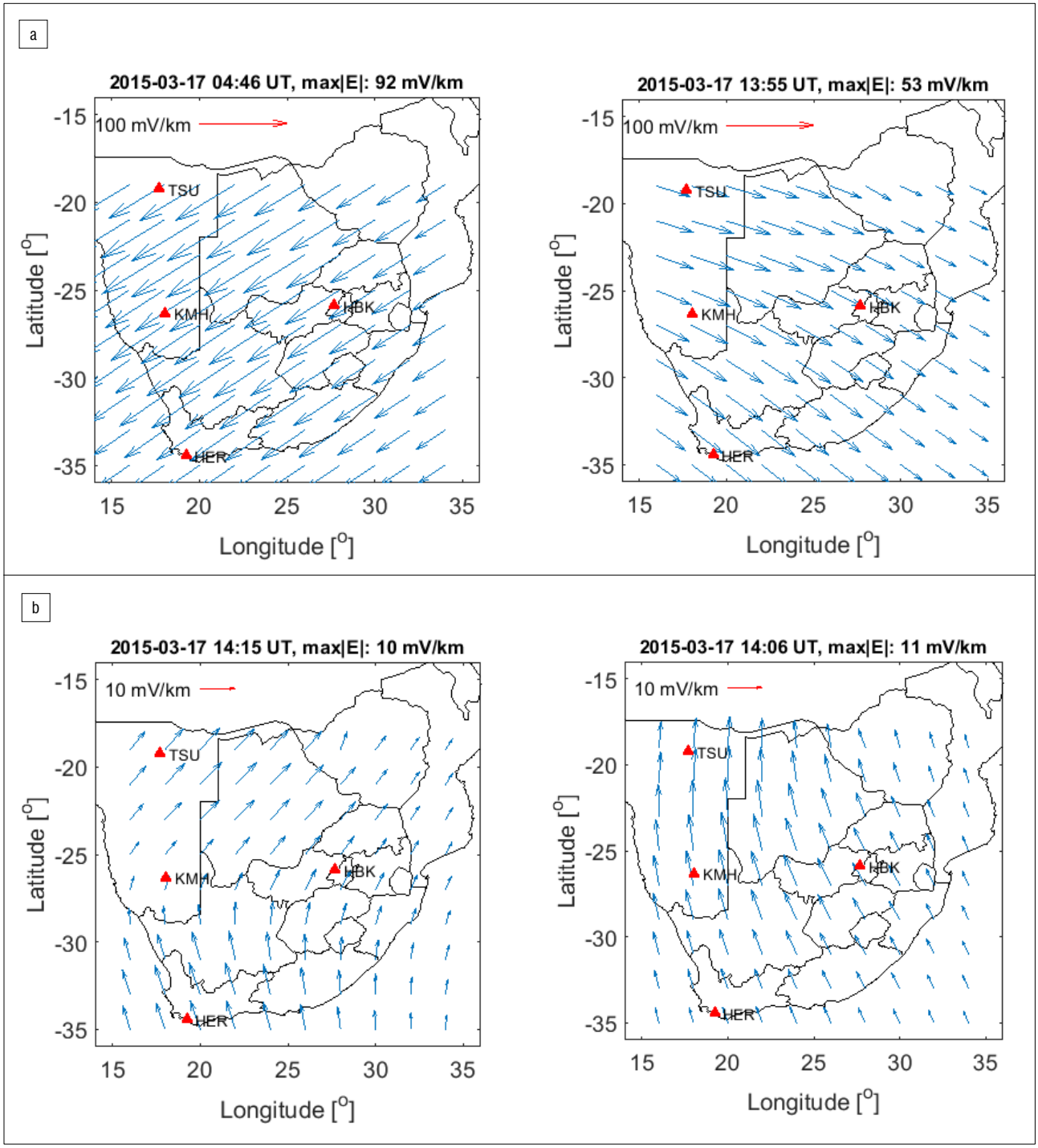


Figure 7: The calculated interpolated horizontal electric field over southern Africa on 17 March 2015 at (a, left) the time when the maximum E-field of 92 mV/km occurred (04:46 UT) and (a, right) the time during the main phase of the storm when the E-field reached 53 mV/km (13:33 UT) and (b) times when there was significant inhomogeneity in the E-field, both in direction and magnitude. The triangles show the locations of the magnetic observatories used to determine the interpolated field.

Discussions

At coastal observatories, like HER, geomagnetic variations are more intense than elsewhere along the same latitude because of the close proximity of salty seawater. This coastal effect is the strongest in the vertical Z-component of the geomagnetic field[20] while the horizontal components like X and Y behave differently. The coastal effect is clearly illustrated during the Saint Patrick's Day storm in Figure 5 where the Z component at HER showed significant differences, particularly during the main phase from 14:00 on 17 March 2015. We also noticed that the induction effect of the ocean at HER is not constant and that it varied with time as the storm developed, with the largest deviation of approximately 65 nT to be observed around 17:00 UT. Hartebeesthoek, located 1250 km to the northeast of Hermanus, does not show a measurable coastal contribution, while Tsumeb, which is about 1500 km north of Hermanus, is influenced by a small induction disturbance.

There is a further enhancement in the electric field close to the coast because of the abrupt change in the surface impedance near the coast. Modelling done by Gilbert[21] has shown that the enhancement to the component of the electric field directed perpendicular to the coast behaves as the inverse of the square root of the distance from the shoreline and this effect extends to a distance on the order of a skin depth inland.

The peak magnitude of the electric field |E| over southern Africa was estimated at 92 mV/km and occurred at 04:46 UT on 17 March 2015 during the SSC phase of the storm. Although no damage to the South African power network has so far been attributed to the impact of the Saint Patrick's Day storm, the peak magnitude of the electric field |E| over southern Africa was in the same order of magnitude as the peak E-field during other storms during which damage was caused in the power network. This peak was about 63% of the peak of 147 mV/km estimated to have occurred at the peak of the 2003 Halloween geomagnetic storm which occurred during the main phase of the storm at 06:40 UT on 29 October 2003 which had a significant impact on the South African power network.[20] The difference in the impact may be attributed not only to the peak value of the E-field, but also to the duration of large values of |E| being longer during the 2003 storm, which is more likely to have caused thermal damage. Note that the E-field was predominantly westward during the period shown in Figure 7a, but turned eastward during the main phase of the storm. During the main phase of the storm of 17 March 2015, the highest value of |E| was 53 mV/km, which occurred at 13:55 UT. Such variations in the magnitude and direction of the magnetic field can only be determined because data are available from a regular distribution of magnetic observatories as in southern Africa, as the spatial variation in both magnitude and direction of the E-field at any particular time during the storm could not be inferred properly from the observations at only a single observatory in the region. The components of the E-field that are parallel and perpendicular to the coast are affected in opposite ways. The parallel component decreases with proximity to the coast while the perpendicular component increases with proximity to the coast.[21] During the peak of the storm, the E-field has a fairly homogeneous spatial distribution over the region (Figure 7a) but during other times the E-field is turbulent (Figure 7b) and exhibits both an increase in magnitude with proximity to the coast (KMH to HER, Figure 7b, left panel), and a decrease in magnitude (KMH to HER, Figure 7b, right panel), which seems to supersede the latitudinal and coastal effects. The scale length of the variations in the E-field during the most turbulent parts of the storm, as shown in Figure 7b, is in the order of the spacing between the observatories.

Figure 8 shows GIC recorded at a generating power station in northern South Africa for 17 and 18 March 2015, with the electric field calculated at HBK according to the Grassridge ground conductivity profile. As far as we are aware, the GIC amplitude, with maximum of about 8 A, was too small to cause significant immediate damage to infrastructure. Records of degradation leading to failures of several transformers after the Halloween geomagnetic storm in 2003, and attributed to GICs, have indicated much smaller currents could initiate damage.[2] Transformer failures attributed to even lower GICs (less than 8 A in the neutral) were reported from the UK[22] with peaks in modelled E_x and E_y, corresponding to storm commencement and main phase, coinciding with peaks in recorded GIC. The GIC currents were measured in the neutral to ground connection of a Y-connected transformer. The sampling rate of the GIC measurements is not known. The only parameters recorded by the power utility are the maximum, minimum and mean values over every 5-min interval. In Figure 8, the minima that have been measured at about 06:30 and 22:00 UTC which are not correlated to peaks in the E-field, could indeed be spikes that are unrelated to the real disturbance. The correlation coefficients of the average GIC with the 5-min averages of E_x and E_y components are -0.6595 and 0.41266, respectively.

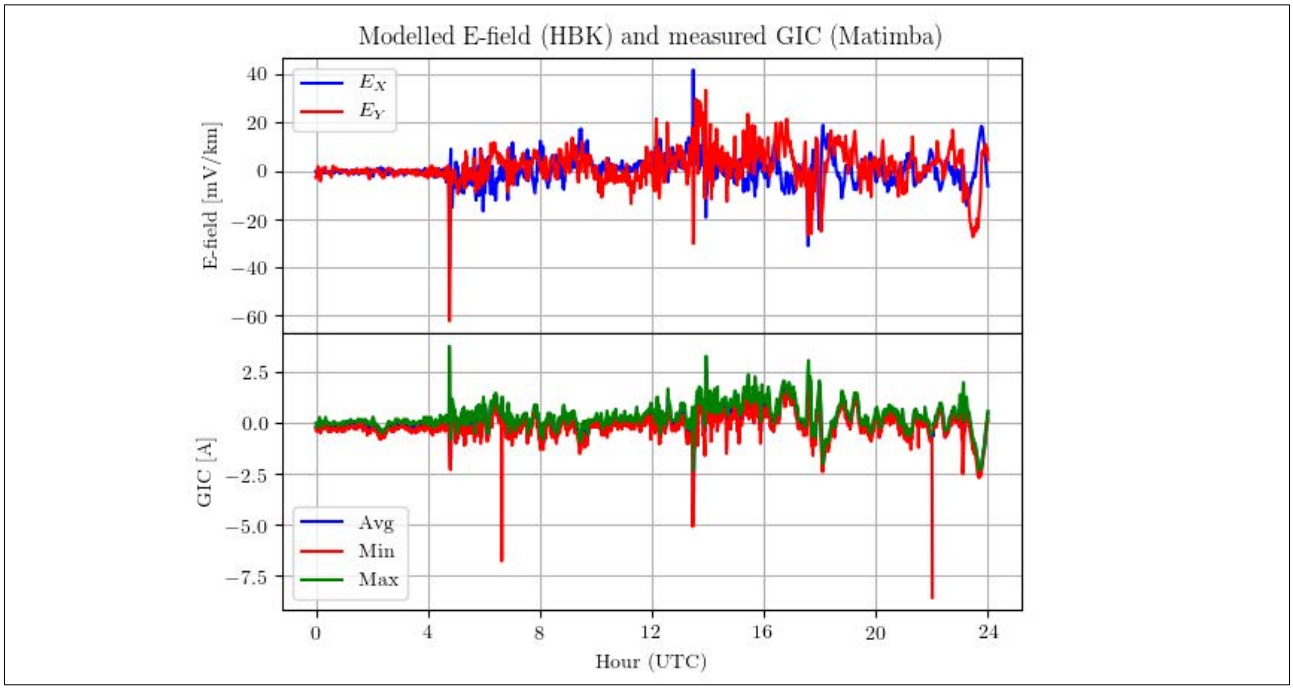


Figure 8: Modelled E-field (HBK) and measured geomagnetically induced current (GIC) (Matimba). E_x and E_y are the X and Y components of the electric field, respectively. The geographic coordinates of the Matimba Power Station are 23.67°S, 27.62°E.

