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South African latrunculid sponges

South Africa's Copyright Amendment Bill

Tracking microplastics in the ocean around South Africa

Developmental stress in South African fossil hominins

The Green Book: New online climate risk and adaptation tool

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Cover caption
Tsitsikamma pedunculata – a South African latrunculid marine sponge species (image: Patrick L. Colin and Lori Jane Bell Colin, Coral Reef Research Foundation). Davies-Coleman and colleagues present the multidisciplinary and collaborative research conducted on the diverse Latrunculiidae family of South African sponges in an Invited Review on page 26.

Reflecting on the nature of knowledge

In February 1905, George Potts (1877–1948) was appointed the first professor of natural science at Grey University College, Bloemfontein, then a constituent college of the University of the Cape of Good Hope. He had been trained in dairy agriculture in England and obtained a PhD in botany from the University of Halle (1902).[1] A council member of the South African Association for the Advancement of Science since its foundation in 1902, Potts was president in 1914 of Section C (bacteriology, botany, zoology, agriculture, forestry, physiology, hygiene and sanitary science). In his presidential address to Section C that year, Potts reflected that '…to anyone acquainted with university education, BA denotes a man of literature and education, a man of culture, but by contrast, when a BSc is given by the same University it implies a barbaric Goth, a technical expert, a mere specialist, more or less respectable, but not admissible into the cultured caste'[2].

Interestingly, Potts did not use the word 'scientist', and it may come as a surprise to many to discover that the term was first coined by William Whewell only in 1833 and was not in general use until many decades thereafter. Whewell, a renowned polymath and co-founder of the British Association for the Advancement of Science, invented 'scientist' (on the analogy with 'artist') to replace the phrase 'natural philosopher' that had, until then, been the professional appellation of those who worked in the 'sciences'.[3]

However, by 1959, exactly 60 years ago, the word scientist needed no introduction and practitioners no apology. That year C.P. Snow's Rede lectures were published as *The Two Cultures and the Scientific Revolution* and created vigorous debate around the primacy of the intellectual enquiry followed through differing academic mega-disciplines – the humanities and the sciences – to which Potts had alluded. There is no doubting that Snow, a Cambridge University PhD chemist at the Cavendish Laboratory, but also a novelist and playwright, over-emphasised the split between the two, but in the post-Cold-War world of the 1950s it was science and technology that dominated the future of human advancement.[4]

Snow's work spawned other investigations of the 'two cultures'. One of the most powerful was biologist E.O. Wilson's 1998 *Consilience: The Unity of Knowledge* (consilience, 'jumping together', is another Whewell-invented word). Wilson discussed the various attempts to unite the natural sciences that might be helpful in bringing them closer to the humanities as the 21st century dawned. Referring to the need for synthesis to aid understanding and progress in a world of complex systems, Wilson sought reductionist laws that would unite the two camps.[5] More gently, Stephen Jay Gould's posthumous *The Hedgehog, the Fox, and the Magister's Pox: Mending and Minding the Gap Between Science and the Humanities* (2003) focused on aspects that were common to the two, not what divided them. These included the possibility (and the thrill) of discovery, creative thinking and the need for evidence-based knowledge. The dichotomy, argued Gould, was a false one.[3] The most recent contribution to this stream of thinking is David Lowenthal's *Quest for the Unity of Knowledge*, a series of lectures that Lowenthal delivered at KTH in Stockholm in 2012.[6] The underlying theme of the book is the fundamental intellectual, and essentially human, conundrum of unity versus diversity, cohesion versus collision, certainty versus doubt. Unlike Snow, Wilson and Gould, however, Lowenthal does not promote any particular path to rapprochement, but explains how various fields of inquiry arose and how they danced around one another for centuries, vying for attention and credibility, the balance shifting with time, place and context. Which mode of knowing was superior or more useful? 'Deterministic generalising' or 'real-life uncertainty'? 'Lumping or splitting'? The general or the specific? The search for order or celebration of disorder?

All too often, we pursue research rather narrowly, without time or opportunity to step back and reflect critically on the philosophy of the knowledge in which we engage and that we aim to produce. I hope that the *South African Journal of Science* will provide a vehicle for discussions on this topic within the context of our country and our continent at a critical time when reliable, creative knowledge in all fields is vital to our continued well-being and the Journal welcoming to all scholarly endeavours.

As incoming Editor-in-Chief, I look forward to working with the multidisciplinary and talented team of Associate Editors, and with Linda Fick, Managing Editor, and Nadine van der Merwe, Online Publishing Systems Administrator, together with Himla Soodyall, Executive Officer of ASSAf, and the Editorial Advisory Board. I thank John Butler-Adam, the outgoing Editor-in-Chief, for his generosity and kindness while I have been taking over the reins from him, and salute him for his energy, efficiency and dedication during his tenure of office that has seen great strides in the quality and reach of our journal.

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CSIR launches novel online climate risk profiling and adaptation tool: The Green Book

The Council for Scientific and Industrial Research (CSIR) has recently launched a state-of-the-art online climate risk profiling and adaptation tool to assist municipalities across South Africa to assess their risk and vulnerabilities, and respond by adapting settlements to climate change. The Green Book looks forwards to the year 2050 by projecting settlement growth combined with quantitative, scientific evidence of the likely impacts that climate change will have on South African towns and cities and its key resources. The tool provides appropriate adaptation measures to be considered for implementation towards the development of climate resilient settlements. The ultimate goal of the Green Book is to contribute to resilient, sustainable and liveable South African settlements through climate change adaptation. Co-funded by the Canadian International Development Research Centre and the CSIR and produced in collaboration with South Africa's National Disaster Management Centre, the Green Book is the result of a 3-year initiative. More than 50 researchers and numerous stakeholders and reviewers were involved in producing the Green Book and reviewing its findings.

There has been a proliferation of weather-related disasters globally and an increase in associated damage in terms of geographical extent, size of affected population and economic costs.[1] The rapidly changing climate is a key global challenge that needs action from all spheres of society. Environmental risks – namely extreme weather events, climate change mitigation and adaptation policy failure, and natural and anthropogenic environmental disasters – are currently ranked among the top ten global risks in terms of likelihood and impact.[2]

South Africa has not been spared from the impacts of climate-related disasters in recent years (Figure 1). Extreme weather events observed over the region have resulted in increased frequency and intensity of fires, floods, hailstorms and droughts.[3] The severe drought that threatened to leave more than 4.2 million residents and businesses in Cape Town without water between April and June 2018 is an indication of the vulnerability of the country to climate change. The economic cost associated with the drought for the 5-month period from January to May 2018 was in excess of ZAR1.2 billion,[4] while damages from the Knysna fires and storm-related flooding in Cape Town in the 5-month period from June to October 2017 is estimated to have cost more than ZAR4 billion. Other parts of South Africa were also gripped by the multi-year drought between 2015 and 2018. Vegetation greenness indices derived from satellite data revealed that six of the nine provinces were experiencing drought conditions in 2015.[5]

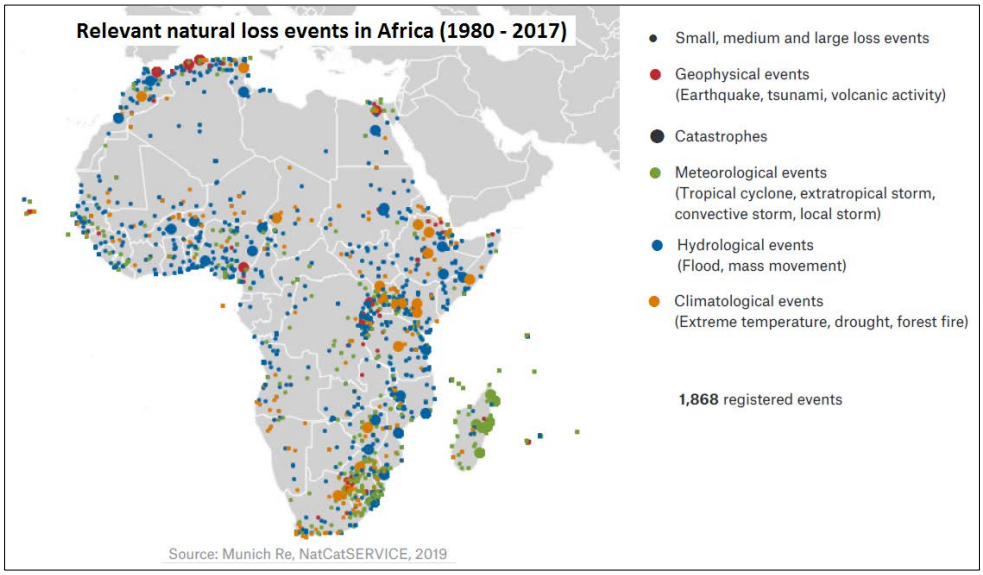

Figure 1: Loss incidents in Africa as a result of natural disasters,1980–2017.[6]

The current development trajectory of many settlements in South Africa is one of urbanisation combined with poor economic performance and growth. This tendency diminishes the coping capacity of many municipalities to deal with climate change and its impacts, and exacerbates the vulnerability and exposure of people and places to social, economic and environmental shocks. The increase in the intensity and frequency of hydrological, meteorological and climatological hazards is furthermore threatening the livelihoods of many vulnerable people as well as the development gains made by local government. Disregarded, these factors have the potential to significantly increase the risk of loss of lives, livelihoods and economic assets.[7] The role of adaptation planning is thus vital in reducing the exposure of municipalities, settlements, neighbourhoods and infrastructure to the potentially devastating impacts of climate-induced hazards.

The Green Book made a number of novel and groundbreaking scientific advances in the fields of climate change, risk and vulnerability. Key advances and significant research findings include: (1) a set of detailed projections of future climate change covering South Africa at an 8x8 km^2 resolution – the most detailed projections of future climate change available for the entire country; (2) new models to quantify the impact of climate change on the exposure of South African

settlements to various hazards (including drought, wildfires, inland floods and coastal flooding); (3) a vulnerability assessment framework and set of indicators to profile all 213 local municipalities in South Africa based on four unique statistically developed indicators, 1637 settlements based on six unique indicators, and two spatial multi-criteria indicators that capture vulnerability on a neighbourhood level; (4) a population potential growth model to forecast settlement growth across South Africa at a 1x1 km^2 resolution – the first settlement population growth model to be developed on the African continent; (5) risk profiles that provide temporally dynamic risks for each municipality and settlements in South Africa for the present and a 2050 future; and (6) a menu of customisable adaptation actions that brings together mutually reinforcing planning and design actions appropriate for the South African context and local planning function.

The research was conceptualised from a strong disaster risk reduction and climate change adaptation science base, grounded in the conceptual framework and definitions of the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change Working Group 2.[8] A framework, approach and set of terminologies that places the concept of disaster risk at its centre (Figure 2).

The Green Book combines several research techniques, analysis methods, models and approaches from various domain disciplines into a coordinated and coherent product, capable of responding to the impending impacts that a shifting climate and urbanising population will have on settlements and key resources. The interdisciplinary nature of the Green Book, which combines high-resolution scientific evidence with adaptation solutions, makes this one of the most novel, innovative and information-dense research platforms about disaster risk and climate adaptation planning on the African continent.

The main output is the Green Book online interactive tool to support long-term municipal planning with the development of climate-resilient settlements, available at www.greenbook.co.za. The Green Book website is structured into three main components:

1. The first component is a series of interactive national story maps for coastal flooding, floods, wildfires, drought, settlement vulnerability, urban growth, climate change, the economy, agriculture, forestry and fisheries, surface water and groundwater. Users are able to browse through these story maps to learn more about the research methodology, findings and recommendations, as well as to access the technical reports and interactive data sets. The 11 story maps can be accessed at https://greenbook.co.za/story-maps.html.
2. The second component is the municipal Risk Profile Tool – an interactive tool that grounds the adaptation process in scientific evidence of the risks each local municipality in South Africa is likely to face under a changing climate by 2050. The Risk Profile Tool provides temporally dynamic risk profiles for each municipality and its settlements in South Africa. These profiles provide information on vulnerabilities, population projections, exposure to climate hazards, and the impacts of climate change on some of South Africa's municipalities' key resources. The Risk Profile Tool is available at https://riskprofiles.greenbook.co.za/.
3. The third component is the municipal Adaptation Actions Tool – an interactive platform to support adaptation planning in local municipalities. The Adaptation Actions Tool provides a range of planning and design actions for consideration to adapt settlements to the likely impacts of climate change, to climate proof settlements, and to reduce exposure and vulnerability to hazards, and thus the risk for disaster. Guidelines for selecting and prioritising adaptation actions to the local municipal context are also provided (https://greenbook.co.za/adaptation-support.html). The Adaptation Actions Tool is available at https://adaptationactions.greenbook.co.za/.[7]

Complementary to the Green Book is *The Neighbourhood Planning and Design Guide* (the Red Book), developed by the CSIR for the Department of Human Settlements. The Red Book is aimed at built environment practitioners, and it supports the development of sustainable human settlements by providing practical information related to the planning and design of the services and infrastructure typically provided as part of a neighbourhood development project. Whereas the Green Book proposes a basket of mutually supportive adaptation interventions to be integrated into a range of local planning instruments to adapt settlements to climate change risks in the future, the Red Book provides more detailed design guidelines for some of these interventions e.g. stormwater design.

The Green Book has been received with much anticipation and enthusiasm by public, private and NGO organisations involved in the climate adaptation field. The South African Department of Environmental Affairs, the National Disaster Management Centre and Santam are committed to partner with the CSIR in Phase II of the Green Book. This phase will focus on rolling out the Green Book for implementation at municipalities most at risk, identifying gaps in research and development of this kind, and building the capacity of officials and departments to deal with climate change adaptation.

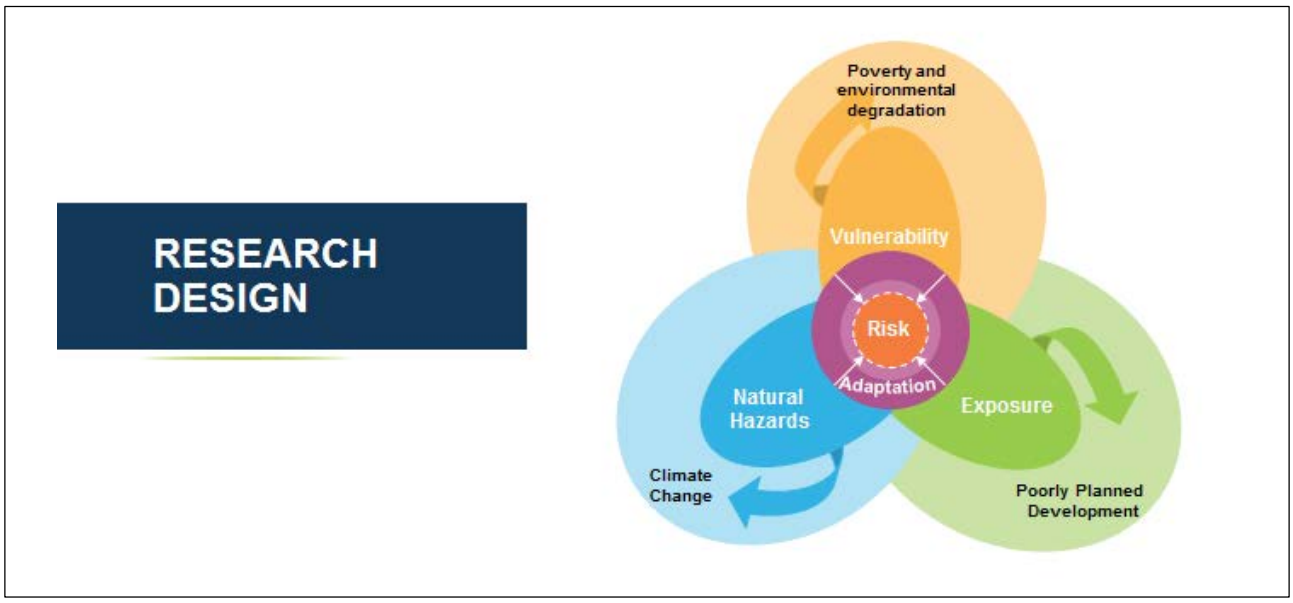

Figure 2: Green Book research design and terminologies (adapted from Niang et al.[8]).

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South Africa's Copyright Amendment Bill: Implications for universities

'Free to Reproduce, Free to Exploit' was first published in *The Conversation* on 14 March 2019.[1] *The Conversation* encourages republication with acknowledgement and *The Star* republished the article on 20 March 2019, changing the title to 'Opening Door to Plagiarists'.[2] Ironically, attribution was missing from *The Star's* version. Perhaps this omission was a sub-editing error? Or maybe it was mischievous on the part of *The Star,* to prove a point on the very day that the National Council of Provinces had approved the Copyright Amendment Bill?

Plagiarism

The point arising from *The Star*'s headline is that the Copyright Amendment Bill might open the door to plagiarism, non-attribution and 'free' reproduction of academic research and data and impinge directly on established rights. The contradiction is clear: *The Conversation* is sponsored by universities that are paying for subscribers to read for 'free'.

The Conversation article was reproduced on Moneyweb. Responses to online stories tend to take on lives of their own as writers muse about what they are reading. One Moneyweb respondent, who no doubt expects his own labour to be compensated at market value, insisted that all information, including academic research publications, must be made free. He is thus denying the right of authors to also earn from their work, and publishers to remain viable.

The real question is: who pays for someone else to consume for 'free'? The issue for the Academic and Non-Fiction Authors' Association for South Africa (Anfasa) concerns sections of the Bill that sanction free use 'for education'. This applies to Clause S.12D that permits educational institutions to engage in product substitution. Substitution involves assemblages of previously published extracts for course packs without permission or compensation to the authors and publishers of those works. As copyright lawyer Andre Myburgh observes, this section 'will also allow for wholesale cut and paste of content from copyright works into assignments, portfolios, theses or dissertations', thus promoting plagiarism. Moreover, he observes that such compilations could be used for personal use, and also 'library deposit or posting on an institutional repository'. For researchers whose value is often measured via the currency of citation, the Bill now enables reproduction to be done without permission with the author's name only having to be stated, worryingly, 'as far as is practicable'[3]. Citations will, under these circumstances, lose their meaning for South African based academic authors. Universities that internally disburse research funds based on citation metrics may need to revisit their policies.

Beguiling discourses

Of concern also to the academic sector are the beguiling discourses, both populist and academic, swirling around this Bill. The Parliamentary process has been described by a Professor of Law as 'shambolic', that the Bill was railroaded for political reasons, and that the state ignored voluminous cautionary submissions from the copyright, author, film, music, arts, software and publishing communities.[4] The pro-Bill discourse has been supported by the not-so-subtle infiltration of the Trumpian 'fake news' narrative emanating from ReCreate ZA, a group of 34 people claiming to represent South African 'creators'. ReCreate's lobbying for the Bill received preference from the ruling party in Parliament over the nine national organisations representing the above creative sectors. ReCreate, in fact, was established to lobby for the Bill so as to retain the exceptionally wide copyright exceptions now labelled as 'creator rights'.

ReCreate's general invitation (14 March 2019) to a Panel Discussion in Cape Town on 19 March organised by them, was expressed thus: 'Although the Select Committee has applauded the Department of Trade and Industry on its public participation process and its attempt to keep all stakeholders in mind during this process, there has been an upsurge in efforts to prevent the Bill from being passed through the spreading of *false* information' (emphasis added).

Numerous commentators have revealed that ReCreate seems to be in the palm of the not-so-hidden-hand of Google and is associated with the architect of a US study published by the Program on Information Justice and Intellectual Property. This Program calls for copyrighted materials to be exploited at no charge by the tech giants.[5] During the August 2017 Parliamentary public hearings, Sean Flynn, one of the authors of the study who was present in addition to many publisher organisations, claimed that a causal relationship exists between countries that have 'fair use' and other 'open exceptions', and a supposedly advanced state of innovation in those economies. The Chief Economist of the Phoenix Center for Advanced Legal and Economic Public Policy Studies, George Ford, has, however, totally discredited the Flynn and Palmedo Google-funded study. Ford concludes that their statistical results 'are merely the consequence of basic errors in both the design and implementation of the empirical analysis, rendering spurious correlations'[6]. Further, Ford alleges many errors in the study, which disqualifies it for policymaking purposes. Myburgh, who was called as an expert witness by Parliament, argued that Flynn's justification of the revised draft[7] accepted by Parliament in December 2018 relies on 'mere slogans substituting for academic consideration'[3].

Flynn advocates for the diminishing of author's rights and the strengthening of 'user rights'. Such rights will benefit only the big tech firms, approving Google's opportunistic phishing for content across the world for 'free' uploading onto the Internet. This content, the outcome of hard-earned labour by authors and creators of all kinds, is then used to attract paying advertisers who are targeting web browsers. No financial benefit is returned to authors or their publishers or the institutions that employ them. So 'free' means at a real cost to author, publishers and universities, who keep the research economy lubricated via the web.

The Google effect

Google Scholar has positioned itself as being the most comprehensive of all tracking devices within the academic monitoring and metrics field. However, Academia.edu, unlike Google, has been able to partly monetise scholarly writing through its Premium feature via which users can retrieve specific data analytics on their readers. Academia.edu is a dot.com operation, not an educational one despite its '.edu' tag. Scholars who provide free data to for-profit companies like Academia.edu are not participating in an open-source environment, thus making our Bill rather ludicrous.

Google's advantage is that it is better able to trawl the Internet and find both publications and citations. But unlike Scopus or Clarivate Analytics, Google applies fewer quality checks. Google is more comprehensive in that its metrics include theses, reports and unpublished materials. Monetisation is linked to traffic attracted – dependent on quantity and quality of content. The larger a firm's data sample, like Google's, the greater is the relevant data that can be mined, captured, stored, processed and commoditised for onward consumption.

Content may be freely accessible, but because access now is mediated by centralised agencies, the process is not truly fair or free. International firms that capture, analyse and exploit huge volumes of data act as the gatekeepers of our media and communications networks, including academic sharing sites. This information imperative is perhaps what Flynn advances in his argument that content freely harvested from publishers will benefit big tech firms, and thereby boost national innovation. Academics get a wider readership, Google gets more traffic, while the universities that sustain the research publication enterprise mainly get exposure – but no income.

This situation is unacceptable. Academics uploading their materials to sharing spaces will in due course be charged to access it, or their uploaded materials will be mined for sale in some manner, whether to advertisers or to other interested parties. As such, these sites are predicated on a parasitic relationship with public education. Academics and their employers are thus labouring without remuneration to help build privately owned platforms by providing the aggregated input, data and attention value. These venture capital enterprises are monetising communication between academics within their networked Internet domains, not providing them free.[8] What the proponents of the Copyright Amendment Bill are really supporting, then, is the commodification of publication sharing, but denying that this is what they are advocating. This is said not to condemn these sites outright as academically suspect, but simply to explain that their business models have implications for academic work and the ways in which researchers imagine themselves to be autonomous of these processes and incorrectly assume that they are participating in an open access commons.

The dilemma of creator rights

The dilemma for South African publishers is that the Bill removes their ability to protect authors' rights, because Clause 33 gives the Minister the right to prescribe compulsory and standard contractual terms to be included in all agreements and applied across all sectors of all creative industries. In the USA, authors can take legal action against copyright infringements, whereas the same legal recourse stipulation is not offered in the South African Bill. Together with the blanket contract and override powers assigned to the Minister in Clause 34, the local Bill pushes South Africa back into a darker, more vulnerable age, with hardly any protection for authors' and creators' rights.

Anfasa points out that what formerly were termed 'user rights' are now relexified by ReCreate and Flynn as 'creator rights', permitting the free reproduction of copyrighted work for educational and other purposes considered to be 'fair'. In other words, the 'user' has become the 'creator' by means of being able to electronically reproduce materials, feeding off and exploiting for gain other authors' creativity and products.

ReCreate appears to target DALRO, a reproduction rights organisation based in Johannesburg that works in the interests of authors, by implying that it does precisely the opposite. Yet, no evidence has been presented that DALRO has not served authors and publishers appropriately. Organisations like DALRO reduce the administrative load of universities by acting on behalf of publishers and authors. If every individual author in the future has to contact every department in every university globally to audit the use of their individual intellectual properties it is certain that everyone will sink under the ensuing administrative weight.

The ReCreate meeting invitation mentioned above was couched in 'fake news' discourse as its claim – by innuendo – that Anfasa and the clear majority of the delegates who spoke at the Johannesburg symposium had succumbed to 'false information' with regard to the potential effects of the Bill.[9] Where *The Conversation* articles are cross-referenced, many offering critical analyses penned for the lay reader, the ReCreate 'othering' discourse lacks any dialectical characteristics. It claims divine right by delimiting the discourse within its own narrow frame of reference that seems to echo those of Google and other tech phishers. Any discussions other than those supporting the Bill are thereby simply deemed to be 'false'. Academics and scholars should be very worried.