Conclusion

The geomagnetic observation network of SANSA in southern Africa plays a crucial role in the proper identification and characterisation of the spatial distribution of disturbance effects resulting from geomagnetic storms. We have shown data for several locations throughout the storm, which reveal the spatial distribution over the region of the storm-related geomagnetic variations. The inhomogeneity at significantly lower values of the calculated E-field during the main phase of the storm resulting from the variation in the geomagnetic field over the region has been demonstrated. The data show that there are differences between global and local indices, which vary with the phases of the storm. The increase in the dB/dt as a result of the coastal effect has been demonstrated. The contributions made by ocean induction on observatory data located near the coast, particularly during magnetic disturbances, can be further investigated using high-precision magnetic satellite data like Ørsted, CHAMP and SWARM. The impacts of the coastal effects on the electric field during geomagnetic disturbances can be further investigated by using measured GIC data from coastal power stations such as the Koeberg Nuclear Power Station on the coast near Cape Town.

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Authors' contributions

E.N.: Writing the first draft of the manuscript, analysing data, participating in the manuscript revision and putting together the contributions from other authors. P.B.K.: Revision of the manuscript for its improvement. P.J.C.: Supporting the writing of the first draft, analysing data and participating in the manuscript revision for its improvement. S.L.: Analysing data and revision of the manuscript for its improvement.

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The influence of science reading comprehension on South African township learners' learning of science

The majority of South African township learners have poor reading comprehension skills, which is known to impact negatively on their understanding of content subjects such as science, although the extent of the impact is not fully understood. We explored this impact, as well as the extent to which reading comprehension accounted for the differential effectiveness observed for out-of-class, text-dependent science intervention programmes. Eye movement and mouse-click data were collected from 65 Grade-8 and Grade-9 township learners as they read texts and answered electronic quizzes about electric circuits and lightning on a computer fitted with eye-tracking hardware and software. These data were used to describe the learners' reading and question-answering patterns and derive a composite English for science and technology (EST) reading comprehension index for each learner. Correlations were sought between this index and the learners' Natural Sciences marks and the benefit gained from two previous out-of-school science intervention programmes. Most learners were able to engage meaningfully with a less text-rich, moderately familiar quiz, but there was a prevalence of reading avoidance, guessing and reliance on superficial text features to answer questions for a more text-rich, unfamiliar quiz. Moderate to strong correlations were found between the EST index and both Natural Sciences and intervention marks. The findings suggest that while a significant number of higher achieving township learners possess sufficient levels of EST reading comprehension skills to benefit from text-based interventions, the majority require help in developing EST reading comprehension skills to enhance the likelihood of the intervention's success.

Significance:

- From this study, we infer that a small group of South African township learners, identifiable by their relatively high Natural Sciences marks, are able to read English science texts with sufficient comprehension to be able to benefit from text-dependent interventions, including engagement with self-study interactive software. The majority, however, read such texts at the frustration level, making it unlikely for interventions to be effective if they rely on the learner being able to engage in independent reading.

Introduction

The approximately 80% of South African learners who attend the poorer Quintile 1–4 schools, mostly situated in rural and township areas, rank at or near the bottom in international tests of reading comprehension[1], as well as of science knowledge[2]. Promotion of general and subject-specific reading comprehension may well be the key to improving performance in science, because reading with comprehension develops generic cognitive abilities[3] and empowers a learner to continue learning from texts beyond periods of class instruction. Minimal possession of such skills, by the majority of South African learners from communities with lower socio-economic status, contributes to the gap that widens over time between lower and higher academic achievers[4,5], as skill breeds further skill, whereas weaker learners' learning trajectories may flatten to the point that they attend school without learning[6]. Further, low teacher content knowledge, large class sizes, low expectations and poor time management in the schools attended by these learners, trap them in their poverty.[7] Much money has been spent on intervention programmes aimed at reversing this situation, with little large-scale success[8], although small pockets of progress are evident.

Problem statement

The first author has been involved in such intervention programmes for the past 5 years, particularly working towards improving the learning of the natural sciences by Grade 8 and 9 township learners. The differential effectiveness of the intervention programmes she has researched during this time (see for example Stott[9]) have led to the formulation of the hypothesis explored in this article, namely that learners' ability to read basic English science texts with comprehension determines the extent to which learners benefit from intervention programmes.

The ability to read basic science texts with comprehension could be seen as a basic form of English for science and technology (EST) comprehension. This ability is dependent on general reading comprehension of the language of learning and teaching (LoLT), English in this case, as well as on the learners' understanding of the technical language of science, which includes prior knowledge of concepts relevant to the text and the ability to engage with a denser and more abstract writing style than is used in conversational language or in genres of text such as fiction.[10] Although the category of EST is broad, including the language used in science texts beyond school engagement such as theses and academic articles, in this article the term EST is used to refer to the kind of English used in age-appropriate and second-language-appropriate texts intended to help South African learners engage with science and technology learning. Here the term includes the kind of language found in South African science textbooks aimed at these learners and approved by the Department of Basic Education.

The ability to read such texts with comprehension makes it possible for learners to extend learning time by engaging in activities such as reading texts at home, successfully completing homework, writing and reviewing notes and engaging with related software for which technical requirements are present. Effective engagement in such practices is known to enhance learning.[11] Provision of timely and appropriate feedback is also known to enhance learning.[12] The ability to read with comprehension in a particular language means that written feedback

given, for example by a teacher or software, in that language, can result in learning occurring, extending the possibilities of provision of beneficial timely, efficient and personalised feedback. However, the extent to which this feedback is feasible in the South African township school context needs to be established because it appears that many of these learners have such low LoLT skills that they instead need skilful and time-consuming face-to-face guidance by a teacher who mediates dialogue in the vernacular and the LoLT as they help the learner bridge language and conceptual gaps.[13]

The intervention described in Stott[9] provided learners with the opportunity to engage with appropriate software to extend teaching and learning time, and to provide immediate, individualised feedback, beyond that given in the face-to-face sessions. The software used included low-language-demand quizzes as described and argued for in Stott[14]. Although this intervention model appears to be both time and personnel efficient, the observed differential effectiveness demands a greater understanding of this situation to ensure appropriate allocation of intervention funds in the future. Therefore, we sought to explore the extent to which EST reading comprehension skills may affect science achievement and explain the differential effectiveness of science interventions in the township context, as was observed in these previous studies (e.g. Stott[9]).

Although it is known that the likelihood of South African township learners passing mathematics can be predicted on the basis of their reading comprehension scores[3], we do not know how strongly these learners' science marks correlate with reading comprehension scores. Further, although it is known that English second language learners in South African townships grow up and are educated in text-poor environments[1,15] where reading for pleasure is almost non-existent[16], that they have poor EST reading comprehension levels, and that they employ superficial textual strategies[17], our understanding of what these learners do as they engage with science texts is limited.

A highly effective way to observe learners' engagement with science texts is through the use of eye-tracking equipment, a research methodology as yet underutilised in the South African township context. We made use of such equipment as we sought to answer the research questions: (1) How do South African township learners engage with the reading required to answer gap-fill and multiple-choice electronic science quizzes? (2) To what extent are South African township learners' Natural Sciences marks related to their EST reading comprehension? (3) To what extent is the benefit that relatively high-performing South African township learners gain from after-school science intervention programmes related to their EST reading comprehension?

Conceptual and theoretical framework

According to Gough and Tunmer[18], reading comprehension (R) is the product of decoding (D) and language comprehension (C): R = D x C. Decoding refers to the ability to recognise written words and language comprehension refers to understanding the language. Language comprehension involves the formation of three levels of representation of understanding: surface, situation and global representation and models.[19] The reader forms a surface representation by understanding the words of a sentence and how they relate to one another. A situation model is formed by integrating successive sentences and a global model through incorporating background knowledge. Formation of situation and global models requires use of inference, knowledge of text structure, employment of comprehension monitoring and considerable working memory usage.[20]

Becoming a skilled reader takes many years of practice, with development initially requiring a focus on decoding, and later on language comprehension.[18] Some people are able to develop the skills of integration, inference and comprehension monitoring needed for developing language comprehension on their own as they practise reading and as their levels of background knowledge, understanding of text structure and metacognitive skills grow with exposure and maturation.[19] Others, termed poor comprehenders[19] or hyperlexic readers[18], tend to 'bark at print'[21-23], i.e. decode without comprehension. Unless these learners receive explicit help in developing comprehension skills[24,25], they will continue to read at the frustration level[26] and will therefore probably employ reading avoidance behaviour, stunting their academic development and reducing the chance of benefitting from intervention programmes[4].

Lesiak and Bradley-Johnson[26] define reading at the frustration level as having less than 90% decoding accuracy and 60% or lower language comprehension. They identify two reading levels above frustration level: instructional (95% decoding accuracy and 75% comprehension) and independent (98% decoding accuracy and 95% comprehension). Learners reading at the independent level are able to direct their own learning through reading, whereas the likelihood of those at the instructional level doing so would be enhanced if they received reading comprehension instruction.