The anticipated effects

A list of articles critical of the Bill would take far too much space here, but they include a financial impact study that predicts significant financial and job losses for the publishing sector.[10] Among the supposedly gullible 80 delegates at the Anfasa symposium were law professors, copyright lawyers, scientists, journal editors, publishing executives, commissioning editors and other stakeholders. The two ReCreate delegates were unable to convince this diverse professional audience as to why the copyright exceptions in the Bill should cause South African authors, publishers, universities and, ultimately, the taxpayer, to subsidise the tech companies.[9] When information is no longer a good with a monetary value, it can no longer be traded. Killing the creator of information is in this scenario the next logical step for Flynn and his starry-eyed artificial intelligence cohorts who cannot 'see the wood for the trees'.[11]

ReCreate contends that the Bill will help propel South Africa's copyright law into the digital age. Indeed it will as an unpaid export, because it will then do Google's bidding and impoverish South African research and imperil our publishing industry – both academic and private.[12] It will also exert negative multiplier effects across the economy, as one cannot sell and tax what has been given away. The impact on GDP and international competitiveness as we head into the so-called Fourth Industrial Revolution will be incalculable.[13]

How can the Bill, as ReCreate claims, elevate South Africa into the digital age given that it positions the country in contravention of several international copyright treaties. Internationally, authors' rights are protected by the Berne Convention. And, from 26 March 2019, the European Parliament's Copyright Directive in the Digital Single Market, in total contrast to the South African Bill, allows benefits sharing between online content creators and their Internet hosts, thus potentially easing cooperation between the two groups. In other words, the EU Directive includes key provisions for the publishing industry and authors who will now receive a share of the revenue that press publications generate online from the use of their work.[14] The operating principle behind this directive is appropriate and proportionate remuneration for authors.

Copyright exceptions in the EU Directive have been set up to enable fair text and data mining, by offering publishers direct control over re-use of their content by Internet platforms, such as online news aggregators. Article 11 sets up a 'link tax', which generates income for content creators, while also requiring websites, which mainly host content created by others, to ensure that all copyrighted materials are posted with due permissions, or face litigation. The implication for publishers and, in turn, universities, is clear: new income streams are opened rather than closed and donated to big capital, as will be the case in South Africa.

Implications for South African universities

ReCreate claims support for the Bill from South African universities, yet our university presses, the first likely casualties, are amongst the most vocal critics of many aspects of the Bill. The Bill will affect research budgeting and performance management and will imbalance the value chain as authors will themselves now pay for publishing, rather than

readers – a cost that is currently absorbed by libraries and spread across global readerships. If copyright law aims to balance the interests of creators with the needs of society, then why does the Bill ignore the interests of creators, ironically the very constituency that ReCreate claims to represent. For universities, this means that author-pays (for publication) so that readers can read 'for free'. The likely impact on the unique South African research economy remains to be assessed, but what is certain is that research funds will now be consumed by massive article- and book-processing charges.

In turn, fewer items will be published because few academics have access to such resources. University presses will be affected, possibly having to merge, cut their inventories and commission fewer books. International publishing partnerships will stall as foreign firms will not want to lose rights to their products. Local textbook production will cease, and with it will end any decolonisation of curricula as international titles written for students everywhere in the world will replace them. Under this scenario authors *and readers* will have less choice, less access and less localisation of content. Many of the 323 self-sponsored South African journals that rely on reproductive permissions to cover their costs might cease publishing, again affecting the scale and scope for South African academic authors whose performance notches and promotions often are linked to publishing output. The Department of Higher Education and Training's publishing incentive, on which universities have become reliant for variable income, could be seriously disrupted, affecting the distribution of resources internal to institutions.

In terms of sustainability locally, the funding available for article-processing charges for open access opportunities to African authors is extremely limited when compared to their overseas counterparts. Globally, 250 funds support academics applying for open access charges, although they are mostly in Europe and North America, with only three funders of article-processing charges (for journals) and two funders of book-processing charges available to Africans.[15] Universities and their authors will now have to fill the gap.

Public participation?

If the 'public participation process' was as open as Flynn and ReCreate insist it was, why is it that the entire publishing sector, as well as the film and music sectors, feel ignored, alienated and bruised? These direct stakeholders have argued that the same exceptions simply cannot apply evenly across all expressive sites: literary, artistic, film and video, musical, sound, published editions and computer programmes. They are each different, with different value chains, with different kinds of contracts.

The bruising occurred, because, as Polity's Deepening Democracy Through Access to Information site misspelled it in its Freudian slip headline, 'NCOP Committee Applauds Board Participation Of Stateholders [sic] On Copyright Bill'[16]. Language does have power, but sometimes the 'fake' will out.

The bias is clear. Shambolic indeed!

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A new era for marine forecasting in South Africa

The International Convention for the Safety of Life at Sea (SOLAS) was established in 1914 as a consequence of the sinking of the RMS *Titanic* in 1912, one of the deadliest peacetime marine disasters and which resulted in the loss of more than 1500 lives. However, the International Meteorological Organisation, born as a direct result of an international maritime conference in 1853, had already initiated weather information for shipping safety, but this was information that the RMS *Titanic* did not believe it needed to heed. In 1950, the World Meteorological Organization (WMO) took on the role of the International Meteorological Organisation, enhancing SOLAS, and establishing METAREAs (geographical oceanic regions in which meteorological information is transmitted to ships) with global responsibilities.

South Africa is responsible for providing marine weather-related information and warnings for the world's second largest METAREA (METAREA VII), which extends from 6°S to the Antarctic continent and from 20°W to 80°E (note from 55°E to 80°E, only south of 30°S falls within the South African METAREA). SOLAS products related to extreme and potentially life-threatening events are disseminated through the Global Marine Distress and Safety Service (GMDSS) and this dissemination is a key objective of the South African Weather Service (SAWS).

Moreover, the SAWS helps neighbouring coastal African countries to assist the ever-growing number of non-SOLAS vessels (i.e. vessels that do not typically undertake international voyages, but must adhere to safety standards according to their size, type and operations). The rapidly increasing coastal populations around the world that are at risk from marine hazards are also an emerging priority. An example is the recent, and devastating, Cyclone Idai, which tore through the port city of Beira in Mozambique. But are we at SAWS doing the very best we can? We believe that the Marine Unit and our novel forecasting system is innovative and extremely helpful.

The oceans are extensively used for commerce and recreation. Shipping is by far the dominant method for global trade and trillions of US dollars pass through the world's harbours annually. The oceans also provide mineral resources such as gas and oil, while precious minerals such as diamonds are mined on the seafloor. Through recreational activities (e.g. ocean liners and sailing yachts, surfers, kite-surfers and beach-goers), the coasts of many countries receive millions of visitors every year – an industry which supports local communities and economies. And, it should be noted, in most countries that have a coastline, much of the population typically lives on the coast.

To manage these issues of safety, an efficient and dynamic marine service is needed – one that can provide essential information that ranges from daily forecasts of passing weather systems and that might impact on safe shipping, to the more extreme and potentially life-threatening events. The latter might include storm surge and destructive wave activity along the coast, hazardous seas in the METAREA, or Marginal Ice Zone navigation and warnings in the Antarctic region.

Marine services not only contribute to shipping information and safety, but also provide information to coastal engineers and environmental managers about best practices of ensuring coastal longevity. Population trends and changing climate conditions have increased the vulnerability of coastal populations and infrastructure, and these are amplified by the effects of weather and conditions in the ocean. Technology has also changed rapidly in the last decade, vastly improving the services historically provided. In addition, effective access, dissemination and alerting systems are critically important for a national meteorological service. For no matter how accurate products are, they must be used wisely in decision-making processes. The ability to facilitate reliable, timely access to information is critical to ensuring that products and services are relevant.

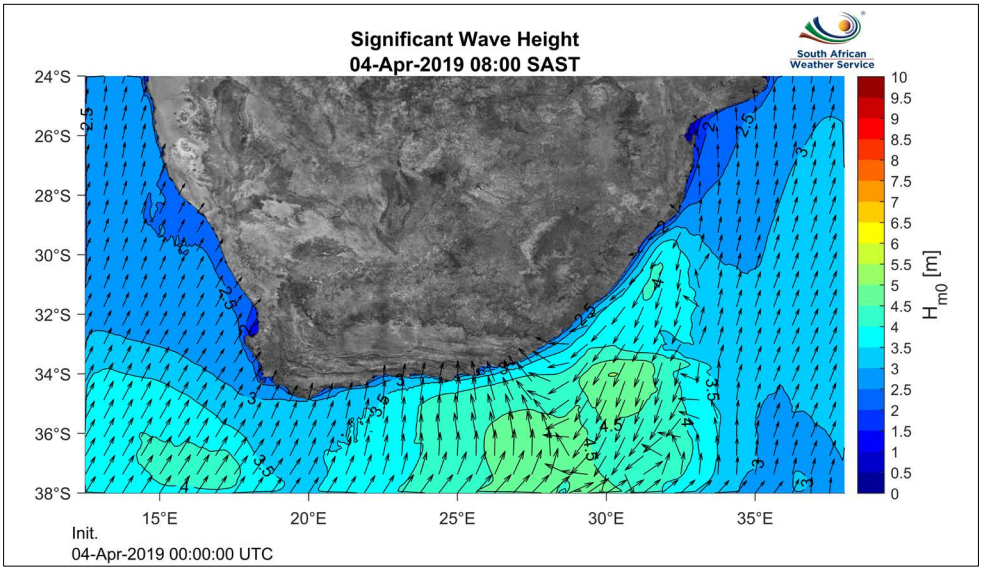

Figure 1: Significant wave height forecast for the entire coast of South Africa.

The Marine Unit of the SAWS has developed a dynamic marine forecasting website for all coastal and marine users. The website is primarily used to disseminate operational high-resolution wave, storm surge and tidal forecasts (72 hours), and additional products are planned as the Unit and its website develop. Figure 1 illustrates the regional wave forecast with a high-resolution snapshot of the Cape Peninsula (Figure 2). This forecast allows coastal and

offshore ocean users, disaster management structures and municipal authorities to prepare for potentially damaging situations in real-time. Our forecasts will also assist small-scale commercial fishermen and recreational ocean users, such as surfers, kayakers and long-distance swimmers, to plan their marine activities in the short term. In addition, the website showcases the research that underpins the Marine Unit's products and services. Projects range from those related to infrastructure and observations (such as ocean surface drifters, Argo floats and sea-ice drifters and observations) to the high-resolution numerical prediction of water levels and waves.

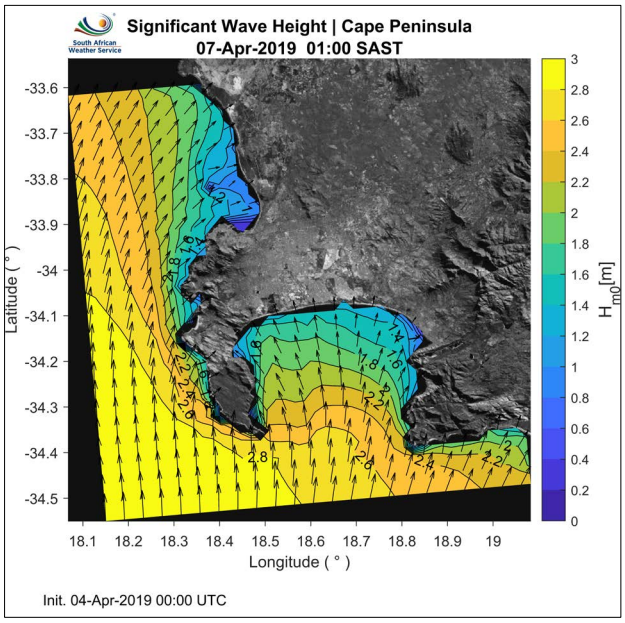

Figure 2: High-resolution significant wave height forecast for the Cape Peninsula.

The Marine Unit is a young and energetic team, comprising an applied mathematician, physical oceanographers and marine meteorologists, with technical support. The Marine Master Plan that explains the Unit's objectives and deliverables is new, having been approved by the Executive Board of SAWS little more than a year ago. Yet already the Unit has doubled in capacity and has exceeded expectations within the first year. In addition, the Unit, working under the technical guidance of the WMO and the International Oceanographic Commission, has been requested to develop a marine services implementation plan that is coherent with the implementation plan of the WMO Strategy for Service Delivery and considers practices from the Global Data Processing and Forecasting System.

Users are finding ways to gather and display information in a manner that meets their own needs, regardless of the SAWS's original intention. The way in which products and services are delivered has to change to accommodate risk-based products that are linked to the capacity of users to interpret information. To improve service delivery to users, marine meteorological and climate observations and research must precede the rollout of any new or improved operational products. Rigorous testing of predictive models must occur prior to the use of the product in an operational setting, once their configurations have been improved. Thus, ongoing research should be seen as integral to the service delivery process.

Strong operational and academic collaborations underpin the Marine Unit's success and range from universities and research councils and academic institutions, to environmental consultancy groups, local and national government departments, and coastal engineering companies. The Unit is keen for all users of met-ocean information to peruse the website at www.weathersa.co.za/marine/. A formal survey of different user communities will be initiated shortly to determine the usability and general perception of the portal. Through the survey we hope to make improvements as needed, and our ideal is to service as large a met-ocean community as possible. Informally, marine users have already commented favourably on having 'old-school' synoptic charts and SOLAS communications available under the 'Observations' tab because many seafarers still rely on these systems for their work, particularly further out from the coastline. Other users have been pleased with the coastal automatic weather station map available under the 'Products and Services' tab (observational data), which assists students, engineering teams and coastal users. Through the development of a map and with relevant feedback from stakeholders, the Marine Unit is also able to motivate for additional automatic weather stations in key areas, such as False Bay, where currently only one station, at Strand, is available. The Unit has also begun work on sea-ice observations and, in July 2019, will be deploying sea-ice drifters to understand how sea-ice drifts in the Antarctic region directly south of South Africa may help us to forecast sea-ice movement in the future. Finally, the Unit aims eventually, through the portal, to make available for all users daily, a Forecaster's Synopsis which will summarise what is forecast through the wave, storm surge and tidal forecasts, coupled with information from coastal observations and meteorological forecasts. During extreme events such as storm surges during which flooding of terrestrial regions, potential loss of life and damage to infrastructure may become a possibility, these forecasts will be updated more regularly to assist in informing disaster management and similar organisations.

Should you be keen to participate in our surveys, or would just like to provide feedback, please contact the Marine Coordinator, Tamaryn Morris at tamaryn.morris@weathersa.co.za. We look forward to continued and enhanced engagements with our coastal and ocean user communities.

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Programme for the development of weather and climate numerical modelling systems in South Africa

Weather and climate numerical models have been in use in South Africa for many decades, both in operational and research mode.[1] All the models currently in use for operational purposes in the country were developed in developed countries. South African scientists started participating in the development or improvement of weather and climate numerical models in 2002, after being inactive in the area for over a decade.[2] The regeneration of model development activities started at the University of Pretoria through a Water Research Commission funded project in which a dynamical core of a non-hydrostatic sigma coordinate model (NSM) was developed from scratch.[3] These activities served to encourage others in the country to also contribute in the model development space. The NSM was later extended to include moisture and microphysics schemes at the Council for Scientific and Industrial Research (CSIR) in collaboration with the University of Pretoria.[4,5] This model is currently only available for use in research mode; however, the underlying dynamics are similar to those used in an operational model used at CSIR.

Most other model development activities in the country build on existing modelling systems from developed countries. For example, Abiodun et al.[6,7] improved the dynamical core of the Community Atmosphere Model (CAM) to use a stretched grid with higher resolution over an area or process of interest while at Iowa State University and continued the development after moving to the University of Cape Town. Model development activities in the country also include the coupling of different components of the earth system. Beraki et al.[8] coupled the European Centre Hamburg Model 4.5 (ECHAM4.5) to the Modular Ocean Model 3 (MOM3) at the South African Weather Service (SAWS).

A recent development is the configuration of the first African-based Earth System Model at the CSIR, through a collaboration with the Commonwealth Scientific and Industrial Research Organisation (CSIRO).[9,10] The Variable-resolution Earth System Model (VrESM) became the first African-based model to register for the Coupled Model Intercomparison Project (CMIP6) in 2016. It uses as atmospheric and land-surface components the Conformal Cubic Atmospheric Model (CCAM) and CSIRO Atmosphere Biosphere Land Exchange (CABLE) models of the CSIRO, whilst the ocean component VCOM (Variable-cubic Ocean Model) was developed at the CSIR. Development activities are focused on different aspects of the earth system, including the carbon cycle, and the project will allow Africa to contribute global simulations towards the generation of Assessment Report Six (AR6) of the Intergovernmental Panel on Climate Change (IPCC) and the associated CMIP6. In 2019, the Global Change Institute of the University of the Witwatersrand launched a new programme in Earth System Model Development, with an associated postgraduate programme.

Despite model development activities beginning over a decade ago, the progress in model development activities in the country has been slow, and the number of people who truly understand models and can contribute to the model development exercise remains low. Discussions on possible collaboration efforts and information sharing amongst those working on model development started in 2017. The intention is that when model developers in the country work together, model development activities will be accelerated. Although the different organisations use different models, similar issues such as a lack of solutions for certain resolutions apply to all models. Some sub-grid schemes are used in a number of models, and so an understanding of the performance of such schemes when linked to different dynamics can be of mutual benefit to all organisations involved. Together, the different organisations can identify common training needs and co-organise training workshops to deal with known shortcomings in the country. Furthermore, through working together, the country can become an independent developer of weather and climate models (whilst strengthening collaboration in this field with international model development centres).

A workshop on model development was held at SAWS on 28 October 2017 during which researchers from SAWS, CSIR, University of Pretoria and University of Cape Town who have made contributions met to discuss ideas on how the country can accelerate model development activities. Prof. David Randall from Colorado State University in the USA, Prof. Robert Plant from the University of Reading in the UK, as well as Dr John McGregor from CSIRO in Australia were invited to contribute through an online platform and provide advice to the workshop delegates. Modelling activities taking place in the participating organisations were discussed, as were future plans to inform the development of a programme that aligns with the strategic objectives of each of the participating organisations/institutions. A plan was developed in 2018 and shared with individuals who have model development experience at the University of Cape Town, University of Pretoria, SAWS and CSIR and was also presented to the meteorological community in South Africa at the 2018 annual conference of the South African Society for Atmospheric Sciences.

The purpose of the programme is to establish an environment that will enable the weather and climate operational obligations of South Africa to be met using homegrown models within 10 years. The homegrown models will also be used for research purposes and to meet policy requirements such as the National Communications on Climate Change and National Adaptation Strategy.

The main goal of the framework is to ensure that there is a coordinated weather and climate numerical model development effort in South Africa which can lead to the following outcomes:

- South Africa becomes an independent developer of numerical weather and climate models.
- South Africa contributes to new trends in model development instead of waiting for others to develop schemes suitable for Africa.

- Local domain expertise on different systems such as African thunderstorms, aerosols and the Southern Ocean is incorporated into the models.
- A closer relationship between model developers at universities and SAWS to ensure that research conducted outside of SAWS benefits operational activities of SAWS, and earth system modelling at the CSIR and University of the Witwatersrand.
- Expertise is developed not only to identify biases and weaknesses in models, but to also improve models.
- Strengthened synergies between the institutions involved in model development and the Centre for High Performance Computing of the CSIR, towards also strengthening high-performance computing skills in South Africa.
- Increased support for postgraduate students working on model development activities at universities and hosting of some of the students by research organisations.
- Model development activities support policymaking and national initiatives.
- Improved understanding of local processes and hence improvement in models.
- Increased collaboration with model developers internationally.
- More opportunities for programming training necessary for model development.

The planned activities consider the past and ongoing efforts in the country, which will provide a good launch pad to enhanced model development. The implementation of the programme will be led by a steering committee comprising individuals from a number of participating local organisations and will also include two international experts as well as one PhD student. Contributions will be made in two main ways:

- Creation of models that are fully developed in South Africa. These may include atmospheric, ocean, land-surface and sea-ice models. This contribution includes model development that builds on existing models with a significant contribution from South Africa to the extent that South Africa can be considered as a lead in the development process.
- Participation in open/partnership model development activities internationally. This contribution will include model development activities in open-source models such as CCAM, Weather Research and Forecasting (WRF) and CAM, as well as somewhat closed/licenced models for which a formalised relationship is required before model contributions can be made.

International working groups focusing on models provide opportunities for the scientific community to discuss common issues in models. One such group is the Working Group on Numerical Experimentation (WGNE), which is responsible for fostering the development of atmospheric circulation models for use in weather, climate, water and environmental prediction on all time scales and diagnosing and resolving shortcomings. WGNE was jointly established by the World Climate Research Programme (WCRP) Joint Scientific Committee and the WMO Commission for Atmospheric Sciences (CAS). Another working group is the Panel on Global Atmospheric Systems Studies (Pan GASS) which is under the Global Energy and Water cycle Exchanges (GEWEX) project. Pan GASS facilitates and supports the international community that carries out and uses observations, process studies and numerical model experiments with the goal of developing and improving the representation of the atmosphere in weather and climate models. Model development activities in the country will consider work done by these international bodies and others. The model development activities will also be conducted in collaboration with partners globally.

Work will be conducted across timescales so that activities are able to benefit weather forecasting as well as climate predictions and projections. South African scientists are involved in a wide range of modelling studies, and some are related to the WGNE or Pan GASS identified topics, as well as the model intercomparisons undertaken through CMIP6 and Co-ordinated Regional Downscaling Experiment (CORDEX). Topics of interest which will be addressed using models with different complexities, including idealised models, are, among others:

- thunderstorms;
- direct and indirect effects of aerosols;
- stratospheric variability influence on weather and climate;
- mid-latitude synoptic storms prediction and changes under climate change;
- precipitation and temperature diurnal cycle;
- heatwave frequency, intensity and duration in the current and future climate;
- ocean-atmosphere and land-atmosphere feedbacks;
- stratospheric-tropospheric coupling problems; and
- baroclinic instability and baroclinic life cycles.

In diagnosing sources of errors identified in the simulations, sensitivity studies will consider different aspects of the model. The different areas to be considered are:

- convection schemes;
- microphysics schemes;
- atmospheric turbulence schemes;
- surface representation;
- interactions of different components; and
- dynamical cores and numerical methods.

Human resource capital development steps will be undertaken through postgraduate studies, and winter/summer schools to increase the critical mass with model development skills. Workshops, seminars and tutorials organised internationally will also be considered. The model development research will be conducted by scientists who are permanently employed at science councils and institutions of higher learning, postdoctoral fellows as well as PhD students.

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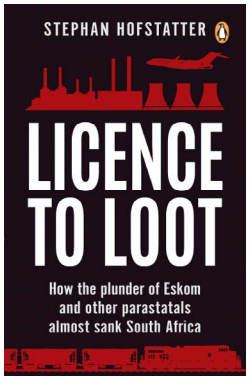

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Learning to doubt and challenge everything related to Eskom and other parastatals in South Africa

The dark cloud of corruption, mismanagement and, in many cases, unethical conduct in the political arena of the first decade of the 21st century in South Africa is examined in Stephan Hofstatter's book '*Licence to Loot: How the Plunder of Eskom and Other Parastatals Almost Sank South Africa*'. With a particular focus on Eskom and Transnet, Hofstatter aims to shed light on the state companies' years of failure. From the first word, it becomes apparent that the book will make the reader doubt everything said by anyone in the public sphere. The author's experience as an investigative journalist is crucial, not only in the provision of the facts, but also in taking the reader on a quest to discover the truth by putting the pieces of the puzzle together.

I suggest the book be read with a bookmark on the flowcharts of the different enterprises and companies associated with Eskom and Transnet given in the beginning of the book. I must admit that some of these linkages are subtle and perhaps no longer exist, but they are all critical in understanding and contextualising every 'story' and conceiving fully their wider impacts.

As in a fictional spy novel, stories and characters such as Jacob Zuma, Zwelinzima Vavi, Julius Malema, Shabir Shaik, Brian Molefe, Matsela Koko, Salim Essa and of course the infamous Gupta brothers (like ghosts, always present in meetings and events and agreements) take the 'stage' in an exciting story – one unfortunately not only *based* on true events. Zuma is portrayed simultaneously as a puppet in the hands of the Guptas and as a person acting only for his own benefit and that of his family; the reader is shown that Zuma and the Guptas were not the only 'villains' in the story, but that others played instrumental roles in the looting.

Hofstatter is excellent in connecting the dots by presenting facts in a timeline that, however, at times, can be pedantic: there are many details that do not always appear to the reader to be important. In addition, the timeline, especially in the second half of the book, becomes difficult to follow as it jumps back and forth for the sake of presenting crucial individuals' roles in the story.