Interventions, such as the one described in Stott[9], which include a component of software engagement, can be undermined by learners' attempts to make progress through the software without engaging in the intended cognitive activity – so-called 'gaming the system'[27]. Howland et al.[28] provide three distinguishing criteria for software usage to promote meaningful learning: it should be used actively, intentionally and constructively. A learner who attempts to game the system may appear active even though their use of the software is random or superficially strategic, rather than involving intentional sense-making central to constructive learning. Eye-tracking equipment has the potential to aid a researcher in making judgements about the difference between activity with or without intentionality.[29] Although this method has even successfully been done using complex models which infer cognitive processing[30], in this research simple observation of gaze direction was considered sufficient because it revealed a prevalence of blatant attempts to game the system, as is discussed below.

Methods

The study was conducted within a pragmatic paradigm using the frameworks for integrated methodology (FraIM).[31] The FraIM is an appropriate methodology for this research because it is flexible and responsive, which was particularly relevant to the iterative process of inductive and deductive analyses engaged in to answer the first two research questions. Although eye-tracking hardware and software has been used to guide inferences about cognitive processing in a number of international studies[29], it has never been used to aid the description of English second language learners' engagement with electronic quizzes and derivation of an EST reading comprehension. Therefore a pioneering approach was required, for which the FraIM's pragmatic guidelines are well suited. Within this paradigm, validity is addressed through the concept of warrantable research, which is based on Toulmin's[32] argument framework. Warrantable research is internally consistent so that claims can be made transparently and critically in response to the research questions.

The sample

The sample consisted of 65 Grade 8 and 9 learners who attended two schools in Botshabelo, a township approximately 50 km from Bloemfontein, at the time of data collection. The first author had been working as a mentor to the science teachers in these schools for the previous 3 years and was therefore aware of the science material to which the learners had been exposed. A subset ($n=50$) of these learners was chosen for inclusion in this research because these learners had participated in either or both interventions reported on in Stott[9] during the previous year, and/or a yet-unpublished mechanics intervention 6 months before the collection of these data. This subsample was used to answer the third research question. These learners had been included in these interventions because they had been identified by their teachers as the highest achieving learners in their grade, although in reality their Natural Sciences marks ranged widely, from under 20% to 90%. The remainder of the learners ($n=15$) were conveniently chosen to be included in this research to increase the range of the sample used to answer the other research questions. These learners were those available at the time testing was done. Inclusion in this research was voluntary and accompanied by written assent and consent from the learners and

their parents, respectively. Identities are protected through anonymous reporting. Ethical clearance for conducting this research was obtained from the University of the Free State (UFS-HSD2016/1391).

Data collection

An eye tracker is a piece of hardware with specialised software which allows eye movements to be captured while a participant looks at a stimulus. For this study, a Tobii TX300 eye-tracker was used to capture data and Tobii Studio 3.4.5 was used for data extraction and analysis. A screen-capture video, which included the learner's eye movements and mouse clicks, was made and a gaze plot was generated for each learner's individual engagement with the tasks described in the next section. A gaze plot shows the gaze of a participant overlaid on the stimulus. Each dot represents a fixation and the size indicates the duration of the fixation. A fixation is a period of time during which the eye is held relatively still in order to look at an object of interest.[33] These videos and gaze plots were analysed to derive a detailed description of each learner's engagement behaviour as well as three reading comprehension sub-scores (for three different task formats) which were combined to form an EST reading comprehension index.

Each learner's Natural Sciences mark for the year was obtained from the school's database. This mark is composed of scores obtained for tests and examinations set by the Department of Education, together with practical work and projects assigned by the teacher, with weightings stipulated by the South African Natural Sciences Curriculum and Policy Statement document.[34] These data were used to answer the second research question.

To answer the third research question, the post-test scores (for the interventions referred to previously) of the 50 learners who had participated in the interventions, as well as the normalised gain from pre- to post-tests for these interventions, were used as indicators of the benefit the learners gained from after-school science intervention programmes. Normalised gain corrects for the distortion caused by the greater opportunity to improve associated with a low pre-test score. Normalised gain is calculated as:

$$\frac{post - pre\ test\ score}{pre\ test\ score - total\ score\ possible}$$

Eye-tracking tasks

The eye-tracking tasks are summarised in Table 1. Each of the authors completed a checklist while watching the video of each learner's eye movements and answer choices and examining the learner's gaze plots per screen. The three reading comprehension sub-scores were derived by applying these checklist data and the scores yielded by the software to rubrics, designed for this research, informed by the conceptual framework and explained below. The average of these three reading comprehension sub-scores was taken as the learner's EST reading comprehension index, and was used to indicate the independent variable for Questions 2 and 3.

Figure 1 shows Screen 2, a modified form of a gap-fill quiz which all the learners had had access to earlier in the year, at least in printed form. Each of the drop-down lists provides only two options: more or less. More grammatically correct variations such as most, least, fewer and fewest were waived in favour of greater simplicity and familiarity for the learners. Modifications were made relative to the original quiz which the learners had had access to so as to determine whether superficial recall played any role in the learners' answers. Modification included amending the final statement in a manner which resulted in a less natural wording. The original statement read 'This is because more resistors in parallel are like a thicker pipe which makes current flow more easily', while the modified statement read: 'This is because fewer resistors in parallel are like a thinner pipe which makes current flow less easily.'

Screen 3 consisted of a text about lightning, as well as an accompanying picture illustrating the charge separation within a cloud and resulting polarisation on the ground before lightning strikes. Each learner was instructed to read the text silently and then progress to the next screen. This text was modified from a prescribed Grade 10 Physical Sciences textbook. We can say with confidence that the learners had not seen this particular text before, as the schools these learners attended did not offer Grade 10 and the access these learners have to any books is very limited. The text was modified by shortening and simplifying sentences and analysed using the Flesch–Kincaid measurement, originally developed in 1948[35] and still widely used as a measurement to ascertain reading difficulty (cf Janan and Wray[36]). This approach enabled us to diagnose the text as being on a Grade 9 reading level. Because the youngest learners in the sample had just completed Grade 8, this was considered a reasonable level of difficulty. This use of both qualitative justifications, namely the context from which the text was taken and a description of how the text was modified, and a quantitative measurement of readability, is consistent with the view that although quantitative measurements are valuable for their ease of use, they do suffer from a variety of limitations.[36]

Screen 4 showed the previous screen's text and illustration on the left half of the screen for reference purposes, and four multiple-choice questions on the right half of the screen, each with four options. These multiple-choice questions were designed with at least one choice that had a superficial link between the question and the text. For example, for the question 'Why do you know that conditions are right for lightning if you feel your hair standing up in a storm?', one of the distractors is 'This

Table 1: The eye-tracking tasks

Screen number	Topic	Familiarity	Task	Purpose	Constructed measure
1	Electric components	Identical to a task done in the year	Match pictures with words	Set learners at ease and verify machine calibration	None
2	Adding resistors in parallel	Similar to a task done in the year	Fill seven gaps by choosing either *more* or *less* from drop-down lists	Observe learners' quiz engagement and reading comprehension of fairly familiar text	Reading comprehension sub-score 1
3	Lightning	Unfamiliar to all learners	Read text	Describe eye movements during reading	Descriptions and gaze plots of eye movements during reading
4	Lightning	Unfamiliar to all learners	Answer four multiple-choice questions based on the lightning text	Observe learners' quiz engagement with unfamiliar text	Reading comprehension sub-score 2
				Measure learners' reading comprehension of unfamiliar text	Reading comprehension sub-score 3

means that you have a tingling feeling.' This corresponds, superficially, to the text: 'If you ever feel your hair standing up or get a tingling feeling during a storm it could mean charges are moving onto you and you may be in danger of being hit by lightning!'.

The test was administered to each learner individually. As a precaution against learners sharing answers, the questions and their options were rendered randomly each time. This did, however, have the undesired effect of altering the probability each learner had of guessing correctly if they simply picked the first option each time. However, the eye-tracking record enabled us to determine when items were chosen before they had been read, reducing the error caused by fortunate guessing.

The software provided feedback to the learners regarding the correctness of their answers. For the gap-fill quiz this feedback was given when the learner pressed the 'Submit' button. For the multiple-choice quiz, this feedback was given immediately after the learner had selected a choice. The software flagged errors for correction, reduced the learner's score on each incorrect attempt and provided a final mark on correct completion of all the items. All the learners were expected to be familiar with these features as they had been exposed to this kind of software earlier in the year.

EST reading comprehension index

Consistent with a pragmatic research paradigm, the EST reading comprehension index used was designed specifically for this research. Transparency in reporting how each component of this index, as well as the final index, was derived, enables the reader to judge the extent to which the resulting claims are warranted.[31] The EST reading comprehension index derived for this research is a five-point scale which is the average of reading comprehension sub-scores 1–3. Each of these sub-scores is designed such that Levels 1–3 refer to behaviours indicative of reading within the frustration level.[26] Level 1 refers to reading avoidance behaviour suggesting inability or extreme difficulty even with decoding, with reading comprehension levels below 20%. Level 2 refers to less reading avoidance than Level 1, suggesting that the learner is engaging with decoding, but that either or both of the learner's decoding and language comprehension skills are so poor that the learner engages in guessing without reading for at least some of the time, with reading comprehension levels below 40%. Level 3 refers to the upper section of the frustration level, with no evidence of guessing without reading being observable, suggesting that the learner is decoding the words, but errors in answer choices suggest superficial language comprehension and/or knowledge employment which result in formation of a superficial surface model but faulty situation and global representations. Reading comprehension levels below 60% are included in this level, corresponding to Lesiak and Bradley-Johnson's[26] criterion of inclusion in the frustration level of reading. Levels 4 and 5 refer to reading above the frustration level with good (60–80%) and excellent (above 80%) reading comprehension levels observed, respectively. Although decoding accuracy was not measured to enable us to utilise Lesiak and Bradley-Johnson's[26] classification system with fidelity, it seems reasonable to label our Levels 4 and 5 as corresponding, at least broadly, to the instructional and independent reading levels, respectively, on the basis of the reading comprehension levels measured.