The book is directed not only to readers interested in politics, economics or energy – it will appeal to the average South African who feels the responsibility to understand what happened and is happening in the political arena, especially in a year with national elections. The ways and methods of politicians should be transparent, ethical, lawful and publicly accepted for a democracy to function properly. In that sense, the book is a good contribution towards transparency, in that it encourages readers to be more critical in determining what to believe and what to challenge, as well as what should be avoided in the future for South Africa to survive the storm.

Chapter 1, 'Zuma's Dubai Bolthole': The introductory chapter takes the reader back in time with the unfolding of the purchase of Optimum by the Guptas in 2016 and the Nene saga in 2015. The interlinking of individuals and situations emerges as the events are presented as a historical timeline.

Chapter 2, 'President for Hire': The reader is taken back to 2008 and the ANC's newly elected president, Jacob Zuma, and preparations for the 2009 national elections. Flashbacks to events thus far indicate Zuma's involvement in corrupt activities such as Shabir Shaik's conviction, the Scorpions saga, the notorious arms deal, and his sons', Duduzane's and Duduzile's, financial adventures. In this chapter, Zuma's meetings with Zwelinzima Vavi and Blade Nzimande are already signs of the president's priorities.

Chapter 3, 'The DRC Moment': This chapter discusses Zuma's 2010 visit to the UK and what is referred to as the 'DRC moment' of Zuma's era. The complicated web of companies and deals within the mining sector – especially that related to the ArcelorMittal–Sishen scandal is important in this chapter. Shares changing hands, laws taken advantage of, and shady meetings in Saxonwold all have a common denominator: the Zuma and Gupta families.

Chapter 4, 'What the Driver Saw': The story continues with an interesting description of a key witness's diary on important people and their visits to Saxonwold and the Guptas in 2010–2011, accompanied by a report on the notorious family's attitude and behaviour. Among the frequent visitors to Saxonwold was Brian Molefe; we read more on his credentials and history in politics, and the role he played in numerous corrupt deals involving Transnet, Eskom and the government.

Chapter 5, 'Trains and Planes': This chapter begins with Transnet's importance to the South African economy as well as the challenges of its operation, amidst tendering processes that were tampered with and deals proposed 'under the table' in the name of Zuma, with serious repercussions to project value pricing. But who is Salim Essa – a shadow in all these deals or a protagonist?

Chapter 6, 'Sharing the Spoils': This chapter explains how Transnet embarked on a strategy to stimulate demand based on future projections of not only local but also global growth and demand of commodities. Amidst other economic events, these forecasts were optimistic, so much so that the investment was in a sense redundant. This situation can occur with any company (especially in the current uncertain economic conditions), but the chapter explains the peculiarity of this strategy in South Africa – with players such as China South Rail, the Guptas and Molefe, and McKinsey and many others.

Chapter 7, 'Indecent Proposal': This chapter takes the reader through a brief history of events leading to the 2008/2009 crisis, in a timeline parallel with that of Brian Dames' involvement with the national utility. Dames, the youngest chief executive in Eskom's history, made as his sole purpose the resolution of the problems with the old fleet and the management of the utility. However, he encountered political hurdles, primarily in the face of

Malusi Gigaba and other individuals from the Eskom board, until 'the last line of defence against the looters' was also gone.

Chapter 8, 'Making Hay': This chapter shows that the political involvement in Eskom and other utilities did not stop with Dames 'removal' in 2014. Tsholofelo Molefe (finance director of Eskom at the time – in 2005) had to face proposals for 'advice' to Eskom from various involved parties. Even though several objections were raised from within Eskom, this chapter shows that they made no difference.

Chapter 9, 'Turn Off the Lights': This part of the story follows the efforts – behind the scenes – to surpass the past problems, especially with coal supply, whilst corruption established itself, leading to the next load shedding in 2014. Last-minute coal deals made with politically connected companies to avoid another crisis (or with that as the excuse) created opportunities for further exploitation that brought Eskom to its first bailout by government in 2014; Eskom management's reasoning was that they were not allowed to charge 'cost-effective tariffs'.

Chapter 10, 'Tsotsi in the Boardroom': The chapter is devoted to Zola Tsotsi, 'Zuma's man at Eskom' and his role in the looting, and compares and contrasts what happened in the public eye with that behind the scenes, as well as what was discussed in parliament a few years later. Hofstatter provides thought-provoking facts, such as the 'approval requests' to the Guptas on the board and others. Those that were not *with* them, eventually became *against* them and exited Eskom.

Chapter 11, 'Stacking the Deck': The arrival of Brian Molefe at Eskom and his role in the story is presented in this chapter. The high expectations of him to sort out the problematic utility are discussed, as are the obstacles to those expectations materialising.

Chapter 12, 'Engineered Emergency': The coal market dynamics are again the focus in this chapter, coupled with the importance of accurate forecasting that enforces coal price and supply negotiations. The role of Exxaro and Optimum in the network of individuals and companies connected with Zuma and the Guptas is discussed subsequently. This chapter exposes a number of conversations in which the decisions of individuals placed in crucial positions were made on behalf of Zuma.

Chapter 13, 'Trillian's Billions': The usual team of puppeteers – well known by now to the reader (Essa, McKinsey and Trillian, Guptas) – brings more players into the game. This chapter details how Bianca Goodson and Mosilo Mothepu were used to enable looting by the network.

Chapter 14, 'Show Me the Money': The plot thickens once more and the buying and selling of companies through money transfers continues. The Optimum deal and its aftermath is in the spotlight in this chapter, with explanations of how a mine, that on paper was a liability, was turned into a money-making machine.

Chapter 15, 'Things Fall Apart': Thuli Madonsela's investigation was considered by many to be the beginning of the end. This chapter presents and explores the change in dynamics and behaviours after the investigation was initiated, such as how Molefe changed his claims.

Chapter 16, 'A Brazen Thief': From Molefe to Koko (and the business links of his wife), the Eskom leadership seems to be trembling in 2016. Molefe's retirement plans, however, do not show a 'clean face' in the saga. Lynne Brown openly criticises the Eskom board while 2017 is marked as the year that various media publish a series of leaked emails that shed more light on the story. The Cyril Ramaphosa presidency tries to clear the air in 2018 by removing involved parties.

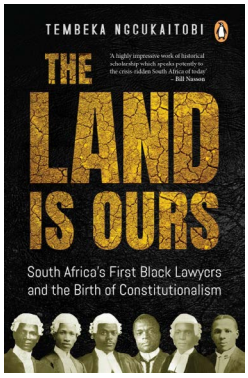
Chapter 17, 'Secrets and Lies': This chapter starts with describing the internal turmoil in Eskom and parliamentary political swordsmanship. Brown insists she was lied to, while behind the scenes Essa tries to get Daniels 'out of the game' by any means possible.

Chapter 18, ' Tea Money': Anoj Singh is at the centre of a number of scandals regarding Transnet and Eskom, all associated with the Guptas. Changing drivers at Eskom's steering wheel from Molefe to Dladla to Maritz also created its own consequences, as discussed in this chapter.

Chapter 19, 'On the Run': The first arrests in now infamous Saxonwold in the beginning of 2018, certain individuals leaving the country, and Zuma's resignation as President were the nodal points for the possible end to the looters' world. This chapter discusses the conditions leading to that day.

Chapter 20, 'Garden of Hope': Hofstatter discusses the status quo of Eskom: the debt, the corruption, the politics. He summarises the instrumental individuals and their role in the current problematic situation that has brought the South African economy to its knees. The book closes with the hopeful conclusion that '…the licence to loot has been revoked'.

BOOK TITLE:
The land is ours: South Africa's first black lawyers and the birth of constitutionalism



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Tracing the origins of South African constitutionalism

In this comprehensive and eloquent account of South Africa's first black lawyers and activists and the essential role they played in the struggle against racial oppression, Advocate Ngcukaitobi illuminates histories that have gone woefully unrecognised and underappreciated. Alfred Mangena, Charlotte Maxeke, Alice Kinloch, Richard Msimang and Pixley ka Isaka Seme are some of the trailblazers whose stories are chronicled in this impressive volume.

Some of the names, such as Seme, we have known in the context of the history of the formative years of the African National Congress. I suspect, however, that many of us were not aware of the parts these individuals, and others, played as legal practitioners and strategists who attempted to use law and litigation to challenge the copious violations perpetuated against black South Africans by the British colonists and the Afrikaner nationalists alike. Indeed, it appears that, until this volume, there has been insufficient recognition of these pioneering black legal intellectuals and practitioners who 'fought the good fight' in the face of tremendous obstacles and barriers. Ngcukaitobi has done us a great service by uncovering and resuscitating these histories and narratives.

He introduces us to the achievements and failures of these individuals, on personal and professional fronts, in addition to the political and legal battles waged against the British and Afrikaner authorities and the in-fighting that took place within the ranks of their organisations. In the context of their careers, some were denied the opportunity to practise their trade while others, who were allowed to represent clients in court, were often discriminated against by their white peers and denied access to professional bodies. They were plagued by a multitude of problems that included, amongst others, an inability to sustain financially their practices and the tendency to over-extend and over-commit. Indeed, Ngcukaitobi provides a holistic picture of these multidimensional personalities, which includes their dedication to the fight for the humanity and dignity of black South Africans while at times simultaneously holding elitist, condescending and paternalistic attitudes towards their uneducated brethren.

In telling these narratives, Ngcukaitobi also highlights the intersections and connections between South Africans and the African diaspora at the end of the 19th and the beginning of the 20th centuries. In particular, the reader is introduced to the interlocking histories of the black, educated elite of South Africa and African America: among other things, that a number of South Africans were educated in the USA at institutions that included Wilberforce University, Hampton Institute and Lincoln University, places of higher education that were established to provide training and education to ex-slaves. Further, we learn of the Trinidadian Henry Sylvester Williams – crusader, advocate and founder of Pan Africanism – his sojourns in England and South Africa and the manner in which he and South Africans like Alice Kinloch and J.T. Jabavu and African Americans such as W.E.B. du Bois, amongst others, met and collectively strategised with regard to combating racism and uplifting black people across geographic boundaries. These accounts make for fascinating and intriguing historiography.

Moreover, Ngcukaitobi offers insightful accounts of some of the first strategic impact litigation to be carried out in South Africa. Here, the reader learns that this type of legal practice did not begin in the late 1970s and early 1980s with the establishment of public interest law centres such as the Legal Resources Centre, the Centre for Applied Legal Studies and the Black Lawyers Association Legal Education Centre. Rather, it began in the early 1900s with efforts of Williams, Mangena, Seme and others. Although many of the cases brought were unsuccessful, these activist legal practitioners attempted to use the law to promote equality, and sometimes they succeeded. In a context in which law was used to subjugate and deny, they tried to use it as an instrument to remedy violations of fundamental human rights.

Although I appreciate and admire the thoroughness of this presentation, there were times during my reading when I felt overwhelmed by the detail and I noticed some repetition. In these instances, I thought that the volume could have benefitted from closer editing. Take, for example, when Ngcukaitobi provides an account of the rugby prowess of Richard Msimang or the comprehensive list of all the areas of law in which he was examined or the exhaustive report of Seme's years in the UK. Was this information crucial in providing the reader with an understanding and appreciation of the influence and contributions of these early crusaders for equality and human rights? I wonder.

In the big picture, however, these are minor criticisms. On the whole, this book does a noteworthy job on a number of fronts. It gives voice to individuals who have been ignored or written out of the mainstream historical narratives, and of special note is the attention paid to female activists such as Alice Kinloch and Charlotte Maxeke. It focuses attention on the ways that, in the early 20th century, black legal practitioners attempted to use law and litigation to challenge racial discrimination and exploitation. Further, through its careful and meticulous presentation, it traces the history and documentation of land dispossession that occurred during the late 19th and the first 40-odd years of the 20th centuries. In the context of current debates surrounding land reform and land redistribution, *The Land is Ours* provides a timely evidentiary record of the deliberate and violative removal and dispossession of black South Africans from the land.

Accordingly, I would highly recommend this volume not only to legal practitioners, historians, other social scientists, policymakers and analysts, but to anyone interested in learning and understanding more about the rich, and under-told, histories of the men, and women, who scattered barriers and engaged in some of the first legal battles against racial oppression in South Africa. By taking on this fight, these black intellectuals and legal practitioners planted the conceptual seeds of a bill of rights and constitutionalism that germinated over the course of the 20th century and came to fruition, at least in part, during the 1990s.

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Quantifying a sponge: The additional water in restored thicket

Restoration of degraded subtropical thicket in the Eastern Cape, South Africa, can result in the return of more than 30 tonnes of soil organic carbon per hectare.[1,2] Given that soil carbon is usually positively correlated with soil water-holding capacity[3-5], we hypothesised that restoration of thicket would greatly increase the sponge effect of its soils. As a first step towards examining this hypothesis, we used a model that predicts how changes in soil texture and soil carbon affect soil water-holding capacity.

In sandy and loamy soils, increases in soil water-holding capacity will tend to range from ~1% to ~8% for each per cent increase in soil organic carbon.[3,5-9] By contrast, within clayey soils, and within a particular range of soil carbon, an increase in soil organic matter can be expected to reduce, not increase, soil water-holding capacity. An increased sponge effect is consequently not a *fait accompli* in thicket restoration (see Figure 1).

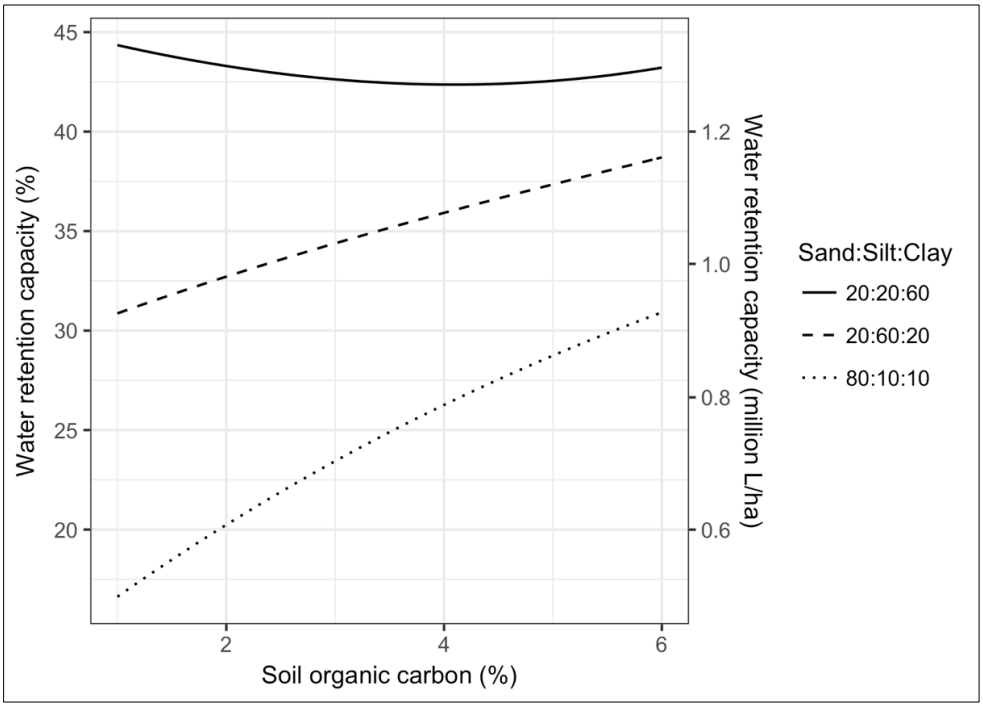

Figure 1: Modelled relationship between soil organic carbon (%) and water retention (%) using the equations of Rawls et al.[3]

The texture of soils across subtropical thicket varies greatly, but a large proportion are sandy (~80% sand content), with relatively small amounts of clay (~10%) and silt (~10%).[10] We consequently used a ratio of 80:10:10 sand:silt:clay to estimate how much water is likely to be stored when restoring thicket. Assuming that soil carbon increases from 2% to 5% in the top 30 cm of soil[11], the model predicts that an extra ~255 thousand litres of extra water would be stored per hectare. Across a farm of, for example, 5000 hectares, the amount of extra water stored would be 1.28 billion litres, and across the ~1 million hectares of the subtropical thicket biome that is degraded[12] the amount would be 255 billion litres. In conclusion, restoring degraded subtropical thicket at the biome-scale is likely to result in the additional storage of more than 200 billion litres of water. To put this amount in perspective, Theewaterskloof Dam, Cape Town's main storage dam, holds ~400 billion litres when full.

The additional water storage in subtropical thicket soils would result in myriad benefits for society, including greater productivity of the landscape for livestock and game (particularly during droughts), flood mitigation, and greater flow of water from groundwater into rivers.[13] It would be instructive for government and private landowners to have a hydrological model that shows how creating an underground dam of 200 billion litres would increase supply of water to farmers and towns across the Eastern Cape. Our hypothesis is that the economic returns from the additional water alone would be well worth the costs of restoring the 1 million hectares of degraded thicket.

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Building assessment practice and lessons from the scientific assessment on livestock predation in South Africa

After at least two millennia of human–wildlife conflict over the predation of livestock in South Africa[1], the recently completed scientific assessment on livestock predation[2] (PredSA) brings the power of a formal scientific assessment to focus on the topic. PredSA represents a global first in terms of applying this increasingly recognised approach to informing policy to the issue of livestock predation at a national level. Here we explore the process behind the assessment, its structure and policy relevance, and some lessons learnt and suggest some avenues for the way forward.

Scientific assessments are a relatively recent societal tool. Operating at the science–policy interface, they serve to collate and interrogate transdisciplinary information relating to a complex problem and, through consensus, evaluate the relevance of the findings to policy development. Having emerged over the past three decades, there is a growing body of best practice guiding the basis for scientific assessments and how these should be conducted.[3] Briefly, an assessment should have demonstrable legitimacy (a valid issue requiring attention at the behest of a relevant authority), saliency (the focus on stakeholders' interests in the problem) and credibility (reflecting scientific rigour by recognised experts) to be accepted by, and useful to, society.[3] To achieve these criteria, the governance of an assessment process needs to be transparent and demonstrate a commitment to being broadly participatory.[3,4]

The need for an assessment on livestock predation in South Africa was identified by the national Departments of Environmental Affairs (DEA) and Agriculture, Forestry and Fisheries (DAFF), as well as the livestock industry. Discussions around this need developed through the Predation Management Forum, the latter representing the wool, mohair, red meat and wildlife industries, as well as the regulatory bodies. Financial support was provided by DEA and DAFF as well as the National Wool Growers Association, Mohair Growers Association and the Red Meat Producers Organisation. This support reflects the legitimacy of the assessment, emerging as it does from both the policy/regulatory domain and stakeholders directly affected by predation on livestock.

The Minister of Environmental Affairs and the Department of Agriculture, Forestry and Fisheries formally endorsed PredSA at its launch in 2016.[4] The route to the assessment launch, however, started in 2010 with dialogue between the abovementioned role players and the Centre for African Conservation Ecology (ACE) at Nelson Mandela University. This dialogue, facilitated by seed funding from Woolworths SA, resulted in a proposal for the assessment to be hosted by ACE, which engaged recognised experts nationwide and followed the transdisciplinary approach of the 2008 Elephant Management Assessment.[5]

The process

A key early step in PredSA was the establishment of a governance framework to ensure that the requirements of saliency, credibility, transparency and participation were adhered to during the assessment. Guided by the framework developed for the Shale Gas Assessment[6], a 'process document' articulated these commitments and provided for an independent 'Process Custodianship Group' (PCG) that was tasked with overseeing the fairness of the process but with no mandate to influence the content or perspectives of the authors. The PCG comprised representatives from industry (two individuals), both affected government departments (a representative each), an independent environmental non-governmental organisation (a representative) and an independent academic. The independence of the PCG was strengthened by the appointment of an independent chair.

The PCG reviewed and confirmed the proposed structure and scope of the assessment, thus defining the manner in which the issue of livestock predation would be addressed – thereby confirming its saliency. The PCG then reviewed the names and credentials of proposed lead authors, and subsequently the contributing authors (proposed by the lead authors collectively) for each chapter to ensure the credibility of the assessment. In executing its tasks, the PCG paid attention to ensuring that the appointment of authors was used as an opportunity to contribute to transformation and development objectives of South Africa. Additionally, the PCG reviewed the appointment of external reviewers (as proposed by the authors collectively) in terms of their independence and recognition as experts, as well as for their diversity and international representation.

Scientific assessments culminate in a body of information captured in a document. The process to generate this document follows a series of steps. Starting with a zero-order draft (document structure with brief detail, compiled by the lead authors), through a first-order (ready for technical review, compiled by the full author team), then second-order (ready for stakeholder review) draft leading to a final product. The PCG oversaw the process, ensuring transparency and credibility, to generate each of the drafts. The first-order draft underwent a technical review by a team of 24 recognised, independent experts (of whom 9 were from outside South Africa), and was then revised by the authors. All the reviewers' comments were made available online and author responses comprehensively documented for presentation to the PCG. The second-order draft was then made available for public stakeholder review. Stakeholders were alerted to the opportunity to provide input through various fora (e.g. National Wool Growers Association, Predation Management Forum, South African Wildlife Management Association), agricultural publications, and also through targeted emails directed to known interest groups and individuals. Stakeholders were invited to register on the PredSA website in order to provide their input. Stakeholder input was captured through an online process and documented, together with the authors' responses, for presentation to the PCG, and available online for transparency.

The PCG verified that each comment by the reviewers was formally addressed in an appropriate manner by the authorship team. This led to the final assessment product.

Filling information gaps

Early in the process, the team leading the assessment recognised that there is little information in the literature on livestock predation or its management in rangeland under communal tenure. It was clear that this information gap would have unknown implications for policy development, and therefore limit the relevance of the assessment. This gap posed a challenge, as the collection of data does not typically fall within the scope of scientific assessments.[3] In a departure from the conventional focus of an assessment of collating existing information, the PredSA team chose to address the gap. A survey of the nature of livestock predation and its management in communal rangelands was commissioned and undertaken by an independent research group already working in communal rangelands. Interview-based data were collected in seven communal rangelands in the country and the resulting report[7] was used to inform the assessment.

The product

The completed assessment[2] is presented in the form of a 280-page book, which was published in November 2018 and is available in traditional printed form as well as an e-book. The nine chapters (each functionally a peer-reviewed paper) cover a broad range of topics – highlighting the inherent transdisciplinary nature of human–wildlife conflict including: the background to the assessment, the history, socio-economic impacts, ethics, law, and management of the conflict, as well as chapters on the black-backed jackal *Canis mesomelas* and the caracal *Caracal caracal*, other predators implicated in livestock predation, and the role of mesopredators in rangelands. There is, in addition, a summary for policymakers[8], which is a distillation of the assessment into a format that is policy relevant. A total of 43 authors contributed to the writing of the assessment, representing the diversity of disciplines reflected in the chapter structure. The authors represent 22 institutions across South Africa (some being affiliated to more than one institution). This transdisciplinary and multi-institutional engagement highlights the networking value of an assessment and the potential for building research collaboration among the contributors.

Key messages to policymakers

An assessment's key role is to inform policy, and PredSA provides a number of key messages to policymakers, these are summarised here.

There is an urgent need for legislation addressing livestock predation and its management across South Africa to be updated and standardised. As a consequence of South Africa's complex political history and the associated complexity of the development of legislation, the current applicable legislation varies across, and even within, provinces.[9] The constitutional recognition of concurrent national and provincial responsibility towards environmental management requires extensive and ongoing coordination and revision of legislation to ensure there is a uniform legal framework regulating the management of livestock predation.

The assessment has placed the **economic costs of livestock predation in better perspective**. Previously published statements of livestock predation costing in excess of ZAR1 billion per year[10], are contextualised. A conservative estimate of losses as a result of livestock predation equates to about 0.5% of the Agriculture, Forestry and Fishing sector's GDP and 0.01% of national GDP.[11] Thus livestock predation appears to have a relatively small impact at the national scale. From a policy perspective, this figure needs to be balanced against the impact of losses borne by individual farmers, and the consequences for rural livelihoods, employment and food and fibre security. These issues are particularly pertinent in marginal farming areas where many households are poor and losses from livestock predation could have significant impacts and possibly contribute to increasing social tensions.[11]

Both **communal and commercial farmers face the same fundamental predation management challenges**; these challenges revolve largely around the main predators of livestock (black-backed jackal and caracal) and the legislative framework. A clear difference lies in the capacity of each group to absorb predation losses financially, and to invest in the management of predators' impacts on livestock.[12] There is also an imbalance in the research effort on livestock predation in communal vs commercial areas[1], and research and funding institutions need to address this imbalance as a matter of urgency.

Effective predation management is likely to consist of a range of complementary methods/activities (including selective, humane lethal methods where necessary) and no single approach should be regarded as a 'silver bullet solution' to the problem. A multitude of management methods aimed at reducing the impact of predation on livestock has been attempted – much of the time there is, however, insufficient scientific information to confirm or contest their effectiveness.[12] Reported impacts of these management approaches vary, depending on many factors, as well as spatially and temporarily. There is a strong and urgent need for applied research of high scientific standards (i.e. randomised with repeats and controls) to better inform policy development around predation management.

There is a growing appreciation of the need to understand the biodiversity consequences of removing both the apex predators and the mesopredators from a landscape. Our current understanding of the issue is limited to recognising that there will be consequences and that these consequences will likely be broad and ecosystem specific.[13] PredSA highlights the fact that we have much to learn about the ecosystem responses to predator management in order to anticipate and address unexpected consequences.

The assessment highlights that **much research still needs to be done in the field of livestock predation and its management**. The gaps in knowledge that need to be addressed through additional research were identified and listed in each chapter. This information will assist researchers and funding agencies to develop strategic research plans and funding priorities.

It is apparent when undertaking a transdisciplinary exercise like PredSA that research into the issues around livestock predation, and its impact and management, has historically proceeded in a series of independent and unconnected initiatives, with few exceptions. In contrast, it is clear that the legislative and management solutions need to be comprehensively integrated across disciplines. PredSA highlights that **we cannot afford to maintain the single discipline research approach of domain specialists**, and must also recognise the role of policymakers and livestock managers in contributing to developing solutions. We need to advance our approaches to managing livestock predation through an explicit commitment to coproduction of knowledge.[14] This will need to be achieved through collaborative (including researchers, policymakers and farmers) and multidisciplinary research. Furthermore, an adaptive management framework is recommended that provides an effective mechanism for scientists, policymakers and managers (farmers) to identify key research questions and address them in a collaborative fashion which improves our management of the problem.

Lessons around scientific assessments

Setting up an assessment is not a trivial task. It requires initiative to identify the problem, buy-in from the 'clients' (those for whom the assessment problem has relevance[3]) and funding. For PredSA, this process started in 2010, and was originally focused on the problem of predation on small livestock, reflecting the initial interest in an assessment by the sheep-farming sector. Expanding the focus to predation on all livestock reflected the broader interest of the two government departments, as well as the Predation Management Forum. Only in 2016 was the full range of clients identified (now including all elements of the livestock industry and government), the central question finalised, and the funds secured. In contrast, undertaking the assessment was relatively quick – requiring under 2 years from launch to the completion of the book ready for printing. Those interested in undertaking or commissioning assessments therefore need to recognise the potentially long lead time before the actual assessment.

Scientific assessments are undertaken by individuals on a voluntary basis who benefit from the learning, recognition and increased publication outputs.[3] However, it is not only established experts who can contribute and benefit. Scientific assessments can serve as developmental opportunities, bringing younger and underrepresented scientists into a mainstream opportunity. PredSA specifically encouraged and facilitated the inclusion of younger and underrepresented (in gender and demographic contexts) scientists as authors and reviewers. This inclusivity takes effort as these individuals are not necessarily as well known in the established scientific community and may need to be 'sought out'. In the case of PredSA, individuals were able to benefit, learning about the process of collaboration and producing an assessment, building networks and gaining confidence in their own ability to contribute meaningful science, while at the same time boosting their curriculum vitae and publication records. There is risk in securing authors, with some individuals not being able to keep to their initial commitments. From a national perspective, PredSA provided an opportunity for individuals to develop capacity necessary to address the growing numbers of complex societal problems that are best addressed through an assessment.

Obtaining stakeholder input into societal processes can be a challenge. The PredSA process reached out to stakeholders through a variety of channels, including through the Predation Management Forum (representing livestock producers and the affected government departments), learned societies, and targeted requests for input to known interest groups or individuals. Stakeholder input from the communal farming sector was encouraged through existing mechanisms established by the National Woolgrowers Association and Conservation South Africa. This raised difficulties relating to technology (the input was channelled through the PredSA website) and language (the assessment material is in English). These issues were not budgeted for. The absence of stakeholder input from the communal farming sector highlights the need for those planning scientific assessments to identify potentially marginalised stakeholder groups in advance and plan (and budget) accordingly to facilitate input from these groups. Input from individual commercial farmers was also limited. A further broad category of stakeholder that was underrepresented in the stakeholder feedback was that of those government officials tasked with implementing the legislation around predation management. While there was input from the NSPCA, there were no contributions from other animal welfare and rights groups, despite specific requests to known representatives of such groups. As a consequence, the stakeholder input received was largely focused on the management and scientific aspects of the assessment. Clearly, a focused outreach process to create awareness around an assessment, and to encourage and facilitate stakeholder engagement, is a key investment for future assessments.

Assessments are specifically designed to interrogate existing knowledge around a focal problem, and not to undertake novel research.[3] However, where there is a known knowledge gap (as in the case of the information on livestock predation in communal farming areas identified here), the assessment leadership should consider the option of commissioning a strategic, focused and independent research project to address this gap. When considering such a research intervention, it is important to ensure that delivery of the results is within the assessment timelines. It is also important to ensure that the outcomes are publicly available, even if this is via email on request. The alternative of not addressing a known, but potentially fixable, knowledge gap is that the period of relevance of the assessment will be considerably shortened.

Way forward

A number of scientific assessments have been undertaken in South Africa. These include the regional Millennium Ecosystem Assessment in 2004[15], Elephant Management in 2008[5], Shale Gas SEA in 2016[6], and now PredSA in 2018. In addition, South Africans are active participants in international assessments, most notably the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, and contribute to the literature on assessment practice.[3,4] Clearly, South Africa is developing capacity to undertake scientific assessments, albeit in an ad-hoc manner. It would be valuable to develop formal training in this field, as well as to encourage South Africans to publish on best practice and lessons for assessments. It is also notable that the assessments undertaken within South Africa have been largely environmental in their focus. While this is in line with the National Biodiversity and Research Evidence Strategy[16], it would be valuable to roll out this approach of undertaking assessments to other areas of societal interest.

The fact that Africa lacks 'synthesis centres' has recently been highlighted and identified as a limit that African nations face in developing capacity to address big issues facing society.[17] In contrast, beyond the continent a large number of such centres have been developed.[18] Presumably, this lack of African synthesis centres reflects resource constraints. One way to overcome this lack of synthesis capacity is to explicitly recognise that scientific assessments serve as virtual, highly focused, synthesis centres that can be initiated on demand, and which are cost effective because of the high levels of focus and small, efficient management teams. Adopting this approach does, however, carry the risk of the opportunity costs of missing institutional memory that synthesis centres provide. Alternatively, it may also be argued that the review and stakeholder consultation aspects of a scientific assessment avoids the risks of a synthesis centre becoming an 'ivory tower'. This perspective highlights the value of growing assessment capacity in South Africa and facilitating its development elsewhere in Africa.

A scientific assessment is by definition an attempt to contextualise the policy relevance of existing knowledge for a specific societal challenge, reflecting societal values at the time of the assessment. Given that both the state of knowledge and the societal values change, each assessment will become less relevant over time and need to be repeated after a period. What triggers a re-assessment is not currently clear. Developing a measure of when an assessment's findings are falling behind current knowledge and changing societal views, as well as mechanisms to rapidly and efficiently redo assessments, will be key steps in growing the use of assessments, and also ensuring the policy derived from assessments is current and topical.

The topicality of assessments clearly reflects their ability to serve their ultimate purpose of informing policy to address a focal issue. In systems where baselines[19] are rapidly changing, assessments will need to include these shifts to maintain their relevance. Three examples illustrate how such shifting baselines were either effectively addressed in PredSA, or not. The first issue is that of the re-establishment of populations of large predators within areas of South Africa from which they had been extirpated.[1,20] This poses a challenge as policymakers and livestock managers need to be aware of this process and 'lift their baselines' to accommodate changing circumstances.[21] This point was effectively identified in PredSA.[1] The second issue is that of how climate change may influence livestock predation and its management, through, for example, altering the natural prey base of predators or changes in livestock management. This point was touched upon briefly in PredSA, but merits further focus. This focus will, however, require more scientific research on the relationships between climate change and livestock predation. The third issue, that of accelerated land reform in South Africa, sprang to the forefront of societal issues in South Africa as the assessment was drawing to a close. Given that land reform may profoundly alter the dynamics around management of livestock predation, this development needs to be considered by policymakers, but may first require an extensive research programme to provide the scientific evidence to support policy development.

Concluding comments

PredSA delivered on its original mandate of timeously providing an effectively governed scientific assessment on the contentious issue of livestock predation. In addition, by setting the precedent of a scientific assessment commissioning research, PredSA has contributed to the growing body of assessment practice. Finally, PredSA has also contributed to developing assessment capacity in South Africa.

This assessment was conducted at a national level. As the body of practice around dealing with complex societal problems expands, thought will need to be given to the issue of what scale of question – i.e. local, national or international – is appropriate for which to use an assessment methodology. There are clear demonstrations, cited earlier, supporting assessments at the global and national levels, but what of a question at the level of a province or a city?

One of the remaining challenges is for policymakers to be able to effectively use the assessment product, which despite its focus on policy relevance, is still technically dense and heavily scientific in its language. This is the nature of the beast. Few policymakers, particularly politicians, are comfortable when faced with a body of evidence such as this. A step in the right direction would be to empower policymakers with the capacity to ask key questions as to the implications and limitations of the available evidence[22], and grow their understanding of the issue. They can then craft this understanding into policy. The current policy aimed at developing evidence-based environmental policy in South Africa[16] is silent on the capacity of decision-makers (or their advisers) to be able to understand, interrogate and interpret scientific evidence. This gap needs to be addressed to provide an environment in which the full power of scientific assessments can be brought to bear on robust policy development.

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Progress towards obtaining valid vaccination coverage data in South Africa

In March 2019, the South African National Department of Health (SANDoH) launched South Africa's first national household vaccination coverage survey to be held since 1994. The need for this survey is driven by several imperatives. First, the World Health Organization (WHO) Global Vaccine Action Plan (GVAP) 2011–2020, had set a 2020 global target for countries to reach 90% national coverage of all their primary series vaccines.[1] The administrative fully immunised under one year old coverage (FIC) of the Expanded Programme on Immunisation of South Africa (EPI-SA), reported through the District Health Information System (DHIS), shows that EPI-SA is not on track for reaching GVAP's target.[2] EPI-SA's FIC steadily increased from 83.6% in 2012/2013 to 89.8% in 2014/2015, before dropping to 82.3% in 2016/2017.[2]

Second, for the past decade, EPI-SA has reported much higher administrative vaccination coverage than the WHO and United Nations Children's Fund Estimates (UNICEF) of National Immunization Coverage (WUENIC).[3] South Africa is one of many low- and middle-income countries (LMICs) with annual administrative coverage rates that differ substantially from WUENIC.[3] WUENIC are based on both administrative coverage rates and population-based surveys, including household surveys using the WHO EPI vaccination coverage cluster survey method[4], and Demographic and Health Surveys (DHS)[5].

Third, the SANDoH's DHS (SADHS) conducted in 2016 reported a national FIC for 12–23-month-old children of only 52.7%[6], which was 36.5% lower than 89.2%, the DHIS FIC for 2015/2016[7]. While the sample size of 677 12–23-month-olds was very small for a national survey (ranging from 12 children in the Northern Cape to 180 in Gauteng[6]), the FIC result was nevertheless concerning.

Fourth, reports from published South African population-based studies[8-13] and sporadic measles outbreaks[8,14-18] provided the SANDoH with evidence that FIC targets are not being reached. Thus the SANDoH recognised that a large-scale national vaccination coverage survey was needed to provide them with a clearer picture of true FIC, and identify pockets of low coverage too small to be noticed within aggregated data reported through the DHIS.[5] Planning for this survey began in 2012; however, funding was a major obstacle, as these large surveys are very costly.[5]

Immediately following the release of the SADHS 2016, the SANDoH convened a workshop for all stakeholders on the 'SADHS Findings and EPI-SA Turn-around Strategy'. A key issue identified during this workshop was that the planned large national household vaccination coverage survey was long overdue, and funding for the survey was subsequently secured from the vaccine industry. The Wits Health Consortium is conducting this survey, with technical support from WHO and UNICEF. The survey was launched on 8 March 2019 by the Minister of Health, after which data collection commenced, being conducted by 1600 field workers who were trained by Statistics South Africa. It has been estimated that 1.1 million houses will be visited in all 52 districts of South Africa within 90 days, in order to reach a targeted sample size of 55 120 children.

Because of the high costs associated with large national surveys,[5] it is difficult for LMICs such as South Africa to conduct these surveys regularly. Yet it is these resource-constrained countries which are most in need of up-to-date valid survey data for identifying current gaps at district and facility level. To overcome these cost constraints, which may prevent the SANDoH from conducting another large national survey within the next decade, we suggest an affordable, practical alternative with high validity. The suggested methodology is based on the experiences of the South African Vaccination and Immunisation Centre, based at the Sefako Makgatho Health Sciences University, in conducting four small-scale South African vaccination coverage surveys.[19-22] All of these studies had the common objectives of determining the (1) FIC of children aged 12–23 months, and (2) reasons for some children not being fully vaccinated. These studies were all funded as part of postgraduate research dissertations, with some students paying for the costs themselves, while others were funded through research grants. All studies received ethics approval from institutional review boards – the first three from the Medunsa Campus Research Ethics Committee, and the fourth from the Sefako Makgatho Health Sciences University Research Ethics Committee. In the following discussion, particular attention is paid to issues impacting on affordability and validity, with the view of suggesting a method which could form the basis for countrywide application.

The studies

All four studies adapted the WHO vaccination coverage cluster survey method, with the first three using the 2005 version[23], while the fourth study used the 2016 version (subsequently updated in 2018)[4]. All studies aimed for a sample size powered at 80–90% at a 95% level of confidence, with a design effect of 2 for 30 clusters.[4,23] For all studies, consenting caregivers of children aged 12–23 months during the study period, who were in possession of their vaccination records , were included. If no eligible child (i.e. a child of the correct age with a vaccination record) was found, or if informed consent could not be obtained, the next closest house was visited. If more than one child in a household was eligible, for the first three studies, data were collected on the youngest eligible child,[23] while for the last study, data were collected on all eligible children[4]. All studies used researcher-administered questionnaires adapted from the WHO protocol.[4,23]

The first study[19] was conducted in 2012 in Bela-Bela Township in Bela-Bela Municipality, Limpopo Province. The survey was confined to six wards where low-cost/informal housing predominates. The sample size was increased to 240 (30x8), with 30 clusters (blocks bordered by roads) of 250–300 houses per cluster being based on a map provided by Bela-Bela Municipality. The first house visited in each cluster was randomly selected from the map, and then every n^{th} (number of houses per cluster ÷ 8) was visited following a pre-determined pattern. The

researcher (R1) was a nurse at a local clinic serving the community being surveyed. There was thus a risk that caregivers of unvaccinated/partially vaccinated children may fear that the vaccination status of their children would have repercussions on future health care from the clinic, thereby introducing nonresponse/volunteer bias. To avoid this, three research assistants (with a minimum qualification of matric) were recruited and trained according to the WHO protocol[23] for interviewing and collecting data. R1 supervised the research assistants via cellphone calls during data collection, and at the end of each day checked questionnaires for adherence to the inclusion criteria, completeness and consistency. Questionnaires were discarded where inclusion criteria were not adhered to, and research assistants returned to the cluster to continue recruiting eligible participants. Where inconsistencies were found (e.g. subsequent dose received without previous dose), the research assistants returned to re-check the vaccination record the following day. Of all houses visited within 4 weeks, 243 had an age-eligible child with a vaccination record. Of the 243 caregivers, 3 declined to participate, giving a response rate of 98.8% (240/243). Data were captured by R1, and subsequently checked against the questionnaires by R1 to ensure reliability of data capture.

When the results of this study were shared with EPI-SA officials, they pointed out that without copies of vaccination records for data validation, interpretation of these data may not be worthwhile. Furthermore, the data were collected by research assistants who reported back to R1 daily, thus real-time supervision was lacking. To address specific issues potentially impacting negatively on validity, all subsequent studies made use of electronically mailed digital photographs taken with a cellphone camera, ensuring that data collection was conducted under constant supervision.

The second study[20] was conducted in 2014 in informal settlements on plots in Muldersdrift, a relatively sparsely populated rural part of Mogale City Municipality, Gauteng Province. The Mogale City Municipality provided a register of informal settlements, including plot names, numbers of houses per plot, and geographical position of 39 plots where such settlements were documented. The 30 plots with the largest number of houses (24–1540) were selected as clusters for a sample size of 210 (30x7; 80% power). The first house visited in each plot was that closest to the plot entrance, and then every n^{th} (number of houses per plot ÷ 7) house was systematically visited. The researcher (R2), a community liaison officer employed by the local municipality, with no relationship to the local clinic/health services, collected data on her own. After entering vaccination record data onto the questionnaire, a photograph of the vaccination record was taken using a cellphone camera and sent to the overall study coordinator via Facebook Messenger, with the date and time of photographing recorded on the corresponding questionnaire. Of 30 clusters, 23 were successfully surveyed according to protocol. All houses were visited in the other seven clusters, with only three eligible children being found. As the demographics of the seven clusters differed substantially from the successfully surveyed clusters, the three questionnaires were excluded. The previously excluded nine clusters with 10–23 houses per cluster were then surveyed. All houses were visited, but no eligible children were found. The response rate was based on the 23 successfully surveyed clusters, in which 242 houses were visited. An eligible child was identified in 66.5% (161/242) of these houses, with all caregivers consenting to participate. The survey took 16 days, with photographs being sent to the study coordinator in real-time during the first week, and thereafter being sent in batches at the end of each day. After capturing data from the questionnaire, R2 compared these data to those on the corresponding vaccination record photo. Finally, during data cleaning, the photos of vaccination records with inconsistent data were used for data validation.

The third study[21] was conducted in 2015 in Refilwe Township in Cullinan, Tshwane Municipality, Gauteng Province. The Tshwane Municipality provided an aerial photograph for dividing Refilwe's 6111 houses into 30 clusters (blocks bordered by roads), with ~200 houses per cluster. Systematic interval sampling was planned for 210 houses as described above. The researcher (R3), a scientist employed by the South African Vaccination and Immunisation Centre, participated in and supervised data collection, and was assisted by three research assistants who were trained according to the WHO protocol.[23] Field work was conducted by two teams, with R3 being responsible for overall supervision and leading one team, while a MSc student led the second team. Data collection was conducted as for the second study, except that on day one of the survey, the original plan of visiting every n^{th} house was abandoned as no-one was found at home in most houses. Instead, all 6111 houses were visited in a period of 6 weeks, with someone found at home in 33.4% (2041/6111). Of these, 8.5% (173/2041) had an eligible child with a consenting caregiver. An attempt to survey the four local crèches failed as none of them required proof of vaccination from caregivers, and thus did not have copies of vaccination records. Data were independently captured by the team leaders, resulting in two data sets which were independently analysed and compared for inconsistencies. Data cleaning and validation proceeded as for the second study.

The last study[22] was conducted in 2017 in Region 5 of Tshwane. Tshwane Municipality provided a map showing all houses in Region 5, which was divided into 30 clusters, with 400–520 houses per cluster for a sample size of 780 (30x26; 90% power). The first household visited in each cluster was randomly selected from the map using Research Randomiser Software® for clusters with house numbers on the map. For informal settlements, the first house from the main road was visited. Thereafter the closest households on the right were visited until the target of 26 was reached or all the households were visited. If there was no-one home, the house was revisited the following day or weekend if the neighbours reported that there was an eligible child in the house. The researcher (R4), a pharmacist with no relationship to the local clinics/health services, participated in data collection and overall supervision of two teams as described above. Photographs of vaccination records were emailed, as recently introduced Facebook privacy policies blocked Global Positioning System (GPS) coordinates from being transmitted. Unfortunately, the number of households provided by Tshwane Municipality included vacant/undeveloped numbered stands, and gated communities/security complexes, which was discovered only during data collection. Hence there were only 24 clusters instead of 30. In addition, houses enclosed by security fencing were inaccessible. Of the houses visited, someone was found at home in 87.2% (7032/8060), with an eligible child being found in 4.7% (327/7032). Of the caregivers of eligible children, 84.4% (276/327) consented to participate in the study. Data capture, cleaning and validation proceeded as for the third study.

Discussion and recommendations

Masters-level research projects for vaccination coverage surveys

Globally, a growing number of universities offer online Master of Public Health (MPH) degrees, allowing health professionals from LMICs to acquire crucial skills and knowledge for improving the health of their populations. These mature students who enroll for the 2-year online MPH at Sefako Makgatho Health Sciences University come from several African countries, and are generally highly motivated early to mid-career health professionals. Many use the opportunity provided by data collection for their MPH projects, to reconnect with their communities by conducting community-based surveys, including vaccination coverage surveys. Similarly, pharmacists undertaking Master of Pharmacy research at Sefako Makgatho Health Sciences University tend to be early to mid-career pharmacists who are passionate about improving public health and serving the community. Other masters-level students who may be interested in conducting vaccination coverage surveys include clinicians undertaking Master of Family Medicine or Community Health degrees; and nurses undertaking Master of Community Nursing research. Because these targeted surveys are relatively small in terms of sample size and geographical area, operational costs are low and many postgraduate students are able to self-finance their data collection, while others benefit from research grants from external funding agencies.

Usefulness to health authorities

While the results of population-based vaccination coverage surveys can be used to identify gaps and strengthen immunisation programmes, these results must be based on studies with high reliability and validity. The feedback on the first study from EPI-SA resulted in vast improvements

in reliability and validity, with cellphone technology allowing constant, real-time supervision. Importantly, these changes in study design have produced much more credible data from the subsequent studies without increasing the budget appreciably. Furthermore, the independent double-data capture and analysis used in the last two studies ensured reliability of data capture – an aspect of postgraduate research often overlooked by students. Also, health authorities are likely to find targeted surveys such as these very useful for pinpointing underperforming clinics. This may not be possible when conducting large national vaccination coverage surveys, as a major disadvantage of these is that they do not reflect health system performance at the local level.[5]

Low-cost, high-quality data

The high definition of cellphone photographs allows valid data to be captured in the field. As cellphones are ubiquitous in most LMICs including South Africa,[24] this method of capturing data does not necessarily add to the budget. While emailing photographs to supervisors adds to the budget, it is relatively inexpensive, with 1 GB of data (far exceeding that needed for 210 vaccination record photographs) currently costing ZAR149.

Low-cost, continuous supervision

Using email to send real-time data ensures ongoing supervision throughout data collection, with mistakes being recognised and corrected immediately. In addition, most modern cellphones are equipped with GPS locator technology, allowing the supervisors to track the movements of data collectors, by viewing the GPS coordinates embedded in the vaccination record photographs.

Representativeness

Because these surveys were confined to small geographical areas, it was possible to divide the areas into contiguous clusters and sample within all clusters, instead of randomly selecting 30 clusters within a large geographical area, as happens in large national surveys.[4,23] While the last three studies had high reliability and validity, none managed to reach their intended sample sizes, despite visiting all the houses in most or all clusters. A major limitation of the Refilwe study was that only 33.4% of houses had someone at home, suggesting that there may be an underrepresentation of employed caregivers in the final sample. This assumption is supported by there being four crèches in the township, suggesting both a demand for child care and the means to pay for it. A previous study, conducted in Ga-Rankuwa in northwest Tshwane, found a statistically significant positive association between employment and knowledge and awareness about immunisation.[25] This suggests that the FIC in this study may in fact be higher than reported.[21] To avoid this selection bias in the last study, data collection was extended into early evenings and was also conducted over weekends. A major limitation of this study was that gated communities/security complexes and houses with security fencing were inaccessible. Caregivers living in these communities may have higher rates of Internet access, which may result in higher rates of vaccination hesitancy and lower FIC than reported.[22]

Conclusion

In 2019, the SANDoH will be producing South Africa's first national vaccination coverage survey data for all districts since 1994. Thereafter, periodic coverage surveys are essential for tracking progress and identifying gaps in EPI-SA. Masters-level research can contribute greatly to public health in South Africa and other LMICs, by employing an affordable method for obtaining valid vaccination coverage figures. From our experience, the following is essential:

- Recent aerial satellite images (e.g. Google Maps™) of the site to be surveyed should be used instead of maps.
- Cellphones with GPS locator technology must be used for photographing and emailing photographs of vaccination records to supervisors, to allow for real-time remote supervision.
- For urban areas with high employment rates, data collection must not be confined to weekdays during working hours. Personal safety and security are always of concern when conducting household surveys in urban South Africa, thus it may be necessary to conduct the surveys during daytime over weekends. Unfortunately, this means that each survey will take longer than the 30 days recommended by the WHO,[4,23] unless a larger number of research assistants are employed, which will add considerably to the budget. However, these costs could be budgeted for in a grant application, so this option is a viable one that needs to be considered.
- Innovative methods for obtaining access to gated communities/security complexes must be investigated. In the last survey, an unsuccessful attempt was made to gain access by emailing the project details and request for participation to the estate manager, following telephonic contact. Online surveys advertised on Facebook may also be an option, although the response rate to a recent human papillomavirus vaccination online survey was very low.[26]

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Colourful chemistry of South African latrunculid sponges

Marine sponges – in common with many other sessile marine invertebrates seemingly devoid of obvious physical forms of defence against predators, e.g. spines or shells – are the sources of a diverse array of organic chemical compounds known as marine natural products or secondary metabolites. Recent research has indicated that the production of natural products via cellular secondary metabolic pathways in some sponge species may not occur within the sponge cells themselves, but rather in microbial endosymbionts which inhabit the surface and interstitial spaces within the sponge tissue. Regardless of their biosynthetic origin, the bioactivity, e.g. toxicity, of many of these marine natural products may be utilised by sponges as chemical feeding deterrents to discourage predation or to provide a chemical anti-fouling competitive edge in the intense competition for living space amongst filter-feeders on space-limited benthic reefs. Paradoxically, a small number of sponge natural products have serendipitously shown potential as new pharmaceuticals, e.g. novel anti-cancer drugs. Marine biodiscovery (or bioprospecting) is the search for new pharmaceuticals from marine organisms. Exploration of the taxonomy, natural products chemistry and biomedicinal potential of the rich diversity of South African latrunculid sponges (family Latrunculiidae), at Rhodes University, the South African Department of Environmental Affairs and the University of the Western Cape has continued unabated for over a quarter of a century as part of a collaborative marine biodiscovery programme. A short review of this multidisciplinary latrunculid sponge research is presented here.