Sub-scores 1 and 2 were obtained from rubrics which are summarised in the findings section and guided by the principles described above. Sub-score 3 was obtained from the average of the comprehension percentages for the four multiple-choice questions on Screen 4, using the cut-off percentages per level, as given above. The comprehension percentages were obtained as follows: questions answered by guessing without reading, as inferred from the eye movements, were assigned 0%; and other questions were assigned 100% if the correct answer was obtained on the first attempt, with 25% deducted for every successive attempt.

Data analysis

The checklists and descriptions of each learner's reading and quiz-engagement behaviour were analysed qualitatively using summarising descriptions guided by Question 1. To answer Questions 2 and 3, respectively, Pearson's regression value was calculated between the EST reading comprehension index and: (1) the learners' Natural Sciences mark and (2) the post-test score and the normalised gain obtained in the relevant interventions. For all analyses, $r > 0.6$ was taken as showing strong correlation, 0.6–0.3 as moderate, 0.1–0.3 as weak and $r < 0.1$ as no correlation; $p < 0.01$ shows statistical significance. Additionally, the data were represented in manners which aid comprehension of trends within the data as guided by the research questions.

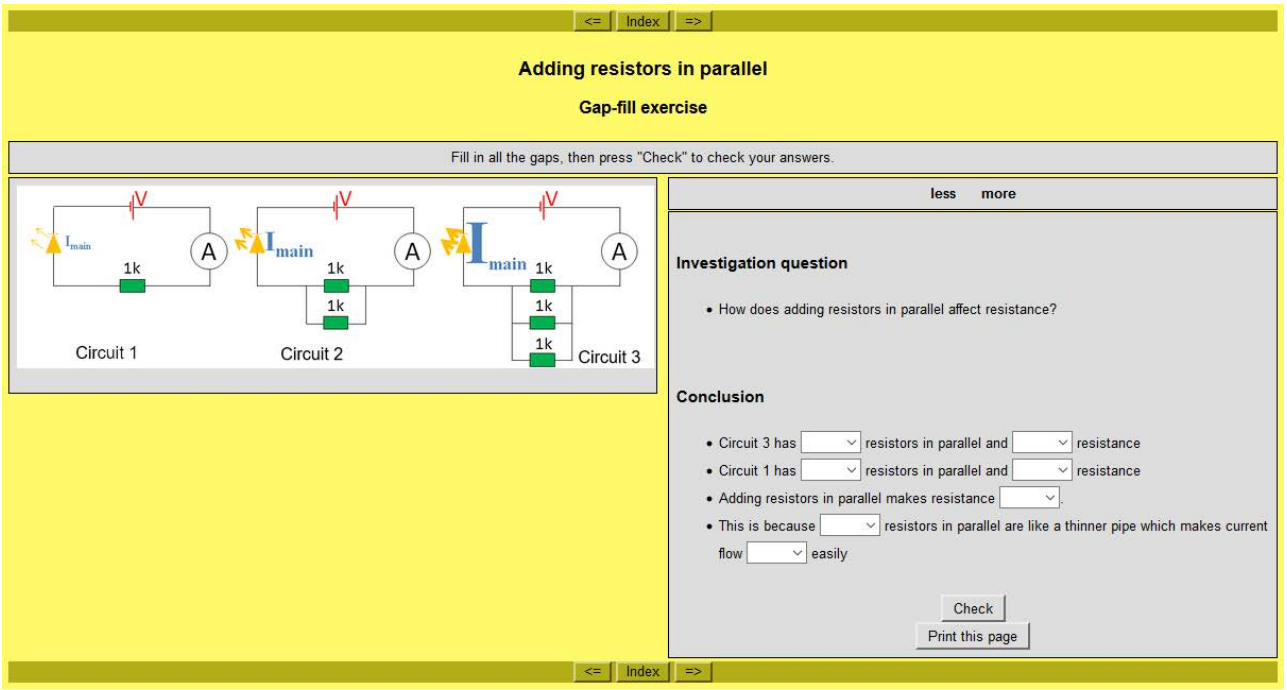

Figure 1: Screenshot of Screen 2 in the eye-tracking tasks.

Results

Quiz engagement

Metrics of the participants' eye movements are discussed in detail in a related article[23] in which we used the same data set to pursue an understanding of the eye-movement characteristics of barking at print. There are slight discrepancies in the numbers between these two articles because of the different focus of each, coupled with some gaps in the data, dictating slightly different participant exclusion from the original even larger sample.

Table 2 shows the number of learners assigned to each category for reading comprehension sub-score 1, derived from the task which was moderately familiar to the learners. Only one learner answered all the questions correctly. This learner is referred to as Sifiso, and was the only learner to attain a deep level of understanding in the intervention described in Stott[9]. The unnatural wording of the final question, unsurprisingly, caused difficulty for all the remaining learners. Five of the learners categorised as being fluent (Level 4) completed the final question in the manner to be expected from a natural wording, i.e. as in the original wording, before even reading the full sentence. The remainder of learners seemed to notice the changed format of the sentence, halted in their reading and, in most cases, read the sentence more than once.

Table 2: The criteria used and number of learners assigned to each level for reading comprehension sub-score 1 (n=65)

Criteria		Category and assigned value	Number of learners
No evidence of guessing without reading	All answers correct	Perfect (5)	1
	Error(s) only in final question	Fluent (4)	32
	Error(s) in other knowledge-based questions	Knowledge limited (3)	13
Some evidence of guessing		Comprehension limited (2)	13
No evidence of reading		Only guessing (1)	6

The 13 learners classified as having limited knowledge (Level 3) correctly answered the questions based directly on the diagrams, i.e. related to the relative numbers of resistors in each. However, they made errors in knowledge-based questions linking relative numbers of resistors in parallel to relative resistance. The 13 learners classified as displaying limited reading comprehension as a consequence of showing evidence of some guessing (Level 2) displayed systematic eye movement across the text, and movement of the eyes between the text and the diagrams for much of the time, suggesting some engagement in decoding and a search for language comprehension. However, they answered some of the questions without having read enough of the text to be able to answer from comprehension and/or they incorrectly answered the questions based directly on the diagrams. The six learners classified as having only guessed (Level 1) showed no systematic eye movements across the text or the diagrams. Instead, the options were the only parts of the screen to which they apparently directed their eyes with purpose. Three of these learners did not even address the options in the normal reading sequence, i.e. from left to right within a row, and from top to bottom between rows.

Two of the six learners who showed no evidence of reading for Screen 2's task also showed no evidence of reading for any of the other screens, despite telling us that they had finished reading. These two learners moved their eyes randomly across the reading passages and guessed the answers to the questions without apparently reading anything on the screen. Figure 2 is a gaze plot for one of these learners. For the purpose of comparison, the gaze plot of the highest achieving learner, referred to as Sifiso, is given in Figure 3. Surprisingly, one of the learners who showed no evidence of reading had been chosen as one of the top 30 learners in her class to participate in the intervention described in Stott[9]. However, her inclusion seems to have been a result of a selection error, because her failing Natural Sciences mark of 17% does not place her in the top 30. Unsurprisingly, she gained little from the intervention, being classified in the 'little memory' category with a post-test score of 6%. An additional 10 learners appeared to read and skip chunks of text alternately, moving their eyes randomly for some of the time, and systematically tracking blocks of text for the rest of the time.

As shown in Table 3, more than half (37) of the learners guessed, without reading, at least one answer, 11 of whom guessed all four answers for the multiple-choice questions on Screen 4. The majority of the remaining learners[18] made at least one choice based on superficial correspondence between the distractor and the text, for example, choosing the option about tingling, described earlier.

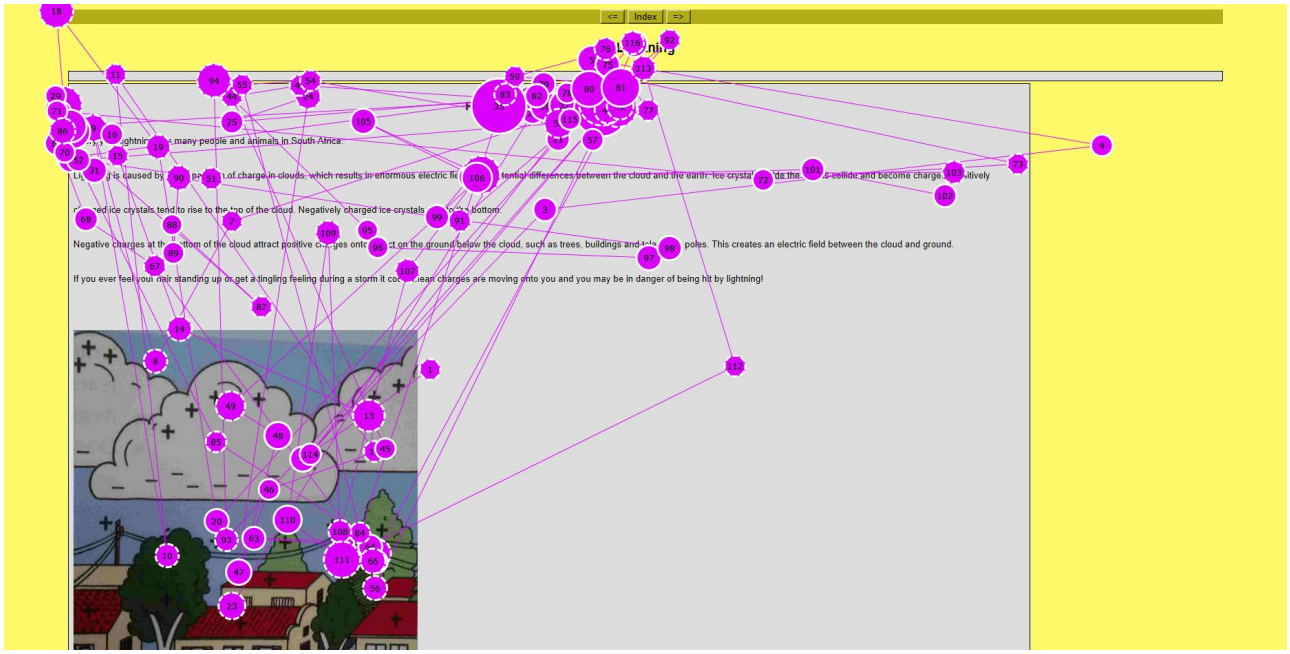

Figure 2: Gaze plot of one of the two learners who showed no evidence of reading.