Significance:

- Research into the taxonomy, chemistry and microbiology of latrunculid sponges is the most comprehensive, multidisciplinary investigation of any group of African marine sponges.
- The potent cytotoxicity of the pyrroloiminoquinone alkaloid pigments isolated from latrunculid sponges may have biomedical applications.
- This review underlines the importance of conserving and protecting South Africa's unique marine invertebrate resources.

Introduction

The first marine biodiscovery programme centred at a South African university was initiated by a SCUBA collection of approximately a dozen marine sponges by a team of Rhodes University ichthyologists, from a sub-tidal reef in the Tsitsikamma National Park, situated on the Southern Cape coast of South Africa during the spring of 1990. This small collection of marine sponges unearthed a single specimen of a dark brown coloured sponge (Figure 1). This sponge was identified by Samaai and Kelly as *Tsitsikamma favus*, the first species from a new genus in the family Latrunculiidae Topsent, 1922.[1] Subsequent detailed studies of the taxonomy, marine natural products chemistry and marine microbiology of *T. favus* formed the basis of the first PhD studies at the University of the Western Cape in sponge taxonomy[2], and in marine sponge natural products chemistry[3-5] and marine sponge microbiology[6] at Rhodes University.

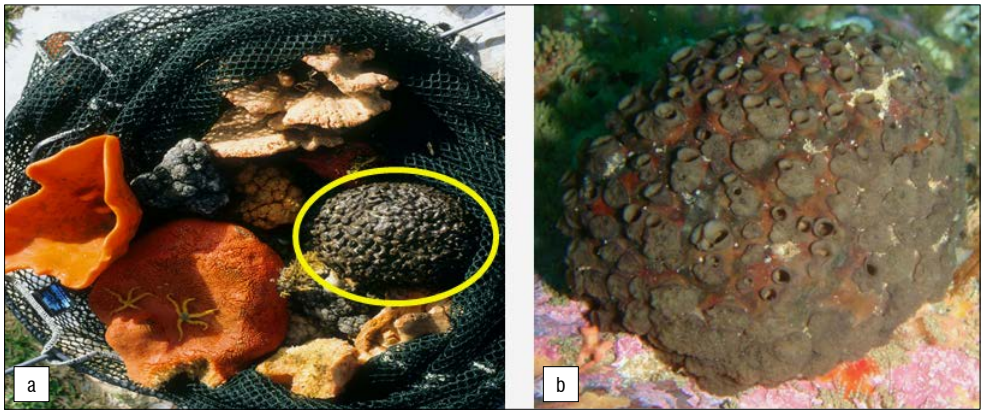


Figure 1: (a) *Tsitsikamma favus* (circled) in a mixed collection of sponges and soft corals from the Tsitsikamma National Park and (b) an underwater photograph of *T. favus* in Algoa Bay, South Africa (photos: M. Davies-Coleman and T. Samaai).

Biodiversity of South African latrunculid sponges

In the southern hemisphere, sponges belonging to the family Latrunculiidae (Demospongia, Poecilosclerida; Figure 2) are commonly found on exposed coastal environments attached to hard rocky substrata (<50 m depth) in the cold, inshore, upwelled water environments around South Africa, New Zealand, southwestern Australia and Tasmania.[7] The

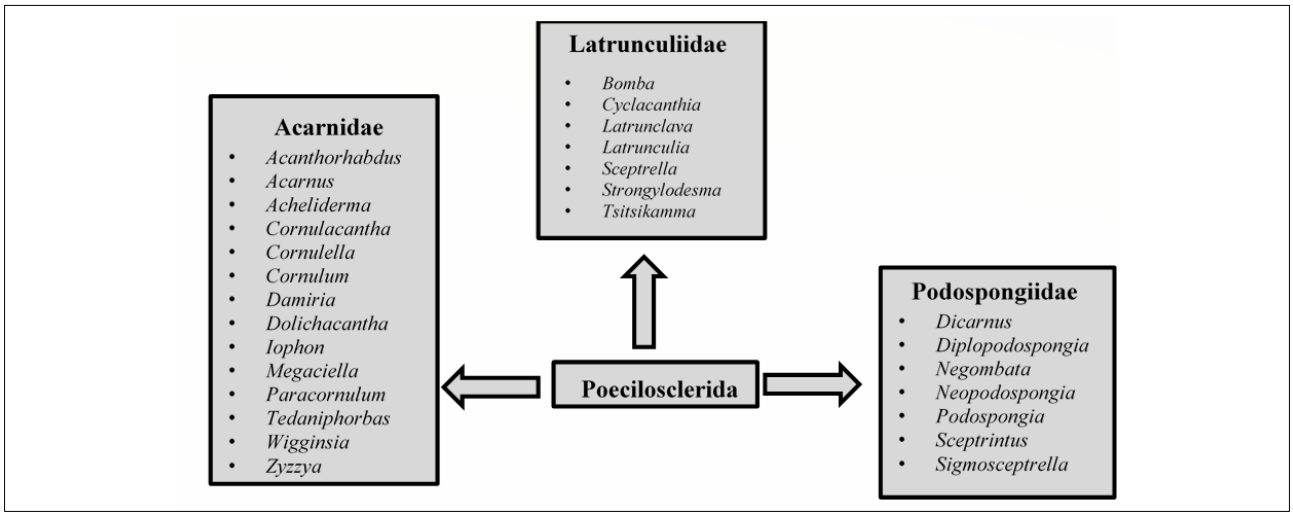


Figure 2: Three taxonomic families ascribed to the sponge order Poecilosclerida.[7,8]

family Latrunculiidae was retained in the order Poecilosclerida, following a recent revised proposal for the classification of the Demospongiae (Figure 2).[8] The family comprises seven genera[7], of which four (*Latrunculia, Cyclacanthia*, *Strongylodesma* and *Tsitsikamma*) include species that are endemic to the Agulhas ecoregion of South Africa[9]. *Tsitsikamma* and *Cyclacanthia,* known from six species respectively[7], are genera endemic to South Africa. The coastal regions of South Africa are recognised as a global hotspot of latrunculid sponge biodiversity.[1,10]

The pioneering, collaborative, marine invertebrate biodiscovery expeditions, coordinated from Rhodes University (1990–2004),[10] revealed for the first time the significant latrunculid sponge diversity off South Africa. The continual discovery of new latrunculid species and genera from these expeditions fuelled increasing interest in these sponges and ultimately led to a taxonomic revision of the family Latrunculiidae in parallel with the natural products chemistry and bioactivity studies of the isolated natural products.[1,2,11,12] Four genera – *Latrunculia, Sceptrella, Strongylodesma* and *Tsitsikamma* – were recognised in this revision (Figure 2). The genus *Tsitsikamma* is endemic to South Africa.[13] The identification of sponges belonging to this family was predominantly based on a number of key morphological features, including, in most genera, the presence of the characteristic silica-based discorhabd microscleres which differ structurally between the different genera (Figure 3).

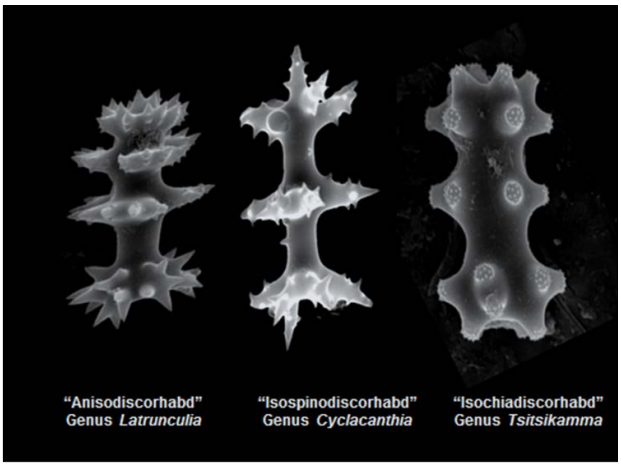


Figure 3: Silicon discorhabd microscleres characteristic of the genus *Latrunculia* and the two endemic South African genera *Cyclacanthia* and *Tsitsikamma*.

However, the genus *Strongylodesma* is an enigma within the family Latrunculiidae, because species within this genus do not contain these distinctive discorhabd microscleres.[13] Shortly after this taxonomic revision was published, the family Latrunculiidae was further expanded to include another new endemic South African genus, *Cyclacanthia*, which incorporated three new species collected from the Agulhas ecoregion (*C. bellae*, *C. cloverlyae* and *C. mzimayensis*).[14] The type specimen for this genus, *C. bellae*, described from Algoa Bay, was originally misidentified as *L. bellae* (Samaai and Kelly, 2003) and placed in the genus *Latrunculia*.[13] Interestingly, *Cyclacanthia* differs from the genus *Latrunculia*, inter alia in ontogeny, morphology and presence of isospinodiscorhabd microscleres, in which there are three major whorls of projections, as opposed to the four characteristic of the anisodiscorhabds of the genus *Latrunculia* (Figure 3).[15]

The genus *Latrunculia*, comprising some 30 species of which over a half occur in the southern hemisphere, was further expanded to include another three new South African species: *L. algoaensis,* collected from Algoa Bay and *L. gotzi* and *L. kerwathi* collected from deep water reefs situated on the Agulhas continental shelf off South Africa.[16] Latrunculid sponges from the genus *Sceptrella* are also deep water sponges; however, no representatives of this genus have yet been discovered off the South African coast and this genus appears confined to the northern and western Atlantic Ocean.[1,17,18] The genera *Bomba* and *Latrunclava* have recently been added to the family Latrunculiidae, and representatives of these two genera are similarly not known to occur off southern Africa.[7,18] A list of the new latrunculid sponges species collected off South Africa, their sites of collection, and references to their published taxonomic data are presented in Table 1.

Pyrroloiminoquinone alkaloids isolated from South African latrunculid sponges

The general name pyrroloiminoquinone refers to the central chemical structural motif common to the group of alkaloid secondary metabolites isolated from sponges belonging to the families Latrunculiidae and Acarnidae (Figure 2).[21] The pyrroloiminoquinone structure is characterised by a five-membered pyrrole ring (A) fused to a six-membered iminoquinone moiety (B), as typified by the chemical structure of the ubiquitous discorhabdin A (Figure 4).

Biosynthetically, the pyrroloiminoquinone motif is derived from tryptophan via decarboxylation and oxidative cyclisation. Subsequent addition of tyramine to a putative tricyclic pyrroloimininoquinone intermediate, affords a group of alkaloids known as the makaluvamines, which may be further elaborated via oxidative, intramolecular cyclisation to yield the discorhabdins and tsitsikammamines (Scheme 1).[22]

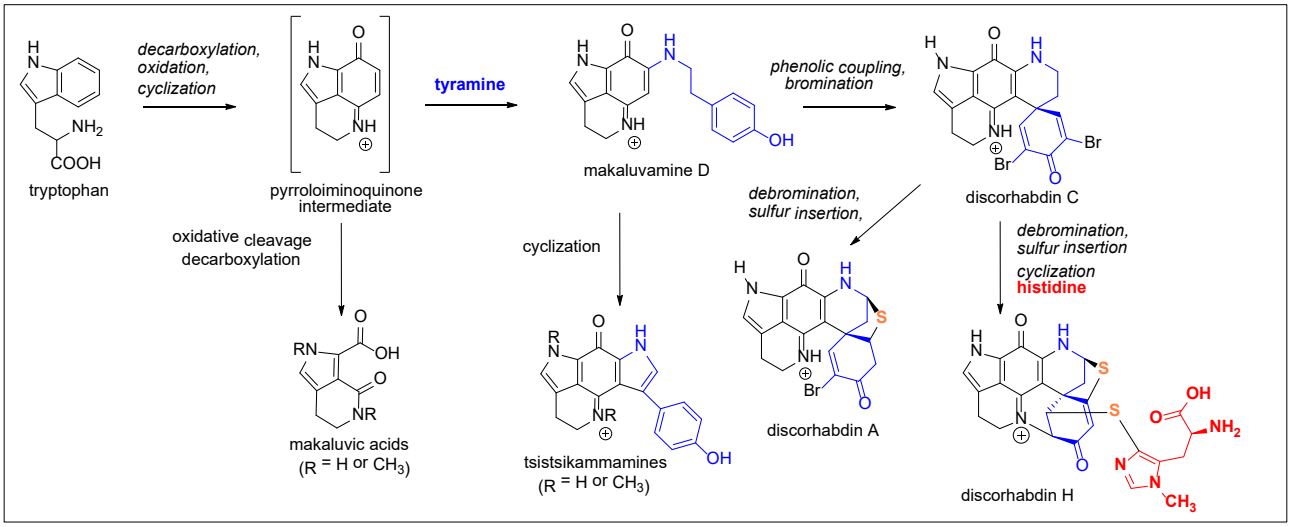
The name 'discorhabdin' originates from the name given to the discorhabd microscleres used by sponge taxonomists to identify latrunculid sponges, and was given to this group of marine natural products by Munro and colleagues, who isolated and identified the first discorhabdin compounds from a New Zealand *Latrunculia* sponge in 1986.[23] Varying in colour from red and orange to dark green, pyrroloiminoquinone metabolites have been shown to be concentrated in the outer 0–2 mm of sponge tissue in the dark green or brown coloured sponges in which they are produced.[24] Accordingly, pyrroloiminoquinone metabolites serve a dual purpose in latrunculid sponges, both as pigments and, because of their potent cytotoxicity and general bioactivity *vide infra*, as feeding deterrent compounds to deter predators.[24]

The isolation of the highly polar pyrroloiminoquinone compounds from methanolic extracts of marine sponges, and the subsequent determination of the chemical structures of these compounds, is not trivial. Nuclear magnetic resonance (NMR) spectroscopy is the pre-eminent spectroscopic technique used to elucidate the chemical structures of natural products.

In the contemporary NMR spectroscopy toolbox, inverse detection, two-dimensional NMR spectroscopy experiments, e.g. heteronuclear single quantum coherence, heteronuclear multiple bond correlation are among the most useful to establish the chemical structure of an unknown organic compound.[25] These experiments are designed to define the position in the chemical structure of magnetically insensitive nuclei with a low relative abundance and gyromagnetic ratio, e.g. carbon nuclei (^{13}C), via a radio frequency pulse sequence that exploits the highly magnetically sensitive surrounding hydrogen protons (^{1}H). ^{1}H has an approximate four-fold greater gyromagnetic ratio compared to ^{13}C and is normally more than twice as abundant as carbon atoms in organic compounds. Unfortunately, the relative paucity of hydrogen atoms in pyrroloiminoquinones in comparison with carbon atoms, as reflected, for example, by the molecular formula of discorhabdin A ($C_{18}H_{15}BrN_3O_2S$), often hampers the structure elucidation of these complex, highly conjugated, polycyclic compounds by NMR spectroscopy and thus provides an intriguing challenge for marine natural product chemists.

Table 1: Latrunculid sponge species collected off South Africa (1990–2016)

Species	Collection site	Ecoregion	Year(s) collected	Depth range
Cyclacanthia bellae[13,14]	Algoa Bay, Ryi Banks	Agulhas	1998, 1999	20–22 m
C. cloverlyae [14]	Christmas Reef, Umhlali, Tugela Banks, Durban	Natal	2003	17 m
C. mzimayensis[14]	Mzimayi Reef, Sizela, Umkomaas, Aliwal Shoal, Durban	Natal	2003	18–29 m
Latrunculia algoaensis[16]	Algoa Bay, Port Elizabeth	Agulhas	2010	22–30 m
L. gotzi[16]	Alphard Banks	Agulhas	2009	41 m
L. kerwathi[16]	45-Mile Banks	Agulhas	2009	85 m
L. lunaviridis[13,19]	Ouderkraal, Cape Town; Hout Bay	Southern Benguela	1996, 2003	17–32 m
L. biformis[13,19]	Rheeders Bay, Tsitsikamma National Park	Agulhas	1995	28 m
L. microacanthoxea[13,19]	Rheeders Bay, Tsitsikamma National Park	Agulhas	1995	28 m
Strongylodesma algoaensis[13]	Algoa Bay, Port Elizabeth	Agulhas	1994	15 m
S. tsitsikammaensis[13,20]	Rheeders Bay, Tsitsikamma National Park; Algoa Bay, Port Elizabeth	Agulhas	1996	1.5–15 m
S. aliwaliensis[15]	Umkomaas, Aliwal Shoal, Durban	Natal	1994, 2003, 2004	15–18 m
Tsitsikamma favus[1,13]	Rheeders Bay, Tsitsikamma National Park; Algoa Bay, Port Elizabeth, Jeffreys Bay, St Francis Bay, Plettenberg Bay	Agulhas	1990, 1993, 1994, 1995, 1998, 1999, 2010, 2016,	13–40 m
T. pedunculata[13]	Thunderbolt Reef, Algoa Bay, Port Elizabeth	Agulhas	1999	40 m
T. scurra[13]	Hout Bay	Southern Benguela	2000, 2003	28 m



Scheme 1: Proposed biosynthesis of pyrroloiminoquinone alkaloids.

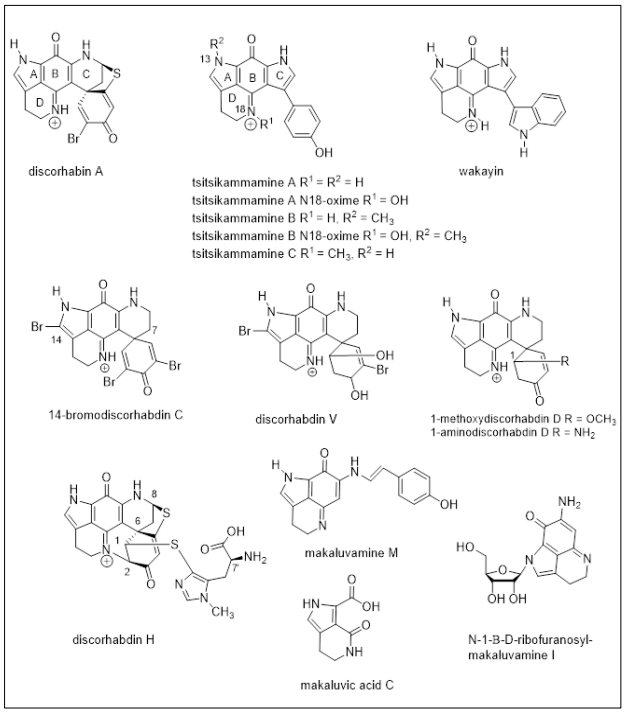


Figure 4: Chemical structures of selected pyrroloiminoquinone pigments isolated from South African Iatrunculid sponges: tsitsikammamine C from the sponge *Zyzzya fulingosa* and wakayin from a *Clavelina ascidian*.

Over 100 marine pyrroloiminquinone natural products have been isolated from marine organisms collected from across the globe and the chemistry and bioactivities of this group of compounds have been regularly reviewed in the chemistry literature.[21,26-28] Of the pyrroloiminoquinones isolated thus far from marine sponges, 30 (of which 16 were new compounds) have been isolated from five South African Iatrunculid sponge species: *T. favus*[12,29], *T. pedunculata*[12], *C. bellae* (formerly *L. bellae*)[12], *S. algoaensis*[12] and *S. aliwalensis*[30,31] (Figures 1 and 5), and the names of these compounds are presented in Tables 2 and 3. Selected compounds from Tables 2 and 3, with novel chemical structural features observed for the first time in this group of compounds, are presented in Figure 4 and the significance of their discovery will be briefly discussed here.

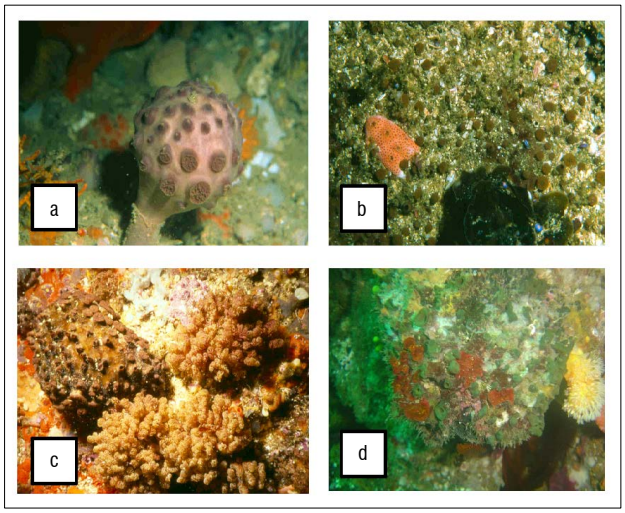


Figure 5: Underwater photographs of (a) *Tsitsikamma pedunculata*, (b) *Cyclacanthia bellae*, (c) *Strongylodesma algoaensis* and (d) *S. aliwaliensis* (photos: P. Colin and T. Samaai).

Table 2: Pyrroloiminoquinone alkaloids isolated from *Tsitsikamma favus* and *T. pedunculata*. IC_{50} (μm) cytotoxicity against human colon tumour cell line (HCT 116)[12] presented in parentheses.

South African Iatrunculid sponge species	Pyrroloiminoquinone alkaloids
Cyclacanthia bellae	damirone B (3.10 μM)
	makaluvamine C (1.09 μM)
	makaluvic acid A (28.40 μM)
	discorhabdin G* (0.33 μM)
	discorhabdin M (2.25 μM)
	1-amino-discorhabdin D (0.12 μM)
	1-methoxy-discorhabdin D (0.23 μM)
	1-alanyl-discorhabdin D (0.36 μM)
Strongylodesma algoaensis	1-amino-discorhabdin D (0.12 μM)
	3-dihydro-discorhabdin C (0.32 μM)
	discorhabdin A (0.007 μM)
	discorhabdin D (0.60 μM)
	discorhabdin H
S. aliwaliensis	damirone C [55.7; 78.3;77.8]
	makaluvamine I
	makaluvamine M [0.7; 6.8; 3.2]
	makaluvic acid C [>150; >150; >150]
	N-1-β-*D*-ribofuranosyldamirone C [37.9; 85.5; 66]
	N-1-β-*D*-ribofuranosylmakaluvic acid C [60.6; >200; >200]
	N-1-β-*D*-ribofuranosylmakaluvamine I [1.6; 5.7; 3.2]

Tsitsikammamine A and B were isolated from a 1:1 methanol:chloroform extract of *T. favus* (Figure 1) specimens collected from the Tsitsikamma National Park, along with the first discorhabdin analogues substituted at C-14 e.g. 14-bromodiscorhabdin C (Figure 4).[29] The tsitsikammamines were the first bis-pyrroloiminoquinone (with two pyrrole rings A and C fused to either side of the central iminoquinone ring B) to be isolated from a sponge[29], but were not the first compounds from this structural class to be isolated from a marine organism. Wakayin, which also possesses a bis-pyrroloiminoquinone structural scaffold (Figure 4), had previously been isolated from an ascidian, *Clavelina* sp.[32] The biosynthesis of marine natural products, in common with the biosynthesis of terrestrial plant natural products, is not random and the chemical structures of the major natural products usually reflect family and genus structural generalities and species specificity. Therefore, the occurrence of natural products with almost identical chemical structures in two different marine phyla is unexpected and may be a possible indicator of a shared microbial endosymbiont primary producer of the natural product(s), as opposed to serendipitous convergent evolution of secondary metabolic pathways in phyletic disparate marine organisms. In an effort to unequivocally establish the biosynthetic origin of the tsitsikammamines, a detailed community structure analysis of the symbiotic bacteria found in *T. favus* sponges collected from Algoa Bay is currently underway at Rhodes University.[9,33] The microbial community analyses are coupled to a metagenomic search for microbial biosynthetic gene clusters that might ultimately be responsible for the biosynthesis of the tsitsikammamines.

The structural novelty and bioactivity of the tsitsikammamines has attracted interest from synthetic chemists and tsitsikammamine A was first synthesised by Delfourne and co-workers.[34] A follow-up natural products study of Tsitsikamma National Park specimens of *T. favus* afforded two further minor metabolite analogues of the tsitsikammamines, both of which contain an N18-oxime moiety (Figure 4).[12] Marine natural products possessing either N-oxides or N-oximes moieties are rare and these two are the only examples of N-oximes amongst the known pyrroloiminoquinone metabolites. The closely related sponge, *T. pedunculata* (Figure 5a), collected from Algoa Bay yielded the same suite of discorhabdin compounds as that found in *T. favus,* in addition to four new minor discorhabdin metabolites also with C-14 substituents, e.g. discorhabdin V (Figure 4).[12] Interestingly, the tsitsikammamines were not present in extracts of *T. pedunculata*, and are therefore not genus-specific chemotaxonomic markers as tentatively initially proposed.[29]

Table 3: Pyrroloiminoquinone alkaloids isolated from *Cyclacanthia bellae*, *Strongylodesma algoaensis* and *S. aliwaliensis*. IC_{50} (μM) cytotoxicity towards either human colon tumour cell line (HCT 116)[12] or oesophageal cancer cell lines (WHCO1; WHCO6; KYE30)[40] presented in parentheses. The paucity of discorhabdin H and makaluvamine I isolated from *S. algoaensis* and *S. aliwaliensis* respectively, prevented an investigation of their cytotoxicity towards either human colon tumour or oesophageal cancer cell lines.

South African Iatrunculid sponge species	Pyrroloiminoquinone alkaloids
C. bellae	damirone B (3.10 μM)
	makaluvamine C (1.09 μM)
	makaluvic acid A (28.40 μM)
	discorhabdin G* (0.33 μM)
	discorhabdin M (2.25 μM)
	1-amino-discorhabdin D (0.12 μM)
	1-methoxy-discorhabdin D (0.23 μM)
	1-alanyl-discorhabdin D (0.36 μM)
S. algoaensis	1-amino-discorhabdin D (0.12 μM)
	3-dihydro-discorhabdin C (0.32 μM)
	discorhabdin A (0.007 μM)
	discorhabdin D (0.60 μM)
	discorhabdin H
S. aliwaliensis	damirone C [55.7; 78.3;77.8]
	makaluvamine I
	makaluvamine M [0.7; 6.8; 3.2]
	makaluvic acid C [>150; >150; >150]
	N-1-β-*D*-ribofuranosyldamirone C [37.9; 85.5; 66]
	N-1-β-*D*-ribofuranosylmakaluvic acid C [60.6; >200; >200]
	N-1-β-*D*-ribofuranosylmakaluvamine I [1.6; 5.7; 3.2]

Natural product investigations of two other Algoa Bay Iatrunculid sponges, *C. bellae* (Figure 5b) and *S. algoaensis* (Figure 5c), yielded a further 11 pyrroloiminoquinone pigments, including the known compound discorhabdin A and makaluvamine C and two new compounds, namely 1-methoxydiscorhabdin D and 1-aminodiscorhabdin D from the specimens of the former species (Figure 4).[12] Interestingly, discorhabdin H (Figure 4) isolated from *S. algoaensis* had also been previously identified from *L. lunaviridis* and *L. microcanthoxea*.[4] The isolation of discorhabdin H provided an opportunity to unequivocally establish the absolute configuration of this compound. Degradative hydrolysis of the (-)-discorhabdin H, followed by comparative chiral gas chromatographic analysis of derivatised hydrolysis products with the equivalent derivative of *L*-histidine, confirmed the 7'*S* configuration of the C-1 thiomethylhistidine residue.[12] The configuration of the remaining four chiral centres in discorhabdin were established, in collaboration with Copp in New Zealand, as 1*R*, 2*R*, 6*R*, 8*S* (Figure 4) by comparison of the electronic circular dichroism spectrum of (-)-discorhabdin H with that of a closely related model compound, discorhabin L, to which the application of time-dependent density functional theory calculations had been used to unequivocally establish the absolute configuration of this latter compound.[35]

A second *Strongylodesma* species, *S. aliwaliensis* (Figure 5d), collected from Aliwal Shoal, a sub-tropical reef system off Umkomaas in southern KwaZulu-Natal, South Africa, afforded three known pyrroliminoquinone compounds: e.g. makaluvamine M, a new pyrroloquinoline, makaluvic acid C, and three novel *N*-β-D-ribofuranosyl substituted pyrroloiminoquinone and pyrroloquinoline metabolites e.g. *N*-β-D-ribofuranosylmakaluvamine I (Figure 4).[30,31] The sugar moiety in the latter three compounds was identified by chiral gas chromatography comparison of the peracetylated aldononitrile derivative of the acid hydrosylate derived from each compound with a similarly peracetylated aldononitrile derivative of D-ribose. The three ribofuranosyl-containing metabolites from *S. alwaliensis* remain the only known pyrroloiminoquinone glycosides isolated thus far from marine organisms.

Biomedicinal potential of pyrroloiminoquinone alkaloids

The impressive bioactivity of pyrroloiminoquinone metabolites, consistent with their ecological role as feeding deterrents in sponges *vide supra*, is continuously reported in the chemistry literature. Pyrroloiminoquinones have been shown to exhibit cytotoxicity in a variety of whole-cell biomedicinal screening programmes, including screens designed to discover new chemical entities with anti-cancer, anti-malaria and anti-microbial activity.[28,36,37] In addition to whole cell screens, the bioactivity of marine pyrroloiminoquinones against medicinally relevant enzyme targets is also of interest.[28,38,39] The isolation of a large cohort of pyrroloiminoquinone metabolites from four species of South African Iatrunculid sponges provided a unique opportunity to explore the cytotoxicity (Tables 2 and 3) and structure activity relationship of 20 of these compounds against a human colon tumour cell line (HCT-116).[12] Discorhabdin A, with an IC_{50} of 7 nM, was the most active compound against this cancer cell line.[12] The tetracyclic pyrroloiminoquinone core structure was found to be essential for activity, while a Δ^7 olefin and substitution at C-1 in discorhabdins were found to enhance cytotoxicity.[12] A subsequent screening of the *S. aliwaliensis* metabolites against oesophageal cancer cell lines (WHCO1, WHCO6 and KYSE30; Table 3) revealed that makaluvamine M (Figure 4) was the most cytotoxic compound amongst those isolated from *S. aliwaliensis*.[40]

Research into the biomedicinal potential and the possible mechanisms of cancer cell cytotoxicity of the tsitsikammamines has not abated. We initially established that tsitsikammamine A's inhibition of the topoisomerase I enzyme, responsible for catalysing the relaxation of super-coiled DNA, and this compound's DNA binding affinity were both comparable with that observed for the structurally homologous wakayin.[12] In a subsequent comprehensive medicinal chemistry study, based around the chemical structure of tsitsikammamine A, Delfourne and co-workers synthesised both tsitsikammamine A[34] and a series of 43 analogues of this South African Iatrunculid sponge natural product[41,42]. Two of these analogues, in which pyrrole ring C was exchanged for a pyrazole ring, exhibited improved topoisomerase I inhibitory activity *cf* tsitsikammamine A[41], while a ring D-opened, bis-pyrroloquinone analogue of tsitsikammamine A exhibited low μM in vitro

growth inhibitory (IC_{50}) cytotoxicity against three different cancer cell lines[42]. The ensuing isolation of tsitsikammamine C[43] (Figure 4) from an Australian sponge *Zyzzya* sp. (family Acarnidae; Figure 2) with potent low nanomolar IC_{50} in vitro anti-malarial activity against chloroquine-sensitive and chloroquine-resistant *Plasmodium falciparum* malaria parasites, has opened the door to a new era of tsitsikammamine anti-malarial drug research.[44]

Conclusion

The taxonomy, chemistry, symbiotic microbial community structure and biomedicinal potential of South African latrunculid sponges continues to attract interest a quarter of a century after the first investigations of the natural products chemistry and cytotoxicity of extracts of *T. favus,* a widely distributed, endemic subtidal sponge within the Agulhas ecoregion. South Africa's position as a global hotspot of latrunculid sponge biodiversity is well established and the search for new latrunculid sponge species continues. The generally non-specific, potent cytotoxicity of pyrroloiminoquinone metabolites continues to hamper their development as new pharmaceuticals. However, research into new targeted drug delivery systems, incorporating pyrroloiminoquinone compounds and currently underway at the University of the Western Cape, may open new opportunities for marine pyrroloiminoquinone metabolites as possible anti-cancer or anti-malarial drugs.

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Authors' contributions

M.T.D-C. is the leader of the original research group working on South African latrunculid sponges and conceptualised the review and prepared the initial draft. E.M.A. and D.R.B. are key members of the original research group working on latrunculid sponge chemistry and bioactivity and provided critical review and commentary and assisted with the correction and editing of the original draft. T.S. is a key member of the original research group working on latrunculid sponge taxonomy and provided critical review and commentary and assisted with the correction and editing of the original draft.

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None

Plagiarism in South African management journals: A follow-up study

Internationally, a rise in plagiarism by academics has been reported. The objective of the present study was to examine the extent of plagiarism in articles appearing in 19 South African management journals published in 2016 and to compare the findings to a study undertaken in 2015 using 2011 data from the same 19 journals. This study progresses the debate around academic ethics and academic integrity in the country – a topic, thus far, that has received little research attention. A total of 454 published articles were submitted through the similarity detection software Turnitin™. High and excessive similarity was identified and over 80% of submissions evidenced similarity in excess of 9%. University administrators, journal editors and publishers, and the South African Department of Higher Education and Training are alerted to this plagiarism that undermines the academic pursuit. This awareness is particularly important as faculty serve as role models to students. Measures should thus be taken to ensure that faculty provide sound role models as ethical researchers.

Significance:

- Plagiarism is an ongoing and increasing problem and is particularly concerning when faculty themselves plagiarise, as it impacts institutional integrity and culture, and negatively influences role modelling for students.
- The present study highlights the increase in plagiarism in the field of management and alerts other fields of academia to this problem.
- University administrators and journal editors and publishers are reminded about the roles they can play to address plagiarism.

Introduction

While student plagiarism and academic dishonesty at universities are internationally recognised to be growing problems[1,2] and have been extensively examined[3-5], plagiarism by faculty themselves has received relatively less attention in the academic literature[6]. Honig and Bedi[7(p.101)], in this regard, believe that research into plagiarism by faculty is largely based on 'anecdotal and speculative evidence'. Plagiarism by faculty is on the rise[8]; Luke and Kearins[9] suggest that while universities often have detailed policies dealing with student plagiarism, they are less adept at dealing with plagiarism by their own faculty.

The objective of this study was to examine the extent of similarity in articles (indicating plagiarism) appearing in South African management journals published in 2016 and to assess whether a reduction or an increase in such plagiarism has occurred since the last published study on the topic in which 2011 data were analysed.

Plagiarism in academic journals is also associated with a financial cost. The South African Department of Higher Education and Training (DHET)[10] has adopted a system whereby universities are compensated, financially, for research generated by their faculty as a way to encourage the production of original and innovative research. Horn[11] notes that such income contributes substantially to institutional funding. In turn, many universities allocate part of this funding to the faculties, departments and individual academics who produced the publications – a practice not considered to be the norm elsewhere in the world[12] and one that could potentially promote unethical authorship[13]. Accordingly, this paper also serves to alert universities to the need to ensure that the research output submitted to the DHET for subsidy, is, in fact, the original work of the given author/s.

Literature review

Plagiarism and ethics

The major sins of academic publishing include duplication of material, co-submission of manuscripts and plagiarism.[14] Academic publications that incorporate the work of others without attribution constitute a serious academic transgression.[6] However, plagiarism is a complicated concept in an environment in which researchers are expected to advance knowledge by building on the works of others.[15] Boisvert and Irwin[16] suggest that cultural differences also play a role in plagiarism, e.g. in some cultures, copying the work of 'a master' is a form of respect.

In essence, plagiarism is considered to be verbatim or near-verbatim copying of text[16], submitting the work of another for credit and utilising words, ideas or data without acknowledgement[17], using someone else's intellectual product implying that it is original[18], intentionally or unintentionally mistaking intellectual property of another for common knowledge, or intentionally or unintentionally citing work in a misleading way[19]. Andreescu[20(p.779)] notes that the core of plagiarism involves 'the act of making one's own that which rightfully belongs to another'. All definitions of plagiarism, in essence, point to the appropriation of the work of someone else as one's own work.[16]

Plagiarism is a form of cheating and, therefore, can be considered to be unethical.[21] Integrity is at the heart of research[22] and plagiarism attacks the core value of academic integrity which is 'part of the bigger picture of personal integrity'[23(p.283)]. Plagiarism also 'strikes at the heart of academe', eroding the value of academic research[15(p.489)] by

calling into question the value of such research[15] and distorting science[18]. Plagiarism is especially devastating as the value of research lies in its rigour, objectivity and integrity.[15]

Hansen et al.[21(p.224)] suggest that plagiarism by faculty, specifically, 'continues to be repressed as an uncomfortable truth' and that such plagiarism constitutes a 'substantial ethical problem'. In this regard, not enough attention is paid to plagiarism, to the peer review process and to academic authorial ethics.[24]

Plagiarism by faculty

Concern about academic misconduct in the field of management has been noted in editorial comment in the prestigious *Academy of Management Journal*[25] and the *Academy of Management Review*[26]. Schminke[26] reports on a survey in which 16 former editors of top-tier management journals noted the ethical violations committed by academic authors. Such violations included the submission of manuscripts that contained work already published in other journals or the submission of multiple manuscripts that examined almost identical variables.

Bedeian et al.[27] collected data from faculty in 104 US business schools. They found questionable research practices that included data fabrication and falsification, plagiarism, inappropriate assigning of authorship and publishing the same data or results in multiple publications. Over 70% of their respondents reported being aware of colleagues who had plagiarised.

Bedeian et al.[27] report that research misconduct starts early in an academic career and is deeply rooted, while Schminke[26] adds that experienced authors contribute to the rise in ethical misconduct with most ethical violations not appearing to be cases committed by junior scholars who are unaware of the rules of academic publishing. Buckeridge and Watts[17] note how the academic culture of 'publish or perish' promotes competition, not cooperation, especially amongst emerging researchers.

Honig and Bedi[7] note the prevalence of plagiarism in research emanating from developing countries and Buckeridge and Watts[17] go on to state that intellectual theft is a hallmark in all 20th-century developing economies undergoing rapid industrialisation because of the absence of regulatory infrastructure and government acceptance of short-termism and practices where 'the end justifies the means'. It is only when societies modernise that the need to conform to international rules begins to apply and that novel and innovative ideas, crucial to competition, are rewarded.

Research has grown steadily in geographical areas that, until recently, had produced little research.[28] In this regard, the rules of research and publication are not embedded in the academic culture, leading to a proliferation of unsound research practices. Similarly, while capacity has been developed in African and South African research programmes over the last decade, largely as a result of the involvement of international research bodies, the advancement of research integrity has not developed simultaneously as a cultural norm.[11] The social value of research is that it is reliable and trustworthy and, accordingly, those who fund, manage, develop and implement research studies must promote ethical research practices and scientific integrity.[11]

Institutional factors that promote plagiarism

The factors that contribute to the increase in academic plagiarism are numerous. At the pinnacle, the quest to develop a university reputation, closely linked to research output, can be considered to be a factor that filters down to faculty and promotes cheating and plagiarism through pressure on faculty to publish. Woodiwiss[29(p.421)] notes how, in South Africa, the national and international reputation of a university is 'entrenched in its research profile which depends to a major extent on its publications and citation of these publications'.

During the 1960s, the phrase 'publish or perish' became widespread in the academic lexicon.[17] The culture that emerged from this mindset has had an impact on academic ethics, particularly the increase in plagiarism[24,27,28,30-32], leading Boisvert and Irwin[16] to remark that we are now confronted with a generation of young faculty who have not been taught the ethical issues that pertain to honest citation of sources. In this regard, the management discipline places great pressure on faculty to be regarded as academically sound by publishing as many articles as possible in the minimum time or be assigned high teaching loads which impact their career progression.[30]

The production of an excessive number of research articles invites institutional rewards such as attracting research grants[29], promotion[33], salary increases[17] and career and reputation advancement[17,24]. The persistence of plagiarism by faculty can be attributed to academic incentives and the publishing system.[34] In this regard, Woelert and Yates[35(p.11)] suggest that faculty have learned to distort output through 'gaming' the system which Kenny[36] then notes shifts the academic effort away from quality research. Coexisting with this internal system of practices is the ready access to tools that make plagiarism easier than in the past, such as the cutting and pasting of text[37] along with a proliferation of information on the web[38].

In summary, the institutional focus on numbers at the expense of quality of output[20] coupled with the pressure on faculty to perform and the attendant compromise of fundamental values such as quality and integrity within the research process[9], can all promote a culture in which plagiarism flourishes.

Role of journal editors and publishers in addressing plagiarism

While concern has been expressed by journal editors about the incidence of published articles containing plagiarism[18,34], dealing with plagiarism has largely not been addressed by these gatekeepers[7,14]. Publishers play an important role in detecting plagiarism as the last line of defence before the publication of plagiarised work.[15] However, although there is discussion about plagiarism, a level of confusion exists about acceptable publishing behaviour with a lack of consensus about the acceptable level of text and figure reuse.[14]

Hopp and Hoover[34] report on confusion in the understanding of the concept of plagiarism amongst a sample of 208 editors of management journals, leading to variations in reporting of plagiarism with only five editors requiring authors to submit their work through any plagiarism detection software programme.

Journal editors may not report cases of detected plagiarism because of the stress induced when conducting a thorough investigation of such alleged plagiarism, believing it may reflect poorly on the review processes and the brand of the journal or may incur conflict and costly legal measures.[15,38] This unwillingness of journal editors to publicly deal with plagiarism or to draw attention to the problem is on the increase.[15]

Enders and Hoover[39] conducted the first substantial survey of perceptions of plagiarism amongst journal editors in the economics profession. At that time, only 30% of journal editors agreed that publishing a notice of plagiarism in their journals would be appropriate. A later Internet survey by Enders and Hoover[40] indicated that approximately two-thirds of their sample believed that plagiarism could be addressed by a profession-wide code of ethics. Over 10 years later, Stitzel et al.[41] expanded the Enders and Hoover[39] study to other disciplines and found that 45% of journal editors in their sample reported having instituted a formal plagiarism policy, against the 19% reported in the Enders and Hoover[39] study. Stitzel et al.[41] believe that, increasingly, the problem of plagiarism is being taken more seriously, with approximately 80% of journal editors suggesting that when clear-cut plagiarism is detected, it would be appropriate to ban the plagiarist from submitting future work to the journal.

Journals and scholarly books provide the outlet for plagiarism.[15] Accordingly, journal editors and publishers are crucial to the academic project as they play a central role in preventing, detecting and disclosing academic plagiarism, and their actions, in this regard, support the integrity of the academic pursuit.

Journal editors and publishers can reduce the incidence of plagiarism in published works by apportioning journal space to discussing the topic of plagiarism to raise awareness and by publicly disclosing plagiarists.[15] Scholarly journals should have clear policies regarding plagiarism and should have authors sign agreement to such policies and guarantee original work[42] – a practice that decreases the incidence of plagiarism[34]. Journal editors and editorial boards should support peer reviewers who report plagiarism.[42] Others[16,43-45] advocate the use of software plagiarism

detection tools as routine practice by journal editors. Overall, journals that have adopted various measures to detect and deal with plagiarism, evidence a lower incidence of plagiarism than those that have less stringent measures in place.[42]

Role of universities in promoting academic integrity

Since the inception of universities, their two major tasks have been to create and spread knowledge and to develop students into professionals and good citizens.[46] Students need to be given knowledge of global matters and be encouraged to develop a moral sensitivity to human issues.[47] Students should be prepared to become critical, risk-taking citizens who will impact the world for the greater good, and be influenced by transformative intellectuals[48], and, accordingly, universities are powerful institutions of social, economic and cultural reproduction[49]. As such, universities should be institutions that provide influential role models to students in the development of ethical graduates who will go on to build ethical organisations.[50]

Faculty play a central role in role modelling ethical behaviour to students.[51] Universities, as the educators of future business leaders, cannot only teach ethical leadership as an academic subject, but must also role model ethical leadership in practice.[9] The educational power vested in universities through the moral climate of the institution, can influence the ideas, values and behaviours of students.[46] Any unethical practices at universities sends a loud message to the generation-in-training and substantial damage occurs when students are led to believe, though role modelling, that success is not linked to merit and hard work but is attained through fraud – plagiarism being one manifestation of such fraud.[31] Heckler and Forde[37] report that students are less likely to plagiarise if faculty take the issue of plagiarism seriously.

In the light of the above, addressing plagiarism by faculty themselves, should be critical in academic institutions. However, Luke and Kearins[9(p.888)] propose that academic leaders 'may have become too busy with the business of education and performance measures' which has distracted them from dealing with breaches of academic integrity such as plagiarism, which is now in danger of being transformed from an individual problem of wrong-doing into an institutional norm in a 'publish or perish' environment. Poignantly, Luke and Kearins[9(p.882)] suggest that academic leaders and institutions 'appear to have lacked a moral script for action'. Lewis et al.[15] note the link between a decrease in plagiarism and the willingness of the academic community to expose academic plagiarists. Errami and Garner[14] support the view that public exposure of plagiarism transgressions could be an effective deterrent. Elliott et al.[52(p.93)] note that 'the tone at the top' drives acceptable or unacceptable organisational behaviour and that when unethical behaviours are not addressed, a culture results in which such behaviour proliferates and is conveyed to staff and students.

While plagiarism may never be completely eliminated, good governance is at the core of addressing this problem.[23] To this end, a culture of academic honesty should prevail in institutions that, in turn, institutionalise an ethical culture amongst faculty.[52] Bedeian et al.[27] extend this view to advocating that the research values of those entering into the management discipline must be shaped and that graduate students must be socialised into ethical academic life, including research. Management faculty have a professional obligation to report research misconduct in spite of their reluctance, desire to avoid conflict and even potential career damage through their own integrity being cast into doubt.[26] Peer reporting of academic plagiarists, protection of whistle blowers and severe punishment for faculty who engage in plagiarism and fraud should be the practice.[52] In this regard, the entire academic community is the first line of defence in preventing plagiarism.[15] Similarly, Long et al.[38(p.1294)] note that 'the responsibility for research integrity ultimately lies in the hands of the scientific community', with educators ensuring scientific integrity in the work of students whom they mentor, with authors committing to originality and accuracy of published work, with volunteer peer reviewers conscientiously reviewing publications, and with journal editors verifying the manuscripts they wish to publish. Other factors that could contribute to addressing plagiarism include the avoidance of unrealistic performance standards and publication pressure, excessive peer competition and brutal careerism.[27]

In summary, when dealing with plagiarism prevention and detection, professional associations that sponsor journals should establish policies and codes for dealing with plagiarism that transcend social and cultural borders, the academic community should be vigilant and support whistle blowers, publishers should verify the originality of manuscripts and articulate, enforce and publicise penalties for authors who plagiarise and plagiarism detection software should be used by universities, professional organisations and publishers.[15]

Method

Sample

All 454 peer-reviewed articles published in 2016 in 19 South African management journals, covering the major management fields, comprised the sample. These 19 journals are the same journals used in the 2015 study by Thomas and de Bruin[53]. The DHET remits subsidy to universities and research institutions for articles published in journals on prescribed lists, amongst which are the local DHET list, the Clarivate Analytics Web of Science (WoS) list and the International Bibliography of the Social Sciences (IBSS) list. The majority of articles were contained in the local DHET list, with 115 appearing on the IBSS list and 100 appearing on the WoS list.

The 454 journal articles were authored or co-authored by 995 researchers, with 67 researchers being affiliated to foreign universities or institutions.