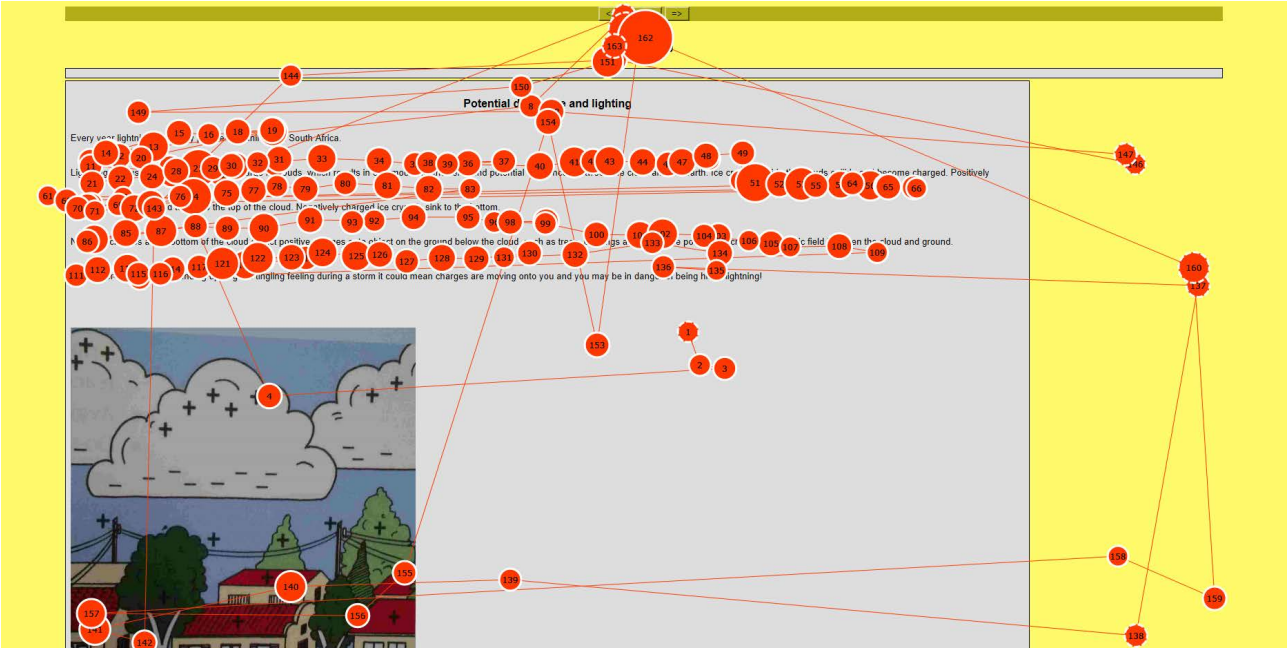

Figure 3: Gaze plot for the highest achieving learner, Sifiso.

Table 3: The criteria used and number of learners assigned to each level for reading comprehension sub-score 2 ($n=65$)

Criteria		Category and assigned value	Number of learners
No evidence of guessing without reading	All answers correct	Perfect (5)	2
	Non-superficial errors	Fluent (4)	8
	Superficial errors	Superficial comprehension techniques (3)	18
Some evidence of guessing		Some guessing (2)	26
No evidence of answering based on reading		Only guessing (1)	11

The third reading comprehension sub-score assigned to each learner is determined by the score they obtained for the multiple-choice quiz on Screen 4, as explained previously. As can be seen in Table 4, just less than half of the learners[30] achieved under 40%, with a fairly large group[14] achieving over 80%.

Table 4: The criteria used and number of learners assigned to each level for reading comprehension sub-score 3 ($n=65$)

Score range	Assigned value	Number of learners
80–100%	5	14
60–79%	4	12
40–59%	3	9
20–39%	2	7
0–19%	1	23

An EST reading comprehension index was calculated for each learner as the average of the three values given in Tables 2–4, respectively. This index is used to answer Questions 2 and 3. As shown in Table 5, 68% of the learners were classified as reading science texts at the frustration level, with just under half the learners[30] being rated at Levels 1 or 2, which suggests poor decoding skills in addition to poor language comprehension, as evidenced by reading avoidance and answer-guessing without reading.

Table 5: Distribution of learners according to English for science and technology reading comprehension index, calculated as average of values from Tables 2–4 ($n=65$)

Reading level (26)	EST reading comprehension index	Number (percentage) of learners	
Independent	5	2 (3%)	21 (32%)
Instructional	4	19 (29%)	
Frustration	3	14 (22%)	44 (68%)
	2	23 (35%)	
	1	7 (11%)	

EST reading comprehension and science marks

Figure 4 shows the learners' EST reading comprehension index, determined in November 2016 in the manner previously described, plotted against their Natural Sciences 2016 end of year mark. A strong correlation of $r=0.60$ was found, with $p<0.01$. All of the learners assigned reading comprehension indices of 4 and 5, and therefore considered to be reading at the instructional and independent levels, scored 50% or higher for Natural Sciences.

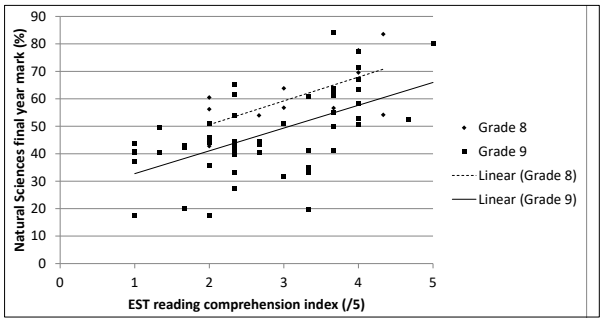

Figure 4: Relationship between the learners' English for science and technology (EST) reading comprehension index and their Natural Sciences mark (n=65).

EST reading comprehension and intervention benefit

Figure 5 shows the reading comprehension index plotted against the post-test scores obtained by the 50 learners who were involved in either or both of the science previously referred to. Of the 92 learners who had participated in the Electricity intervention, and 27 who had participated in the Mechanics intervention, 43 and 16, respectively, were available for the reading comprehension test. Nine of those tested for reading comprehension had participated in both interventions. These learners have been counted and represented separately for each of the interventions in both the statistics given below and in Figure 5.

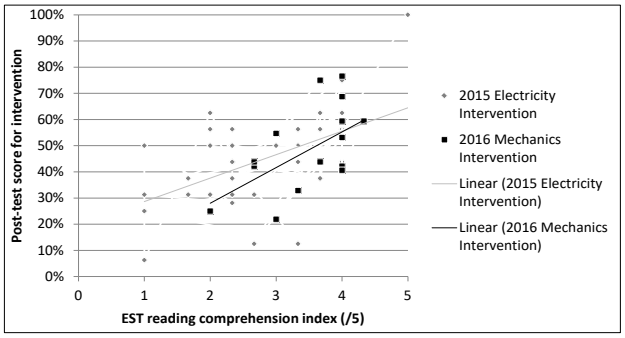

Figure 5: English for science and technology (EST) reading comprehension index, November 2016, versus post-test score for September 2015 'Electricity' intervention (n=43) and July 2016 'Mechanics' intervention (n=16).

A moderate and significant correlation was found between the score obtained at the end of the intervention and the reading comprehension index (r=0.54; p<0.01). A similar correlation was found between the normalised gain for the intervention and the reading comprehension index (r=0.55, p<0.01). The mean reading index for those learners (n=19) who scored below 40% in these post-tests (M=2.5, SD=0.9) falls within the frustration level, whereas the mean for the learners (n=40) who scored above 40% (M= 3.3, SD=0.9) is slightly above the frustration level. All the learners with reading comprehension indices of 4 and 5, and therefore considered to be reading at the instructional and independent levels, scored 40% or higher for the intervention post-tests and exhibited normalised gains of 0.17 (17%) or higher. However, as Figure 5 and the relatively large standard deviation values show, there is a fair amount of variation in the data for learners having a reading comprehension index below 4.

Discussion

Quiz engagement

The high proportion of learners with poor reading comprehension skills is consistent with findings from benchmarking tests such as PIRLS[24,25], as well as a number of other South African studies[3,37,38]. In this study, 68% (44/65) of the learners in this relatively strong sample were classified as reading at the frustration level for Grade 9 level science texts, with almost half (30/65) of the learners assigned reading comprehension indices of 1 or 2 (out of 5). These indices correspond to at least some answer-guessing without reading, suggesting possible difficulty even with word decoding. This corresponds to Pretorius and Spaull's[39] findings of poor decoding skills among the majority of South African township learners. A considerable number of learners (11) guessed all the multiple-choice questions without reading and two did not show any evidence of engaging in any word decoding. Only 10 of the 65 learners were not observed to guess answers, either by answering without reading or on the basis of superficial textual features. This observation is consistent with Dempster's[17] findings of much use of superficial text-based strategies when South African English second language learners answered science questions for the Trends in International Mathematics and Science Study (TIMSS). These strategies included choosing options with familiar words or words present in both the text and the answer options. This shows that the danger of engaging in strategies to 'game the system'[27] is considerable for text-heavy software. This danger seems to have been considerably reduced for the shorter, more familiar quiz (Screen 2).

Learners who read at the frustration level tend not to engage in self-regulated learning which extends beyond contact with the teacher.[26] However, such self-study is vital for a township learner to be able to mitigate the poor class time usage, limited and low-quality teacher–learner contact time, limited and sporadic homework assignment and control and general dysfunctionality of the typical township school.[40] These suggest that good reading comprehension is most needed in the very environments which least foster it. The finding that there was a higher prevalence of reading avoidance and guessing for the less familiar, text-heavy quiz than the more familiar, less text-heavy quiz is unsurprising and illustrates the limitation which a low ability to read with comprehension imposes on effective learning of more complex science concepts.[41]

EST reading comprehension and science marks

The strong correlation found between EST reading comprehension and the learners' Natural Sciences mark extends Pretorius's[3] finding that reading comprehension is a good predictor of whether learners are able to pass mathematics. This extension is both to the context of science and with respect to giving greater detail about the relationship between reading comprehension and school marks. It should be noted, however, that we measured EST reading comprehension, which can be expected to be more strongly correlated to science performance than may have been found had fictional texts been used.

EST reading comprehension and intervention benefit

The quiz-engagement patterns help explain the moderate correlation found between learners' reading comprehension and the benefit which they gained from the after-school interventions. Both interventions required engagement with texts in the form of electronic quizzes and/or paper-based reading. The sample includes nine of the learners who were described in Stott[9] as being able to learn new concepts from science software before being taught these concepts by a teacher. These learners were all classified as reading above the frustration level, with a reading comprehension index mean of 4 and a range from 3.7 to 5. In contrast, the first author's general experience of working with township learners using science quiz and audiovisual software is that besides a small number of the most academically strong, the learners seem only to gain significant benefit from the software when it is used to revise work which has already been taught and practised in class. This observation is consistent with Probyn's[42] findings regarding such learners' dependence on the language-bridging practices of a skilful teacher.

Limitations

Reading comprehension is a complex skill which is difficult to measure validly. Each of the three sub-scores used to calculate the reading comprehension index addressed a somewhat different aspect of reading comprehension and the criteria used to assign each value have been stated. Both researchers rated the learners independently, with Cohen's kappa inter-rater indices of over 0.8. Despite these measures to enhance the validity of the reading comprehension index used,

subjective judgement could not be avoided. Also, although the eye-tracking software facilitates the detection of cases in which learners guess without reading, it is not always possible to detect such behaviour. Further, a weakness of using a rating system is that it suggests that the distance between successive categories is equal, which is certainly not the case here.

Conclusion

Improvement of reading comprehension by improving the teaching of decoding skills and through the explicit teaching of reading comprehension strategies, is sorely needed in South African township schools. For learners who are unable to comprehend the language, and in many cases even lack the ability to decode the words used in software and handouts employed in after-school interventions, such interventions are likely to become exercises in 'gaming the system', which leads to minimal learning. The time, effort and expense invested in placing such learners into such programmes would be better spent, for example, in teaching those learners reading comprehension skills or offering their place to a learner whose reading comprehension skill enables them to benefit from the programme. The strong correlation found between EST reading comprehension and Natural Sciences marks suggests that these marks could be used as a fairly reliable and easily obtainable proxy for EST reading comprehension within the township school context.

In this study, we have shown that there are considerable numbers of learners (32% of this relatively strong sample) in the township context who are able to comprehend EST texts above the frustration level despite having been schooled in an environment which is generally unfavourable to the development of reading comprehension. For these learners, at least, interventions which include text-dependent components such as engagement with electronic software, does seem a viable supplement to the education they receive in their schools as long as appropriate access and motivation can be provided.

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Authors' contributions

A.S.: Conceptualisation, data analysis, writing the first draft. T.B.: Conceptualisation, data collection, data analysis, critically reviewing the writing.

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Comparing mathematics knowledge of first-year students from three different school curricula

Mathematics forms an integral part in the training of scientists and engineers. In recent history the South African school system has experienced several changes in school curricula. In 1994 the traditional knowledge-based curricula were replaced by an outcomes-based curriculum. Owing to implementation problems which resulted in resistance from teachers and the general public, revisions followed of which the National Curriculum Statement (NCS) and Curriculum Assessment Policy Statements had the most direct effect in terms of preparation for tertiary mathematics. We report here on an investigation of the basic mathematical knowledge of three student cohorts representing three curricula, namely the last cohort that received the traditional knowledge-based curriculum, and the first cohorts that received the two outcomes-based curricula. The results indicate that changes in the mathematical content of the curricula did not impact negatively on the basic mathematical knowledge of students enrolled for tertiary mainstream mathematics. The only exception is Euclidean geometry, for which certain topics were transferred to an optional paper in the NCS curriculum.

Significance:

- The introduction of outcomes-based curricula in South Africa initiated a discourse on the preparedness of first-year students for programmes with mainstream mathematics.
- The availability of a homogeneous set of samples and a uniform test provided a unique opportunity to compare the basic mathematical knowledge of first-year natural science and engineering students entering university from three different exit-level school curricula.

Introduction

Role players involved in the training of scientists and engineers have a vested interest in the basic mathematics knowledge of prospective science and engineering students. Changes in school curricula invariably influence the preparedness of students for tertiary studies, especially where mathematics-intensive programmes are concerned. Substantial changes were made to the South African school system since 1994 as a result of a change in the government system.[1] The racially and provincially segregated curricula of the apartheid era were replaced by a unified national curriculum. Whereas the previous fragmented curricula were mainly specified in terms of content knowledge to be learned using a transmission teaching model[2], the new national curriculum was a skills-based constructivist curriculum[3], which was implemented with an outcomes-based management structure[4]. Another major structural change to the curriculum was the merging of the higher grade (HG) and standard grade (SG) curricula documents into a single curriculum document, presumably to diminish the emphasis on individual achievements of a few in exchange for a more rounded approach to education for all learners. Owing to problems experienced with the implementation of the new curriculum, revisions were introduced. Not all of these revisions were sustained up to Grade 12, but, ultimately, three outbound Grade 12 cohorts can be distinguished in South Africa: (1) learners who matriculated in the years up to 2007 who were exposed in Grades 10 to 12 to traditional knowledge-based curricula (TKC); (2) matriculants of 2008 to 2013 who were exposed to a constructivist curriculum implemented through an outcomes-based educational system (OBE) as summarised in the National Curriculum Statement (NCS)[5]; and (3) those who matriculated between 2014 and the present who experienced a revised version of the OBE curriculum, officially documented in the Curriculum Assessment Policy Statement (CAPS)[6].

Since the replacement of traditional, knowledge-based curricula by new, OBE-grounded curricula in countries such as the USA, the United Kingdom, Canada, Australia, New Zealand and South Africa, discourses have developed among academics and the general public on the expediency of these changes. Perceptions were that students experienced difficulty with the transition to tertiary level, especially those enrolled in mathematics-intensive programmes. For example, a survey done in the USA revealed that an increasing number of incoming students needed remedial courses in mathematics.[7] A report on the preparedness of Irish students for tertiary mathematics studies refers to 'grade depreciation', implying that grades achieved in state examinations were not comparable to the same grades obtained 10 years earlier.[8] However, it was not made clear to which extent the perceived lack of mathematical knowledge could be attributed to the introduction of OBE.

In South Africa, lecturers have increasingly become aware of first-year mathematics students' lack of understanding of fundamental mathematical concepts.[9-11] In the study of Engelbrecht and Harding[9], the first-year mathematics cohorts of 2005, 2006 and 2007 were compared using a mathematics achievement test which was designed to determine the level of mathematical competency of students who did not necessarily excel in the final matric exam. The questions were set on topics such as percentages, spatial geometry, parallel lines, word sums, ratio and proportion, number concept and manipulation, functions, graphs and trigonometry. The cohort of 2005 represented students who did not experience OBE at school level, while the cohorts of 2006 and 2007 experienced OBE up to Grade 9, but reverted back to traditional teaching in Grades 10 to 12. Engelbrecht and Harding[9] concluded that, except for geometry, word sums and ratio and proportion, the student performances were on par for these three cohorts. In 2015 we published an article[12] in which we compared the mathematical knowledge and skills of the 2008 cohort at our institution (the last cohort exposed to traditional curriculum in Grades 10 to 12) with the 2009 cohort (the first cohort exposed to the full OBE curricula to reach university) in terms of a framework consisting of three mathematics knowledge types, namely procedural knowledge, proceptual knowledge and conceptual knowledge. The framework was an attempt to investigate if the changes in the curricula impacted on the way mathematics was taught and learned in Grades 10 to 12. The sample was all students enrolled for mathematics, including students

from science, engineering, commerce and education. The comparison showed that the performance of the OBE cohort was not as poor as has been perceived initially; however, the expected outcome that students from the OBE curriculum would have better conceptual understanding because of the emphasis on exploration and searching for patterns only materialised for some questions on the interpretation of graphs.

In the present article we follow up on these comparisons by including the cohort of 2015, which was the first cohort exposed to CAPS in Grades 10 to 12. The focus of this study is to investigate how changes in the school curricula, especially differences in the mathematical content, influenced the basic mathematical knowledge of natural science and engineering students enrolled at our institution. We report on a quantitative empirical study based on the results of multiple-choice tests written by all new first-year mathematics students at our tertiary institution. The main intention of the study was to investigate whether the mathematical knowledge of the cohorts of 2008, 2009 and 2015, which represent three different school curricula for Grades 10 to 12 – namely TKC, NCS and CAPS – are significantly different.

Changes to mathematics curricula in South Africa

In order to gain insight into the influence of each curriculum on the development of basic mathematical knowledge, we give a brief overview of the foundations of these three curricula and their historical implementation in South African schools. The management structure of the new curriculum was grounded in the principles of OBE, where assessment is based on 'demonstration of outcomes', ranging from 'simple discrete content skills' to the 'highly complex open-ended life-role performances required by adults in the real world'[4(p.25)]. An OBE system places greater emphasis on dispositions, resulting in formative, criterion-based assessment, instead of summative assessment and high-risk tests.[13] Three varieties of OBE with rising hierarchical orders of complexity[14] and corresponding decreasing scales of modernism[15] can be distinguished. Traditional OBE is similar to a traditional knowledge-based curriculum in terms of the organisation of learning content in disciplines and an emphasis on academic development, but it differs from the traditional knowledge-based curriculum in terms of its assessment criteria, which are based on mastery of specified outcomes, and on its learner-centred approach and emphasis on life-long learning. Transitional OBE is more future orientated and accentuates the cultivation of higher-order competencies, such as critical thinking, problem solving and communication skills. Transformational OBE is the most complex and extreme form of OBE which defies fixed curriculum outcomes based on conventional subject areas, and strives to change the disposition of learners. In the planning stages of the new South African curriculum, a transformational OBE model was envisaged.[16,17] However, the first implemented version of OBE in South Africa – Curriculum 2005[18] – was described by one researcher[19(p.22)] as a 'potpourri of curriculum proposals with largely unacknowledged origins'. However, with the introduction of cross-curriculum critical outcomes, integrated learning areas and integrated real-life problem settings, Curriculum 2005 could be classified as a transitional model in the OBE hierarchy.