Data collection

All articles were submitted through Turnitin™ to check for similarity between the articles and other published materials. After submission of a manuscript to this software program, the manuscript is compared to billions of Internet pages, online publications, digitised books, journals and student dissertations and theses. A report is generated which provides a similarity index, i.e. a statement of the percentage of text in the submitted document that is similar to other material in the Turnitin™ data base. This report indicates material that could be considered to be plagiarised. The data were inspected twice by the researcher. A conservative approach was adopted in the process of excluding material after each individual report was scrutinised. At the outset, the following items were excluded: strings of 10 or fewer words, quotations, and the bibliography/list of references. The following instances of similarity were also excluded during a second inspection of each report: abstracts that were cited in scientific databases, self-citations, previous conference papers, working papers (previous drafts) or student dissertations and theses on which the manuscript was based, statistical formulae, figures and tables, and country statistics or other country-related data. Thereafter, an independent person with knowledge of the process also checked the data. Whenever there was any doubt about similarity, the author of the manuscript in question was given the benefit of the doubt. The Turnitin™ program itself does not always detect similarity[54-56], again underlining the conservative nature of the findings.

The study was granted ethics clearance by the University of Johannesburg (CBEREC18JBS01). As all data are in the public domain, no ethical issues of disclosure arose. In addition, the names of individual authors, institutions and journals are not disclosed.

Data analysis

The findings relate to data obtained in 2016. These data were then compared with the data collected in 2011 and reported on by Thomas and de Bruin[53] in 2015, hereafter referred to as the 2015 study.

As with the 2015 study, means were trimmed and standard deviations Winsorised to reduce the influence of outliers[57] and analyses of variance (ANOVAs) were conducted to determine differences in similarity scores in journal groups and number of authors.

Independent samples *t*-tests and chi-square tests of independence were conducted to compare the data of the 2015 study to those of the current study. Appropriate effect size tests were employed to determine the impact of the size of the samples on the statistical results obtained.

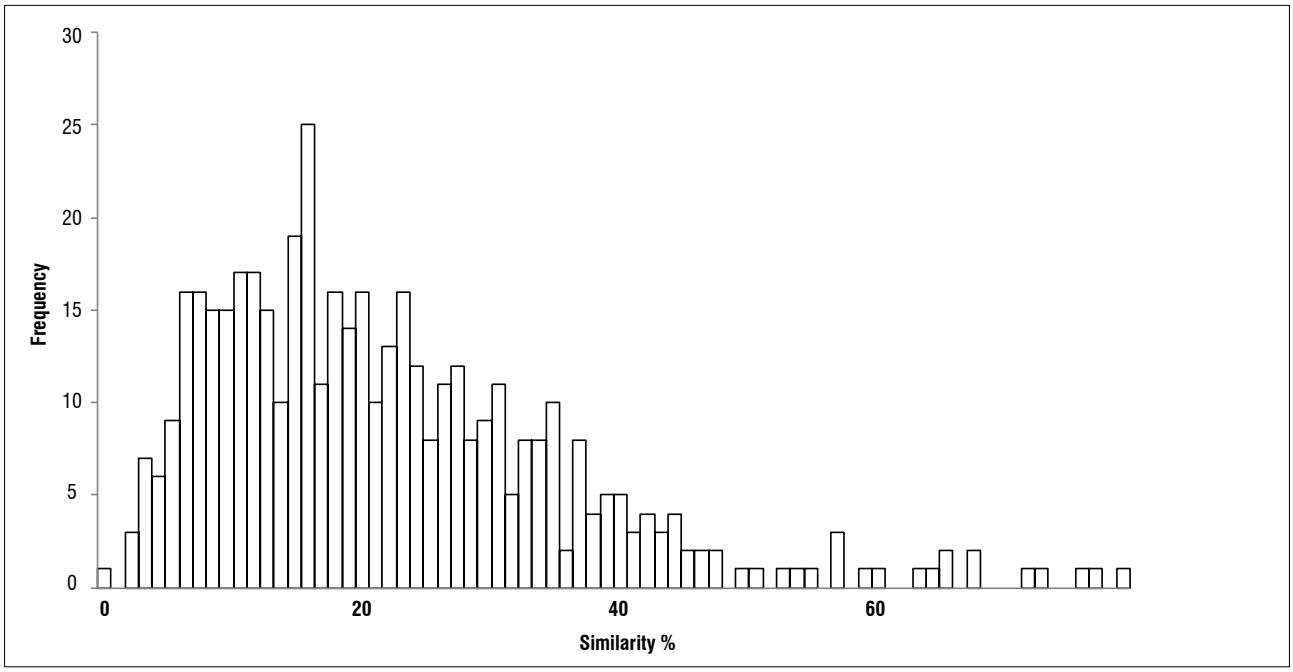

Figure 1: Distribution of the similarity index across 454 articles.

Results

Across the 454 submissions (371 in the 2015 study) the similarity index (i.e. the percentage of similarity between an article and the documents in the Turnitin™ database) ranged from 0% (indicating no similarity) to 75% (indicating substantial similarity). Figure 1 indicates that the distribution of the similarity index across the 454 submissions was positively skewed.

The mean similarity index across the 454 submissions was 20.87 (cf. 17.10 in the 2015 study), s.d.=13.28 (12.15 in the 2015 study). The mode was 15 (9 in the 2015 study), the median was 18 (14 in the 2015 study), and the 20% trimmed mean was 18.75 (14.70 in the 2015 study). The 95% confidence intervals for the 20% trimmed mean were 18.06 and 19.43 (13.61 and 15.89 in the 2015 study). The Winsorised standard deviation was 8.04 (6.67 in the 2015 study).

An independent samples *t*-test on the trimmed mean similarity index of the data in the 2015 study and the present sample suggests that the mean similarity index in the present study is significantly higher (t=-8.4, d.f.=491, p=0.000: eta-squared=0.125, indicating a large effect size).

The relative frequency of plagiarism was categorised, as in the 2015 study, as: 1% to 9% being low similarity; 10% to 14% being moderate similarity; 15% to 24% being high similarity, and >24% being excessive similarity. Table 1 provides a summary of the frequencies for the present study in these categories and a comparison with those of the 2015 study.

Table 1: Similarity according to extent in categories

Category (%)	2015 Study			Present study		
	n	%	Cumulative %	*n*	%	Cumulative %
None: 0				1	0.2	0.2
Low: 1 to 9	118	31.8	31.8	87	19.2	19.2
Moderate: 10 to 14	73	19.7	51.5	78	17.2	36.4
High: 15 to 24	101	27.2	78.7	141	31.1	67.5
Excessive: 25+	79	21.3	100	147	32.5	100.0
Total	371	100		454	100	

Whereas the 2015 study found that the number of submissions falling into the low and moderate similarity categories (51.5%) was almost equal to the proportion falling into the high and excessive categories (48.5%), the current study found that the situation has deteriorated. In the current study, only 36.4% of the submissions fell into the low and moderate categories with 63.6% falling into the high and excessive categories. As in the 2015 study, if a cut-off point is taken of a 9% similarity index, then it is evident that 80.8% (68.2% in the 2015 study) of the submissions evidenced similarity above this cut-off point. Of concern is that 32.5% (21.3% in the 2015 study) of the submissions evidenced an excessive amount of similarity. A chi-square test of independence of the degree of similarity and year suggests degree of similarity was higher in the current study (Pearson's chi-square=24.8, d.f.=4, p=0.000, Cramer's V=0.173 (moderate effect size)).

As in the 2015 study, the means of the similarity indices were compared between journal groups. The results are noted in Table 2.

Table 2: Similarity index (20% trimmed mean) by journal group

Journal group	2015 Study			Present study		
	20% Trimmed mean	Winsorised s.d.	*n*	20% Trimmed mean	Winsorised s.d.	*n*
DHET	13.69	6.45	201	18.61	7.78	239
IBSS	16.67	7.90	108	18.45	7.91	115
WoS	14.89	5.96	62	18.75	8.81	100
			371			454

DHET, Department of Higher Education and Training; IBSS, International Bibliography of the Social Sciences; WoS, Web of Science

Note: Minor differences from the original publication are a result of minor differences in statistical formulae.

An ANOVA found that there was no significant difference in scores across the three journal categories (F=0.6, d.f.1=2, d.f.2=269, p=0.569, previously F=2.2, d.f.1=2, d.f.2=96, p=0.110). This finding is the same as that of the 2015 study. In order to compare whether there was any change in the similarity scores for each journal group,

t-tests were conducted to compare the data from the 2015 study and that of the present study. Only for the IBSS journals was the similarity not statistically different to that reported in the 2015 study (t=-1.8, d.f.=131, p=0.075). In the DHET journals (t=-7.8, d.f.=259.947, p=0.000, eta-squared=0.190 (large size effect)) and the WoS journals (t=-4.2, d.f.=93.71, p=0.000, eta-squared=0.153 (large size effect)), the similarity scores for data in the present study were found to be significantly higher than those reported in 2015.

In the 2015 study, the 10 journals containing at least 20 articles were isolated. The 20% trimmed mean similarity indices for journals in the 2015 study ranged from 10.07 to 22.94. A robust ANOVA on 2015 similarity scores for the 10 journals suggested that there was a significant difference in trimmed means (F=8.5, d.f.1=9, d.f.2=150, p=0.000, eta-squared=0.336 (large effect size)). Post-hoc tests show that the main effect was a result of one journal (that with a similarity index of 22.94) evidencing significantly higher similarity than other journals.

In the current study of the same 10 journals isolated in the 2015 study (n=331), the 20% trimmed mean similarity indices ranged from 12.59 to 28.68. An ANOVA conducted on the current similarity scores for the 10 journals suggested a significant difference in scores (F=12.3, d.f.1=9, d.f.2=189, p=0.000; eta-squared=0.369 (large effect size)). Post-hoc tests showed a number of differences between journals. Three journals evidenced a significant difference in similarity indices (20% trimmed mean) between the 2015 study and the present study (all large effect size).

Of interest, is that the journal with the lowest similarity index in the 2015 study again had the lowest similarity index in the present study. The journal with the second lowest similarity index in the 2015 study, however, evidenced the highest similarity index in the present study.

The similarity indices of single-, dual- and multi-authored articles were again considered. The results compared with those of the 2015 study are shown in Table 3.

An ANOVA performed on the 2015 study similarity scores for the three author groups suggested that there was no significant difference in scores. In the present study, there was a significant difference in scores (F=7.6, d.f.1=2, d.f.2=269, p=0.001; eta-squared=0.053, small to medium effect size) (2015 study: F=2.2. d.f.1=2, d.f.2=220, p=0.106). Post-hoc tests showed that multi-authored articles evidenced significantly higher similarity than single- and dual-authored publications. Single- and dual-authored articles did not have significantly different similarity indices.

Table 3: Similarity index (20% trimmed mean) by number of authors

Number of authors	2015 Study			Present study		
	20% Trimmed mean	Winsorised s.d.	*n*	20% Trimmed mean	Winsorised s.d.	*n*
Single	15.17	8.06	90	17.74	8.67	104
Dual	15.16	6.94	179	17.82	7.70	207
Multi	13.58	6.17	102	20.69	8.06	143
			371			454

Note: Minor differences from the original publication are a result of minor differences in statistical formulae

The similarity scores of single-, dual- and multi-authored articles in the 2015 study were compared with those in the current study. It was found that single-authored indices in the present study were significantly higher than those in the 2015 study (t=-2.4, d.f.=114, p=0.019; eta-squared=0.047 (moderate effect size)). The similarity indices of dual- (t=-3.8, d.f.=230, p=0.000; eta-squared=0.060) and multi-authored articles (t=-8.5, d.f.=144.89, p=0.000; eta-squared=0.333 (large size effect)) in the current study were also significantly higher than the similarity indices of dual- and multi-authored articles reported in the 2015 study.

Discussion

The objective of the study was to identify the extent of plagiarism in articles published in 2016 in 19 South African management journals and to compare the findings to those of a similar study[53] based on articles published in the same 19 journals in 2011. The general finding was that plagiarism has increased from the 2015 study to the current study. The increase seems to be across the board, irrespective of journal, journal group (except one) and number of authors/co-authors.

The findings of the present study in which 2016 data were analysed indicate that similarity, implying plagiarism, has increased substantially since the findings reported in the Thomas and de Bruin[53] 2015 study in which 2011 data were analysed, i.e. over a 5-year period. This finding gives credence to the concern expressed by others about the growing problem of plagiarism[1,2] and the rise in plagiarism by faculty specifically[8,16].

Whereas in the 2015 study almost equal numbers were found for the low/moderate categories (i.e. 1–14% similarity) and the high/excessive categories (i.e. more than 14%), in the present study only 36.4% of articles were in the low/moderate categories with 63.6% residing in the high to excessive categories (i.e. similarity over 14%). In the 2015 study, 21.3% of articles were found to have excessive similarity, while now 32.5% fall into this category. If a 9% cut-off point is taken, 80.8% of the submissions in the present study evidenced similarity of 10% or more compared with 68.2% in the 2015 study. The robust tests indicate the magnitude of these differences and that they are strong and substantive.

When considering the 2015 study, no difference in level of similarity was found between the three categories of journal groups – DHET, IBSS and WoS. This finding indicates that the increase in plagiarism has occurred in publications across the board and is not limited to certain groups of journals. However, only for the IBSS category was there no significant increase in the level of similarity between the 2015 study and the present study; for both the DHET and WoS journal groups, the similarity index was higher in the present study than that reported in the 2015 study.

As in 2015, 10 journals each publishing more than 20 articles were isolated for analysis. In the 2015 study, only one journal published articles with higher similarity indices than those in the other journals. In the present study, three journals showed significant differences in terms of similarity indices. The journal with the lowest similarity index in the 2015 study, again had the lowest similarity index in the present study in spite of more than doubling the number of publications. However, the journal with the second lowest similarity index in the 2015 study was found now to have the highest similarity index in the present study with every article having a similarity index in excess of 9%. These findings would seem to indicate that there may be a slackening of editorial control in this journal. If this is the case, it could be expected that those researchers seeking out means to publish quickly, in the light of the 'publish or perish' syndrome, could target such a journal. This finding demands that journal editors and publishers remain vigilant and publicise their strategies to ensure research integrity as well as clearly state the consequences for those who plagiarise.

Whereas no significant differences in similarity scores were found in the 2015 study between single-, dual- or multi-authored articles, in the present study, multi-authored articles appeared to have a greater degree of similarity. While all authors in a multi-author cohort could, theoretically, hold the same attitudes towards plagiarism and evidence weak research ethics, it could also be true that not all members of a cohort are ethically compromised. This finding strongly suggests that individual authors must be attentive to work submitted for publication even if sections of the manuscript were written by other parties in the cohort.

That plagiarism exists at all in work that has been through a peer-review process and published should raise alarm bells; that such plagiarism has increased over a 5-year period gives greater reason for concern. Plagiarism goes to the heart of academic integrity[15] and calls into question the value of the research being produced in the management field in South Africa.

The DHET pays a qualifying university approximately ZAR100 000 per article published in a journal on prescribed lists. If a cut-off point of >24% similarity is taken (the excessive category), it is noted that 98 articles fall into this category (the balance of 49 articles were produced by foreign authors only or foreign authors/authors at private institutions in conjunction with South African authors). Conservatively, including only the 98 articles, it appears that the DHET paid around ZAR9.8 million in subsidy to universities and research institutions for questionable work (i.e. publications with a similarity index >24%).

Recommendations

Based on the findings of the study, four main recommendations are furnished to faculty, university administrators and journal editors and publishers.

First, universities need to remain vigilant about the quality of research that is being produced by their faculty and a culture of zero tolerance should be created for work that involves cheating and misrepresentation of originality. The quest for research output to enhance reputation[29] must be balanced with the assurance of quality and the incentives linked to research output (overt and tacit) must be examined to ensure that they do not work against a culture of research integrity[12]. In this regard, the practices surrounding the 'publish or perish' syndrome[17] need to be exposed and examined. The role of universities in promoting sound research ethics is all the more important when one considers the influence that universities have on the students who are taught and mentored into researchers.[51] The growing multi-culturalism at South African universities demands that effort be expended on schooling those new to research in the practices of ethical research production. Studies have noted how ethics in research can lag in developing economies.[7,28] In this regard, Horn's[11] plea – for those who fund and manage research projects in the country to be vigilant about the development of integrity in research – should not be lost.

Second, higher education authorities need to be aware of the problem of plagiarism in journals and to re-examine the subsidy policy. The policy, which commenced as a way of encouraging original and cutting-edge research, has unfortunately been exploited by both universities and academics alike. It is highly recommended that the DHET should now require universities to prove that the research for which subsidy is claimed, is unique and original in terms of its policy.[10]

Third, journal editors and publishers are the final gatekeepers before publication. In spite of the time and stress related to vigilance around ensuring that only original work is published, and in spite of costly legal measures that may need to be taken if plagiarism is detected[38], these gatekeepers play a critical role in ensuring that society is informed by original studies. Journals should publicise their policies on research ethics and on plagiarism, and software programs that alert editors to similarity of material should be used, and if substantial plagiarism is detected, measures should be taken to expose the plagiarist. As Shahabuddin[42] notes, those journals that adopt measures to address plagiarism appear to evidence less plagiarism in the articles they publish than journals which have no such measures in place.

Fourth, given that similarity was found to be highest in multi-authored publications, it is recommended that authors themselves remain vigilant when co-publishing papers and that such papers be checked, routinely, for evidence of similarity to other work. As many of the articles appear to be based on student dissertations and theses, it is further recommended that such student work be submitted through a similarity detection program prior to submission for examination – a practice that has now been adopted at some universities in South Africa. This approach would ensure that any potential plagiarism is detected at its source.

Limitations of the study

The major limitation of the study is that in the process of interpreting the Turnitin™ similarity reports, human error in data coding is always a potential problem. This was addressed by the researcher interpreting each report twice and then having a second academic review the lists of raw data to check for anomalies. A second limitation was that not all management journals could be accessed as, in the case of two journals, a protection mechanism prevented the articles from being submitted through Turnitin™. However, the range of 19 journals covered the major fields of management research and was deemed suitable for the present study.

Recommendations for future research

Emanating from the present study, future areas of research could include the following:

- A study that compares similarity in management journals domiciled in developing countries and those domiciled in developed countries could indicate whether or not the problem of plagiarism is currently globally evident or has been addressed since the publication of earlier studies. Such information could alert universities and journal editors to the problem of plagiarism if this is shown still to be on the increase, and measures to address this practice could be adopted in both those domains. In addition, such a study would promote a comparison between the findings of the present local study and international data.
- A qualitative study of South African management journal editors involving their perceptions of plagiarism would provide insight into the steps being taken to detect and address this problem. It would be interesting to gain some insight into the level of concern of journal editors about this problem and the strategies contemplated to deter and deal with submissions that contain high levels of similarity to other published work.
- Chrysler-Fox and Thomas[58] discuss a typology to assist in categorising the types of plagiarism that can occur in academic material. Using this typology, it would be interesting to interrogate the current data to uncover the nature of the plagiarism that exists in the high to excessive categories. Understanding the nature of the plagiarism that has been perpetuated in these submissions could inform strategies to assist researchers in producing original work.

Conclusion

The aim of this study was to progress the debate on ethics in research in South Africa and to alert universities, journal editors and publishers, and the government DHET about the state of plagiarism in management journals.

The findings indicate that plagiarism in South African management journals is on the increase, thus supporting other studies that indicate the rise of plagiarism internationally.[1,2,15] This finding is of immense concern as it threatens the integrity of the information that is shared in society and amongst academics by means of research publications. It also goes to the heart of the academic pursuit which should be that of generating new and innovative ideas to inform practices that create a better society. Faculty who publish in management journals should be concerned about their reputations by association with these practices, as should university administrators, the employers of those who choose to plagiarise. Addressing this problem requires a concerted effort and commitment by faculty themselves, by universities through which the publications are sanctioned and rewarded, by peer reviewers who need to be vigilant in detecting plagiarism and by the ultimate gatekeepers, the journal editors and publishers. It is suggested that only through this united effort will the increase in plagiarism be halted and hopefully eradicated in management publications.

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Nurdle drifters around South Africa as indicators of ocean structures and dispersion

Dispersion processes in the ocean typically involve wind, ocean currents and waves. All these factors were included in an analysis to model nurdle dispersion from an accidental spill in Durban Harbour, South Africa, in October 2017. Nurdle sightings on beaches by members of the public are used as indicators of the dispersion which extended over 2000 km of the South African coastline in a period of 8 weeks. Using known oceanographic current structures, satellite imagery, wave data and surface wind drift values of between 5% and 8% of wind speed, good agreement was found between the modelled dispersion and nurdle sightings. In particular, it was found that nurdles remained in specific sections of the coast for long periods, and that sporadic wind events were required to move them into new coastal areas. Such results may also contribute to understanding the dispersal behaviours and strategies adopted by larval stages of marine organisms, particularly fishes, that have pelagic larval durations that extend over weeks to months. The event was recognised as a major pollution incident rivalling other nurdle spillages reported worldwide, and extensive efforts were made to collect the nurdles, particularly along the northern KwaZulu-Natal coast. However, 9 months later, less than 20% had been recovered. The results emphasise the connectivity of different ocean regions, and in particular that pollution of the ocean is not a localised activity. Matter discharged at one point will disperse over a wide area – in this case, significantly further afield than the area of recovery operations.

Significance:

- Wind drift in the upper metre or two of the ocean has been notoriously difficult to quantify, and the spread of nurdles along the South African coastline can only be explained by using drift percentages two or three times the generally accepted value of 3% or less. Nonetheless, it is important to realise that there are substantial differences in dispersion rates between the upper few centimetres of the ocean and that even a metre or two deeper.
- The rapid manner in which nurdles, and other microplastics, can be dispersed is important in terms of understanding the spread of this form of pollution in the world's oceans. The results also confirm the important role that wind can play in the movement of eggs, larvae and invertebrates and the significance of vertical migrations in and out of the surface layers.
- Finally, the results confirm many of the accepted coastal current regimes on the east and south coasts of South Africa. Moreover, it is shown that certain sections can have very long residence times, where drifters are only removed under sustained wind conditions.

Introduction

On 10 October 2017, a storm caused by an upper air cut-off low hit Durban on the South African east coast. It caused considerable damage, and in particular in Durban Harbour at least two 12-m-long shipping containers were washed off the carrier MSC *Susanna*.

The severely ruptured containers were allegedly left submerged in the harbour for several days before the contents became known. First responders were the public who noted that tiny plastic pellets (nurdles) were washing up on local swimming beaches in the days after the storm. Almost a month later, the scale of the spill precipitated the engagement of local and global salvage and emergency response companies to clean 200 km of beaches north and south of Durban. It is estimated that approximately 49 tonnes – representing some two billion microplastic nurdles – were spilled into Durban Harbour during this incident. Information on the spill was coordinated by CoastKZN, an interactive web-based information portal maintained by the Coastal Zone and Estuaries research groups at the Oceanographic Research Institute (www.coastkzn.co.za), Durban.

Nurdles are small polyethylene pellets – approximately the size of a lentil (5 mm in diameter) – and serve as raw material in the manufacture of plastic products. They are made from synthetic substances and petrochemical products that give them high mouldability for such manufacture.

In the ocean, nurdles are buoyant, float on the surface and come under the direct influence of winds, waves and ocean currents. This and their environmental persistence mean that they are distributed widely in the world's oceans and deposited on beaches even in remote locations. Further information about nurdles, including their fate and effect in the environment, can be obtained from organisations such as International Pellet Watch (www.pelletwatch.org).

Shortly after initial deposition on KwaZulu-Natal (KZN) beaches, these microplastics were found on the entire south-east coast of South Africa and later also to the west along the south coast. The movement of nurdles in this study is based on first reports of where nurdles were found on beaches, primarily by members of the public coordinated by a social media group (the KZN Waste Network) formed to communicate and report sightings. As such it cannot be considered definitive, although media reports served to make this a popular topic, and the public were then particularly aware of what to look for and where to report sightings. Of the estimated 49 tonnes spilled, just over 9 tonnes had been recovered by February 2018. Later, salvage of the nurdles by response teams (25.8 tonnes until October 2018)

may provide evidence for longer-term circulation systems within and beyond the KZN shelf.

Despite the inherent and likely long-lasting effects of this local disaster, it afforded an opportunity to study nurdle movement, firstly off KZN and then off the southeast and south coasts in the context of deposition locations and drift duration before settlement. The analysis presented attests to a remarkably rapid dispersion of this plastic pollution and demonstrates the manner in which ocean regions are intimately connected. As such, these results may also provide valuable insight into the dispersal and population connectivity of the pelagic larval stages of marine organisms such as fishes.

A brief background of known oceanographic conditions in the relevant regions is given first, followed by a discussion of the dispersion effects of winds, waves and currents. Nurdle movement is considered only for the first 8 weeks after the spill as that is when the most specific and traceable movements in the ocean occurred. Thereafter other effects such as deposition on the shore, burial, re-exposure and re-transportation offshore would have become increasingly important.