In practice, there was tension between the critical outcomes of Curriculum 2005 and the formulation of its learning outcomes.[15] At that stage, most teachers were products of schooling in the old dispensation and struggled to come to terms with the implementation of the new curriculum.[20,21] This difficulty resulted in revision of the original OBE curriculum in an attempt to reduce the level of integration of subjects. The Revised NCS for Grades R–9[22] was implemented in the foundation phase from 2004, and the NCS for Grades 10–12[5] was introduced in Grade 10 in 2006. These revisions did not address all the problems teachers experienced, as complaints about implementation issues and administration overload suffered by teachers persisted.[23] Further revisions were necessary to address these problems, and, in 2012, new assessment criteria, referred to as the CAPS, were introduced in Grade 10.[6] In the revised document it was emphasised that the basic philosophy of the curriculum remained unchanged and that the adjustments only related to 'what to teach and not how to teach'[23]. The content organisation of the CAPS is similar to a traditional knowledge-based curriculum, but the critical cross-curriculum outcomes were retained. Some researchers labelled the CAPS curriculum as too prescriptive and restrictive[24,25], arguing that the most dramatic change brought about by CAPS has been its shift in focus from assessment of learning to learning for assessment. Signs are already there that South Africa has moved away from OBE towards the US model of a standards approach to education, with an overemphasis on external assessment of learners in all the school phases.[26] It is therefore not clear, and will be difficult to determine, whether the changes envisaged by the OBE curriclula had an effect on teachers' practices in their classrooms.

In this article we rather focus on the effect of changes in the structure and content of the curricula. Structurally, the differentiation between HG and SG mathematics has been removed, with the unintended consequence that fewer marks are available to differentiate among students who want to enrol for mainstream mathematics. In order to better prepare learners for their future role in society, themes of a statistical nature such as data handling, descriptive statistics and financial mathematics – were added to the core curriculum of mathematics. To make room for these inclusions, absolute value theory and the remainder theorem were omitted from the curriculum and Euclidean geometry was transferred to a separate optional paper, to which a few new topics such as recursive sequences, bivariate data and probability were added.[5] One of the main consequences of this move was that students in the first-year cohorts of 2009 to 2014 were only partly exposed to Euclidean geometry in Grades 10 to 12. Furthermore, the scope of some topics was reduced by limiting assessment of formal proofs and definitions and the focus shifted to the application of rules and theorems in problem-solving situations. For example, the factor theorem was used to find the roots of higher-order polynomials, and the logarithmic rules were applied to solve for the time period of an investment.

The main objective of the OBE mathematics curriculum was to deliver learners who are able to 'transfer skills from familiar to unfamiliar situations'[5(p.5)]. The emphasis shifted from knowing mathematics as facts, rules and principles, to the interpretation and application of conceptual representations such as graphs and algebraic patterns. Learners were encouraged to use graphical representations to solve problems and to search for connections between different topics. For example, in the topic of functions, more emphasis was placed on the connection between algebraic equations and the subsequent shifting of graphs. Another example is the topic of series and sequences in which the general recursive formulation in terms of geometric and arithmetic sequences were reformulated in terms of linear, quadratic and exponential sequences, which could be linked to functional graphs.

With the introduction of the CAPS, the content of the optional paper, which included topics of Euclidean geometry, was reintegrated into the core curriculum, while only the single topic of linear programming was omitted. These additions resulted in an overall increase in the mathematical content of the curriculum. In the CAPS document, the specific mathematical content to be learned was more clearly defined and examples were given for each specific curriculum statement.

Methodology

Research question

The empirical study was undertaken to address the research question: Are there practical significant differences in the basic mathematical knowledge of first-year natural science and engineering students who matriculated from traditional knowledge-based curricula (TKC), the new outcomes-based curriculum (NCS), and the recently revised outcomes-based curriculum (CAPS)?

Research design

The research can be categorised as a quantitative investigation using a comparative analysis of variance (ANOVA)-test analysis of the results of a diagnostic test written by first-year mathematics students in order to quantify the differences in basic knowledge between students from three different school cohorts.

Sample

The sample was conveniently selected and consisted of all bona fide first-year students enrolled for mainstream mathematics in engineering and natural sciences programmes at our tertiary institution in 2008, 2009 and 2015. Only students who wrote the relevant matriculation exam in the previous year were considered in the analyses. For Grades 10 to 12, the 2008 cohort was exposed to traditional knowledge-based curricula (TKC), the 2009 cohort to the new outcomes-based curriculum (NCS), and the 2015 cohort to the recently revised outcomes-based curriculum (CAPS). The admission requirement for enrolment into mainstream mathematics modules for the 2008 cohort was 60% for SG or 50% for HG mathematics in the final matriculation examination. For both the 2009 and 2015 cohorts, the requirement was Level 4 (50%) for mathematics. The sample sizes for the respective cohorts were $n=287$ for the 2008 cohort, $n=357$ for the 2009 cohort and $n=455$ for the 2015 cohort.

The demography of students enrolled for 2008, 2009 and 2015 did not differ considerably. This similarity gave us an opportunity to investigate the effect of changes in the school curriculum on a relatively homogeneous sample of students regarding academic achievement at school level, but with exposure to different school curricula.

Ethical considerations and data collection

Permission was obtained from the director of the School for Computer, Mathematical and Statistical Sciences to conduct the research. Ethical clearance was obtained from the Research Ethics Committee of the Faculty of Natural Sciences (reference number NWU-0007-14-S3). The first-year cohorts of 2008 and 2009 wrote the diagnostic test in the first week of their respective first semesters. The participation was voluntary and individual results were not made public. Since 2011, all first-year students enrolling for mainstream mathematics on campus have been required to attend a mathematics refresher course before the commencement of classes. The first-year cohort of 2015 wrote the diagnostic test on the first day of the mathematics refresher course. Only data from bona fide first-year students who matriculated in South Africa from the relevant curricula were considered for the data analysis.

Selection of test items

The mathematical knowledge test used in the empirical study for the 2008 and 2009 cohorts consisted of 40 multiple-choice questions: 24 items were selected from a test developed to predict students' success in tertiary studies in mathematics[27], and 16 items extracted from previous question papers were added to the core test to broaden its scope in terms of specific topics in mathematics. The 2015 cohort wrote the pre-test of the mathematics refresher course; this test consisted of 35 questions. A total of 25 items appeared in both tests and could be used in the comparative analysis.

Classification of test items in terms of topic areas

The 25 items were grouped into different topics of mathematics, namely algebraic knowledge, functions and graphs, trigonometry, geometry and differentiation. Because of the multidimensionality of mathematical knowledge it is not always possible to classify certain items. For example, the simplification of $\sqrt{x^2+y^2}$ can be classified as algebraic knowledge, but it also requires an understanding of the function concept. For this reason, the items were compared on an individual basis.

Comparison criteria

The differences between the means of the individual questions of the three cohorts were compared using the ANOVA test for Cohen's effect sizes, as given by Ellis and Steyn[28(p.51)]. Effect sizes (d-values) are independent of the sample size and provide a measure of the practical significance of the differences between the means. According to Cohen, d-values are interpreted as follows:

- Small effect: $0.2 \leq d < 0.5$
- Medium effect: $0.5 \leq d < 0.8$
- Large effect: $d \geq 0.8$

Although the sample used is a convenience sample, p-values giving the statistical significance of the differences between the cohorts are reported for the sake of completeness. A p-value smaller than 0.05 indicates that the difference between the cohorts is statistically significant.

Results

The results are presented in Tables 1 to 6 for the different topic areas. The abbreviations 'T', 'N' and 'C' indicate the cohorts from the TKC (2008 cohort), NCS (2009 cohort) and CAPS (2015 cohort) curricula, respectively. The abbreviation 'T/N', for example, indicates the practical difference between the scores for the TKC and NCS curricula. An asterisk in the p-column indicates an acceptable statistically significant difference ($p<0.05$), and asterisks in the d-column indicate a small (*), medium (**) or large (***) effect in practical difference. A positive d-value in a column indicates that the group mentioned first performed better, while a negative d-value indicates a better performance by the group mentioned second.

Algebraic knowledge

The results for algebraic knowledge are listed in Table 1. The cohorts all performed well (>55%) on most of the questions, with the exception of Question 4 (<51%) on simplifying a surd and Question 25 (<36%) on applying rules of logarithms. When comparing d-values for the rest of the questions, five other questions (Q1, Q3, Q13, Q16 and Q17) yielded small (*) to medium (**) practical differences between cohorts. The TKC cohort performed slightly better than the other two cohorts in solving general linear equations (Q1), and when applying long division to determine the remainder of a polynomial (Q16); better than the NCS cohort when simplifying fractions (Q3), and better than the CAPS cohort when solving fractional equations (Q13). Questions 2 and 17 are both set on the application of exponential rules. Question 2 was a direct application of the rules where the expression $(2x^3)^{-2}$ had to be simplified, whereas in Question 17 students first had to use higher-order thinking skills to analyse the question before applying the appropriate rule. The question stated that they had to determine a third of 3^{15}. This higher-order thinking could explain the lower performance of all cohorts on this question in relation to Question 2. The CAPS cohort performed best in both these questions.

Functions and graphs

The results for functions and graphs are given in Table 2. The two questions on the quadratic function (Q6 and Q21) were answered well by all the cohorts (>68%), with the NCS group receiving the lowest scores. The CAPS cohort performed the best in determining the inverse of a function using algebraic manipulation (Q19), while the NCS cohort performed best in the question on linking a graph of an absolute value function to the given equations (Q9). All cohorts performed poorly in linking an inequality to its graphical representation (Q32), with the CAPS cohort performing the worst.

Trigonometry

The results for trigonometry are given in Table 3. The questions on trigonometry tested the application of right-angled trigonometry (Q12) and finding the period from trigonometric equations (Q27). There was no practically significant difference in performance on the question on right-angled trigonometry (Q12). The CAPS cohort performed best in the question on the period of the tangent function (Q27).

Geometry

The results for geometry are given in Table 4. For the items listed in Table 4, the students had to apply the named theorem to perform numerical tasks. In the geometry section, the performance of the NCS cohort was the poorest. The practical difference between the scores for the NCS and the other two cohorts, for the questions on angles in the same segment (Q29), angles in the centre and circumference (Q30), and a line perpendicular to a chord (Q31), ranged from a small (0.40) to medium (0.60) effect. In the question on the theorem of similarity of triangles (Q35), the CAPS cohort performed best with a small effect (0.27) in practice.

Table 1: Question by question comparison for algebraic skills

Question		Mean (%)			*d*-value			*p*-value
Number	Description	T	N	C	T/N	N/C	T/C	
1	Solving a linear equation	80	62	69	0.38*	-0.15	0.24*	0.000*
2	Rules of exponents	72	74	80	-0.02	-0.15	-0.17	0.013*
3	Fractional expression	87	79	83	0.20*	-0.10	0.11	0.016*
4	Simplifying $\sqrt{x^2+y^2}$	48	37	50	0.24*	-0.27*	-0.03	0.000*
13	Fractional equations	80	77	70	0.09	0.14	0.22*	0.002*
16	Long division	83	57	62	0.54**	-0.10	0.44*	0.000*
17	Rules of exponents	63	71	79	-0.17	-0.17	-0.33*	0.000*
22	Roots of parabola	89	87	86	0.07	0.04	0.11	0.268
25	Rules of logarithms	36	27	29	0.18	-0.04	0.15	0.029*
Average for algebraic skills		71	63	68				

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and asterisks in the* d*-column indicate a small (*) or medium (**) effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative* d*-value indicates a better performance by the group mentioned second.*

Table 2: Question by question comparison for functions and graphs

Question		Mean (%)			*d*-value			*p*-value
Number	Description	T	N	C	T/N	N/C	T/C	
6	Intersection of line and parabola	85	71	89	0.30*	-0.41*	-0.13	0.000*
9	Shifted graph of absolute value function	66	77	61	-0.22*	0.31*	0.10	0.000*
19	Finding inverse of function algebraically	52	53	75	-0.03	-0.43*	-0.46*	0.000*
21	Symmetry axis of parabola	75	68	75	0.15	-0.15	0.00	0.031*
32	Finding inequality from graph	32	28	19	0.09	0.18	0.26*	0.000*
Average for functions and graphs		62	59	64				

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and an asterisk (*) in the* d*-column indicates a small effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative* d*-value indicates a better performance by the group mentioned second.*

Table 3: Question by question comparison for trigonometry

Question		Mean (%)			*d*-value			*p*-value
Number	Description	T	N	C	T/N	N/C	T/C	
12	Right-angled trigonometry	82	78	76	0.09	0.04	0.13	0.153
27	Period of tangent function	49	53	62	-0.09	-0.18	-0.27*	0.000*
Average for trigonometry		66	66	69				

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and an asterisk (*) in the* d*-column indicates a small effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative* d*-value indicates a better performance by the group mentioned second.*

Table 4: Question by question comparison for geometry

Question		Mean (%)			*d*-value			*p*-value
Number	Description	T	N	C	T/N	N/C	T/C	
29	Angles in the same segment	92	64	91	0.58**	-0.57**	0.02	0.000*
30	Angles at the centre and circumference	25	8	30	0.40*	-0.48*	-0.09	0.000*
31	Line ⊥ to chord	84	60	89	0.49*	-0.60**	-0.16	0.000*
35	Theorem on similarity	69	61	81	0.17	-0.42*	-0.27*	0.000*
Average for geometry		68	48	73				

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and asterisks in the* d*-column indicate a small (*) or medium (**) effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative* d*-value indicates a better performance by the group mentioned second.*

Differentiation

The results for differentiation are given in Table 5. The questions on differentiation included two questions on limits (Q26 and Q33) and two questions on application of differentiation (Q24 and Q34) (Table 5). Although determination of maxima and minima of parabola is included in all curricula, all cohorts performed poorly on the question based on the maximum of a horizontally shifted parabola (Q24). The TKC cohort performed best in determining the limit of a hyperbole (Q26), and the CAPS cohort performed best in the question based on the interpretation of the derivative as the slope of a tangent line (Q34).

Overall performance

The results for the average performance on all the questions are given in Table 6. There are two sets of comparisons: one including geometry results and one without the geometry results. The former shows a decline in the overall performance of the NCS curriculum with a medium effect of 0.56 with respect to the TKC curriculum, and of 0.55 with respect to the CAPS curriculum. When disregarding the effect of the shift of Euclidean geometry to an optional paper in NCS curriculum, the effect becomes smaller, namely 0.38 and 0.29, respectively.

Table 5: Question by question comparison for differentiation

Question		Mean (%)			*d*-value			*p*-value
Number	Description	T	N	C	T/N	N/C	T/C	
24	Maximum value of $y=-(x-2)^2$	34	34	32	0.00	0.05	0.05	0.680
26	Limit of hyperbole	50	30	27	0.40*	0.06	0.46*	0.000*
33	Finding limit for $\frac{0}{0}$ case	47	42	55	0.11	-0.27*	-0.16	0.000*
34	Differentiation as slope of tangent line	52	54	63	-0.04	-0.19	-0.23*	0.001*
Average for differentiation and limits		46	40	44				

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and an asterisk (*) in the* d*-column indicates a small effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative d-value indicates a better performance by the group mentioned second.*

Table 6: Comparison on overall performance

	Mean (%)			*d*-value			*p*-value
Geometry	T	N	C	T/N	N/C	T/C	
Included	66	57	66	0.56**	-0.55**	0.01	0.000*
Excluded	65	59	63	0.38*	-0.29*	0.10	0.000*

T, TKC (2008 cohort); N, NCS (2009 cohort); C, CAPS (2015 cohort)

Note: An asterisk in the p*-column indicates an acceptable statistically significant difference (*p*<0.05), and asterisks in the* d*-column indicate a small (*) or medium (**) effect in practical difference. A positive* d*-value in a column indicates that the group mentioned first performed better, while a negative* d*-value indicates a better performance by the group mentioned second.*

Discussion of results

The statistical comparison of responses to the individual questions in general did not yield considerable differences for the three cohorts. Responses for some questions were statistically significantly different according to the *p*-values, but most of these differences were not significant in practice according to the *d*-values. There was a slight drop in performance for the NCS cohort in relation to the TKC and CAPS cohorts, but the practical difference was small. The comparison of the questions testing algebraic knowledge showed small differences in practice for questions set on application of exponential rules, solving linear equations, working with different forms of quadratic equations, and solving and simplifying fractional equations and expressions, respectively. This was also the case for functions and graphs, trigonometry and differentiation. Noticeable exceptions were the questions set on the topic of geometry (with the NCS cohort performing poorest), the question on finding the remainder after division (with the TKC cohort performing best), and the question on finding the inverse of a function (with the CAPS cohort performing best). The poor performance of the NCS cohort in the geometry questions can be attributed to the transfer of some topics of Euclidean geometry to an optional paper. In our sample, only 35% of the students of the 2009 NCS cohort wrote the optional paper in the NCS examination of 2008. In the NCS curriculum, the remainder theorem was omitted and students from this cohort had to rely on the algorithm for long division to find the remainder. Although the remainder and factor theorems are briefly mentioned in the CAPS curriculum, this cohort also struggled more than the students from TKC with the application of the remainder theorem. The high score of the CAPS cohort in the question on finding an inverse function with algebraic manipulation is difficult to explain, as finding an inverse function is included in all three curricula.

There were other notable results obtained for some questions, albeit not in terms of a practical difference in results. Although the absolute value function was omitted in the NCS and CAPS curricula, students from these cohorts could apply their knowledge of functions to identify the correct shifted graph of the given absolute value function and surprisingly the NCS cohort obtained the highest score for this question. Despite a scaling down in the rules of logarithms in the NCS and CAPS curricula, all three cohorts performed poorly in the question on logarithms. A low score was also obtained for the question on the simplification of a surd. A common denominator of these two questions is knowledge about algebra of functions, namely that in general $f(x+a) \neq f(x)+f(a)$ or that $f(xa) \neq a\,f(x)$. All three cohorts failed to intuitively identify the maximum of a quadratic function of the form $y=-(x-2)^2$ as zero. All these questions required a conceptual understanding of the mathematics involved and in spite of the intention of the OBE curricula to foster higher-order cognitive skills, all the cohorts performed poorly on these type of questions.

The comparison of the total scores of the three cohorts indicates a lower performance of the NCS cohort relative to the TKC and CAPS cohorts. This can partly be attributed to the omission of Euclidian geometry from the NCS curriculum, and the reintegration of geometry in the core curriculum of the CAPS curriculum. After the exclusion of the geometry results from the overall scores, the NCS cohort still performed slightly poorer.

Conclusions and recommendations

In this study, the mathematical knowledge which is mostly learned in Grades 10 to 12, and which we presume will have the greatest impact on success in tertiary mainstream mathematics, was compared for three cohorts representing three different exit-level school curricula. The comparisons of the overall results and the results of individual questions, which reflect topics of basic mathematical knowledge of Grades 10 to 12, show that in general there was little or no difference in practice for these cohorts. The only mentionable difference was in the domain of Euclidean geometry, in which the NCS cohort performed poorer, which can be directly attributed to the transfer of some topics of Euclidean geometry to an optional paper. The results signal that the omission of certain basic topics can be detrimental to the preparation of learners for tertiary studies where knowledge of these mathematical topics is important. If learners were not exposed to the gradual build-up of basic knowledge of a domain, it would be difficult to remedy the situation within a short duration. Developers of school mathematics curricula should be sensitive to the requirements of tertiary educational institutions regarding the basic mathematical knowledge needed by natural science and engineering students.

The introduction of new outcomes-based curricula led to the perception that students from these curricula enrol at tertiary institutions with poorer basic mathematical knowledge than those from traditional knowledge-based curricula. The results of this study indicate that this perception is not necessarily true. The samples in our study were fairly homogeneous in terms of demography, schooling and selection criteria, and the main difference was in their exposure to different school curricula. We suggest that other factors, such as school management or general societal changes or technological innovations, should be considered as an explanation for so-called grade depreciation. Finally, we want to point out that the results of the study do not reflect on changes envisaged by OBE curricula regarding teaching practices or the development of higher-order thinking skills. More qualitative studies will be needed to investigate these factors.

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Authors' contributions

S.F. initiated the study, formulated the introduction and theoretical overview, and was responsible for the literature section. M.H. performed the statistical calculations. Both authors contributed equally to the data collection, data analysis, interpretation of the statistical analyses, construction of the tables, discussion of the results and the conclusion, and write-up of the empirical study.

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