Moreover, UV-exposure and mechanical abrasion effects on the plastic drifters may influence nurdle buoyancy[1] and as movement of the nurdles under the influence of wind and waves is critically dependent on their position in the water column, the dispersion trajectories could also vary. Some nurdles remained for long periods in close proximity to selected coastal areas, possibly being washed onto beaches and then moved again by subsequent waves, while others were taken far into the deep ocean.

Ocean environment

Investigations into the oceanic environment off the east and south coasts of South Africa have been ongoing for decades[2], and only a brief description of relevant features is given here.

The region is dominated by the Agulhas Current, a western boundary current constrained by planetary vorticity considerations to flow southwestwards along the shelf edge on the southeast coast of South Africa.[3,4] Warm oceanic water from the tropics and subtropics is taken southwestwards as a narrow, fast-flowing tongue of water[5], with a 4° to 5° cooling of surface waters from north to south (Figure 1). Surface current speeds in the core of the Current can exceed 2 m/s, with a marked offshore speed gradient on the inner boundary, as well as with depth.

The core of the Agulhas Current generally lies offshore of the shelf break. However, off the KZN coast, the variations in coastline orientation and terrace-like bathymetry result in a distinct region to the north of Durban and inshore of the Current termed the KZN Bight (Figure 1). The Agulhas Current generally lies 40–50 km offshore in this area and a northwards flow is evident off Durban.[6,7] On the shallow shelf off Richards Bay, Schumann[8] found that the currents were essentially wind-driven, while Lutjeharms et al.[9] confirmed that persistent upwelling occurs in the northern Bight as the Agulhas Current moves offshore north of Richards Bay.

Roberts et al.[10] provide a review of past investigations, and also conducted intensive measurements using a number of different data sources to obtain a synoptic picture of circulation patterns off KZN. Their results corroborated the earlier investigations with a cyclonic circulation evident for much of the time, although on occasion northeast or southwest currents occurred along the entire Bight. With smaller mesoscale eddies evident, a longer residence time of at least 14 days was found, particularly in the northern section.

The shelf narrows south of Durban with a consequent onshore movement of the Agulhas Current as a result of the inherent vorticity structures.[11] Consistent onshore flow occurs some 50 to 60 km south of Durban, with a recirculation northward flow from that area.[12] This is referred to as the Durban eddy[13] and, when present, northeastward currents can reach up to 1 m/s[14].

Meanders in the flow are seen on a regular basis, with the larger-scale Natal Pulse occurring several times a year[15], although the definition of such large meanders is open to interpretation[16]. The origin of the meanders appears to lie off KZN with a breakaway at the Durban eddy, or otherwise farther north in the KZN Bight.[13] At the time of the nurdle spill, satellite imagery does not depict evidence of a Natal Pulse or any other major meanders in the flow (Figure 1).

To the south of Port Edward, the narrow shelf means that the Agulhas Current flows generally close to the coast, while south of East London

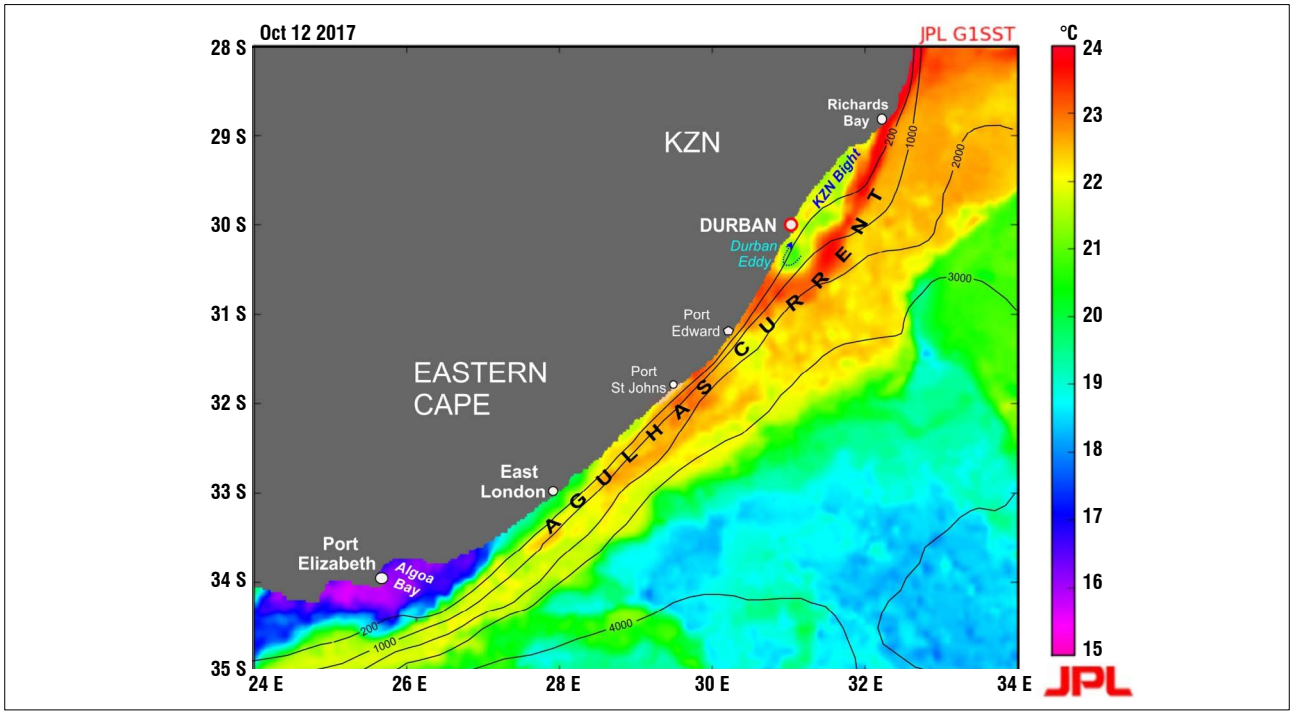

Image courtesy of the NASA Jet Propulsion Laboratory (JPL).

Figure 1: The southeast coast of South Africa impacted by the nurdle release. Sites mentioned in the text are shown, with the nurdle release point at Durban circled in red. Bathymetry is given in metres while the shelf break occurs near the 200-m isobath. The warm waters of the Agulhas Current can be identified on the sea surface temperature (SST) scale.

the shelf widens again, forcing the core of the Current farther offshore. As the coastline veers west, colder water is often observed close to the coast, upwelled by a combination of widening isobaths, bottom boundary flows and winds.[17] The widening Agulhas Bank forms a complex inshore region dominated by winds, insolation effects, coastal morphology and bathymetry as the influence of the Agulhas Current diminishes.[18]

Winds play a dominant role in the motion of the upper layers of the ocean. The major axes of coastal winds around South Africa generally follow the coastline.[19] Nonetheless, local coastal features can result in wind regime changes, e.g. off KZN[20] and Algoa Bay[21].

Effects of winds, waves and ocean currents on nurdles

Nurdles are buoyant and float at or near the sea surface, while it is likely that a small percentage could also protrude above the sea surface. As such, their movement in the ocean is primarily a result of prevalent winds, waves and larger-scale ocean currents. The inherent turbulence in the surface layers ensures a continual movement of nurdles in and out of the surface and the layers immediately below.

Orbital velocities of particles under ocean waves are not precisely circular, and there is a net forward motion, termed the Stokes Drift, which is dependent directly on wave period and height and inversely on wave length. Frictional effects of wind moving over the ocean surface will also induce a movement of water in the direction of the wind, decreasing rapidly with depth. Moreover, these two processes are not independent of each other, because winds are also the primary mechanism in generating waves.

The ocean surface is a very complex regime, and it has been difficult to precisely measure the processes involved in the movement of floating material. Most investigations have considered movement in a near-surface layer a few metres deep and have found a drift of between 1.5% and 4.1% of wind speed.[22] Laboratory and theoretical studies[23] have determined a commonly accepted value of 3%. Veering to the right in the northern hemisphere as a result of the Coriolis force was found to vary between 0 and 34°.

The small size of the nurdles means that it is important to know what happens in the upper 10 mm of the sea surface. A recent investigation by Laxague et al.[24] was able to measure the net surface movement under winds of 4.3 m/s and small waves (period 1.9 s and significant wave height 0.86 m). A drift of over 13% of wind speed was found in the top 10 mm, with this movement more than twice that over the top 1 m and more than four times that over the top 10 m (Figure 2). No veering was found in the upper 0.5 m, but it did increase with depth.

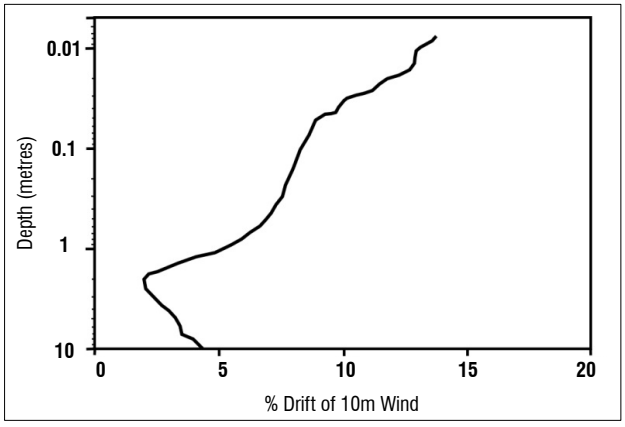

Figure 2: Wind and wave drift profile in the upper 10 m with a wind speed of 4.3 m/s and waves with a wave period of 1.9 s and significant wave height of 0.86 m (adapted from Laxague et al.[24]). Note the logarithmic depth scale.

These results show that wind and waves can cause substantial movement of material floating on the surface of the sea. At this stage it is not clear in what manner these results can be extrapolated to stronger winds and bigger waves; moreover the situation will be more complex if winds and waves are acting in different directions. However, because of the turbulence in the upper few metres, nurdles will be spread out over this whole regime, involving a range of drift speeds. In this analysis movement of nurdles between 3% and 10% of wind speed will be considered as a compromise for the range of depths where nurdles would have been situated; Figure 2 indicates that values could be higher in the very near surface.

Moreover, the effect of an underlying, large-scale ocean current is included as a scalar add-on. In the case of the fast-flowing Agulhas Current the added movement of surface drifters will in many cases be substantially higher than that from wind alone.

At the coast the transport of nurdles onto beaches will have depended on prevalent waves and tides and will also have been in a continual state of deposition and removal. With millions of nurdles present, many would have found their way onto the beaches for people to find – most likely at the wrack line from the highest daily tide.

Data and analyses

The following ocean and atmospheric data were used in this analysis:

- Wind: The South African Weather Service maintains a number of weather stations along the South African coast, and hourly wind speed and direction measurements were obtained for all relevant locations. Weather station sites used are given on the figures.
- Satellite imagery: The NASA Jet Propulsion Laboratory website (https://sst.jpl.nasa.gov/SST/#) combines all available sea surface temperature (SST) data sets at various spatial resolutions to produce global 1-km SST images (G1SST). These false-colour SST images are used to identify possible current structures, in particular the warm Agulhas Current and upwelling features.
- Waves: NOAA host an ftp site (ftp://polar.ncep.noaa.gov/pub/history/waves/) from which hindcast wave data derived from wind fields can be obtained at positions every half degree latitude and longitude.
- Ocean currents: The Copernicus Marine Environmental Monitoring Service determines global ocean gridded sea surface heights during satellite overpasses (www.marine.copernicus.eu). Using these heights, absolute geostrophic currents can be derived, which is especially useful for Agulhas Current flow.

The effect of the wind is shown by means of progressive vector diagrams (PVDs). These effectively show the movement of a mass of water under the influence of the wind by drawing the hourly vector movement of the water, and then adding the next hourly vector onto the end of the first vector. The percentage effect of the wind can be varied as required, and as previously indicated, values from 3% to 10% are used in these analyses.

Time sequence of nurdle beach deposition

Nurdle movement was assessed from reports by the public when nurdles were found on beaches and recorded on the website of CoastKZN.

The storm which resulted in the Durban harbour nurdle release occurred on 10 October 2017. It is evident that the nurdles dispersed immediately, but it took several days for the public to become aware of the event, and sightings were reported only a week or more later. Table 1 gives a record of reported sightings on coastal beaches, which were then incorporated into Figures 3, 4 and 5.

Most reported nurdle sightings occurred north of Durban on beaches along the KZN Bight; in this case only the number of days in October, November and December with sightings are given (Figure 3). The situation south of Durban is considered separately and here the actual dates of sightings are given. Similarly for Figures 4 and 5, the actual dates of sightings are given, with subjective assessments of the volume of nurdles found. Note that the last day considered in this analysis is 10 December 2017.

Table 1: Reports of nurdle sightings by the public and collated by CoastKZN. The sites where reports were received are depicted in Figures 3, 4 and 5, with reported dates given; for Figures 4 and 5, the volume of nurdles found is indicated on the following basis: H, high; M, medium; L, low; P, present.

Figure 3			
North			
	Number of days in month		
Site	**October**	**November**	**December**
1 – Durban Harbour	–	1	–
2 – Durban Beaches	11	17	1
3 – Umhlanga	1	4	1
4 – Umdloti	1	3	–
5 – La Mercy	–	4	3
6 – Ballito	1	2	3
7 – uMhlali	–	–	1
8 – Sheffield Beach	–	3	5
9 – Tinley Manor	1	1	2
10 – uMvoti	–	–	5
11 – Blythedale	2	1	1
12 – Zinkwazi	–	3	1
13 – uThukela Mouth	1	6	5
14 – aMatigulu	1	6	9
15 – Mtunzini Beach	1	–	
16 – uMlalazi mouth	–	–	1
17 – Port Durnford	–	1	1
18 – Richards Bay	1	–	-
19 – iSimangaliso	–	–	1
20 – Bhanga Nek			1
South			
	Number of days in month		
Site	**October**	**November**	**December**
1 – Winkelspruit	25	–	–
2 – Umkomaas	–	26	–
3 – Southbroom	21,22,23	21	1
4 – Munster Beach	31	–	–
5 – Leisure Bay	20,24	–	–

Figures 4 and 5		
Site	**Date**	**Volume**
1 – Umtamvuna	24 Oct	P
2 – Mkambati	25 Oct 2 Nov	P P
3 – Port Grosvenor	27 Oct	P
4 – Mbotyi	23 Oct	H
5 – Port St Johns	28 Oct 2 Nov	P P
6 – Coffee Bay	27 Oct 4 Nov	P P
7 – The Haven	4 Nov	M
8 – Quora Mouth	29 Oct	M
9 – Haga Haga	28 Oct	P
10 – Queensbury Bay	28 Oct	P
11 – Gonubie	29 Oct	P
12 – East London	30 Oct 30 Oct	H P
13 – Kariega	5 Nov	L
14 – Port Elizabeth	31 Oct 14 Nov	H P
15 – Sardinia Bay	1 Nov	P
16 – St Francis Bay	26 Nov	P
17 – Nature's Valley	23 Nov	L
18 – Plettenberg Bay	6 Dec	H
19 – Mossel Bay	20 Nov 21 Nov	M P
20 – Dana Bay	20 Nov	P
21 – Gouritz	6 Dec	H
22 – Gansbaai	5 Dec	H

It must be recognised at the outset that the sighting reports depended on a number of factors:

- The nurdles had to be washed onto a beach and be visible.
- There had to be a concerned member of the public who noticed (and collected) the nurdles.
- The member of the public had to report the presence of the nurdles, in this case to CoastKZN.

There were no other known nurdle sources at the time, and the reports that were received were verified to ensure that they originated in the Durban Harbour spill. Nurdles that have been in the ocean for some time are affected by photo radiation and become discoloured. Also, hydrophobic pollutants such as persistent organic pollutants cause further discolouration by being adsorbed onto nurdles from the surrounding seawater.[1,25]

There is no certainty about the actual dates when nurdles reached specific coastal locations, as they could have been present for some time before being reported. However, given the ongoing publicity afforded to the spill and the number of organised coastal clean-up events to physically remove the nurdles, it is unlikely they remained unobserved for more than a few days. Nonetheless, there were undoubtedly some nurdles on different beaches that went unreported.

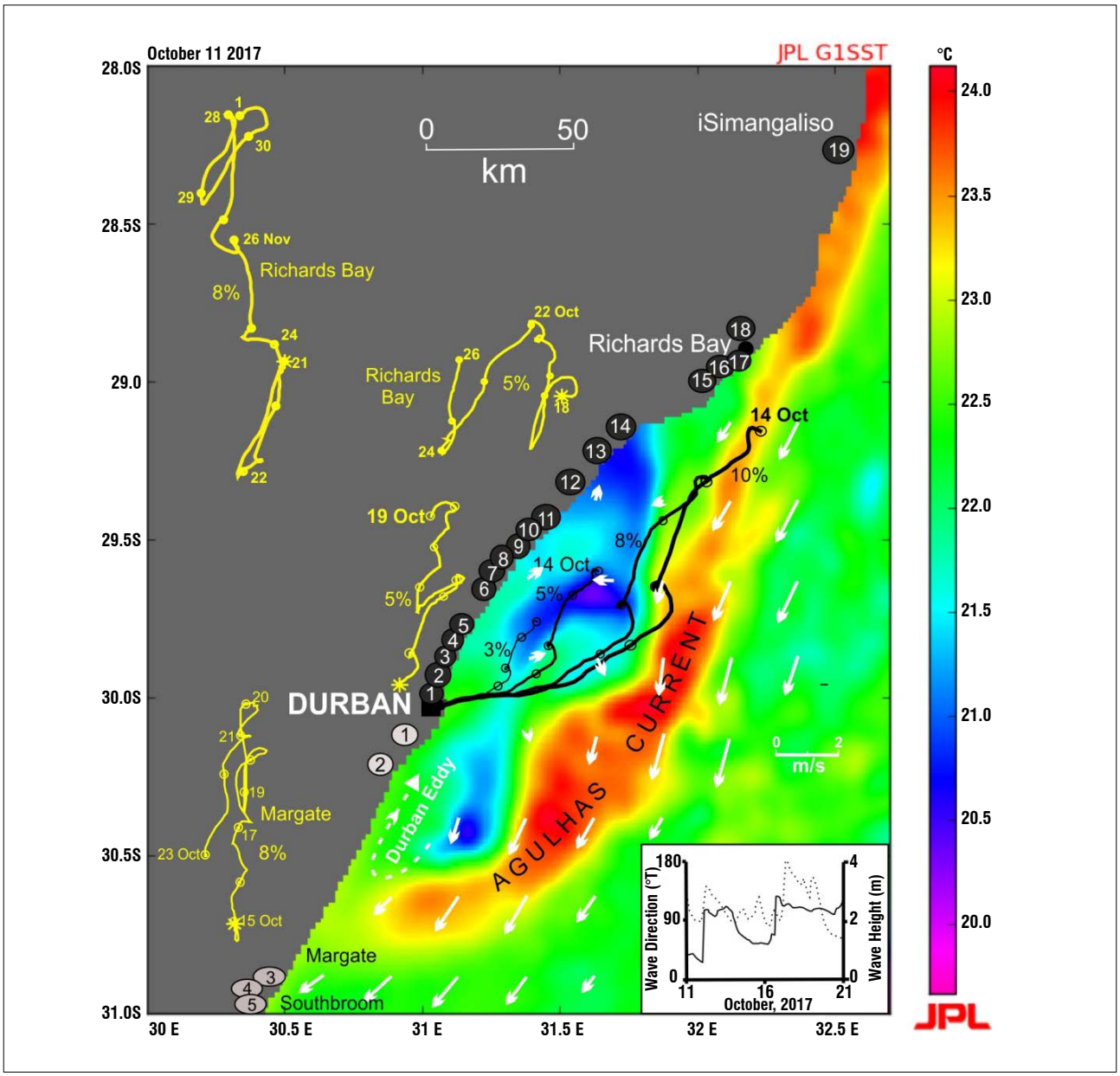

Image courtesy of the NASA Jet Propulsion Laboratory (JPL).

Figure 3: A satellite image for 11 October 2017, depicting sea surface temperatures (scale on right) off the KwaZulu-Natal coast. The warm waters of the Agulhas Current are readily apparent, together with calculated geostrophic currents; currents south of Durban are for 20 October. Inshore the variable flows and cooler waters in the KZN Bight are evident, while the Durban eddy is also depicted. Sites of public reports of nurdles on beaches are given along the coast (see Table 1). Various progressive vector diagrams (PVDs) in October and November are shown starting at the star, with the relevant weather stations given and further day starts indicated by circles and day numbers. In particular, the black PVDs emanating from Durban use wind data from King Shaka Airport at Durban starting on 10 October, with the wind dispersion shown for 3%, 5%, 8% and 10%. In the bottom right-hand corner, hindcast wave direction and height (dotted) for 30°S and 31.5°E are given for 11 to 21 October 2017.

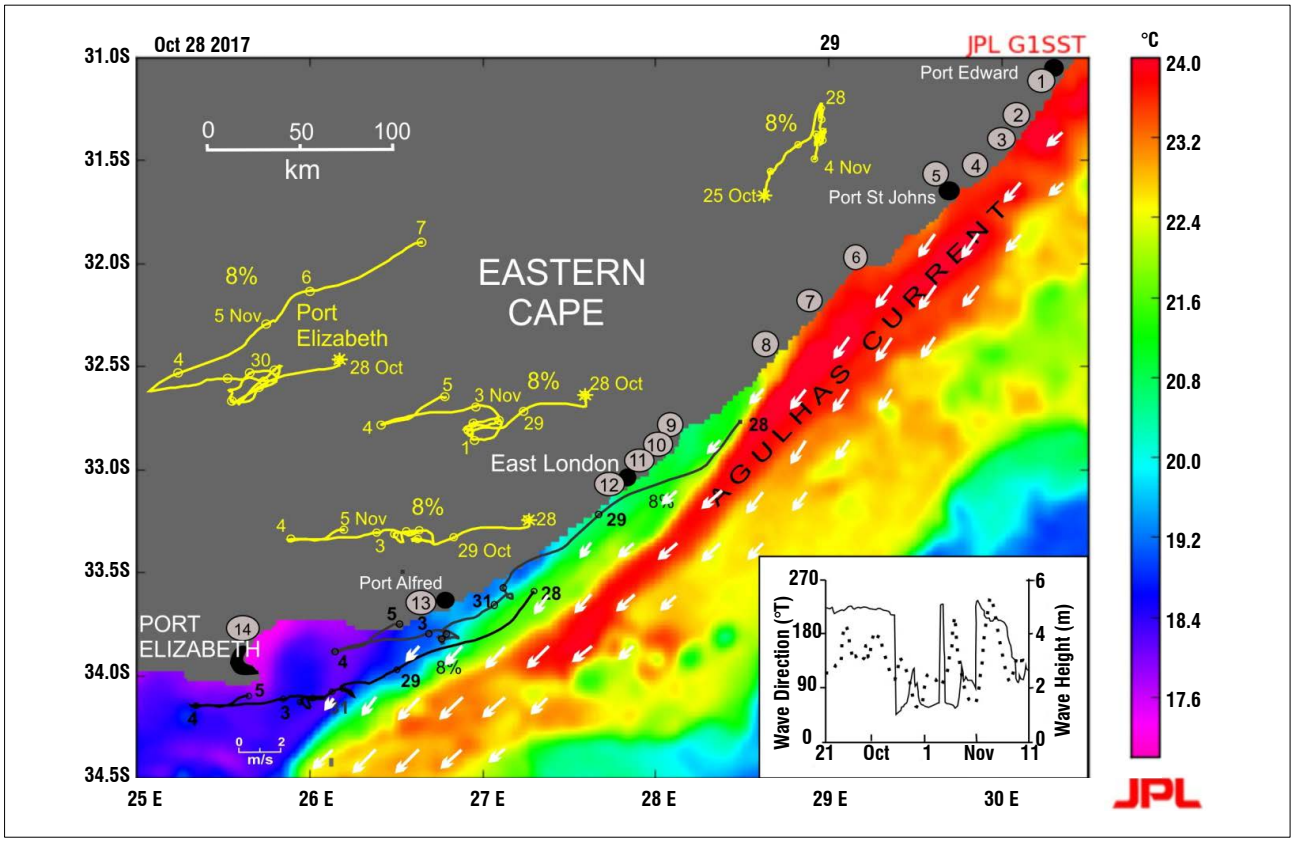

Image courtesy of the NASA Jet Propulsion Laboratory (JPL).

Figure 4: A satellite image for 28 October 2017, depicting sea surface temperatures (scale on right) off the Eastern Cape coast. The warm waters of the Agulhas Current are readily apparent, together with calculated geostrophic currents. The different sites where nurdles were reported are shown (Table 1), while various progressive vector diagrams with relevant weather stations are given together with day starts indicated by circles and day numbers in October and November. In the bottom right-hand corner, the hindcast wave direction and height (dotted) are given for 33.5°S and 28.5°E.

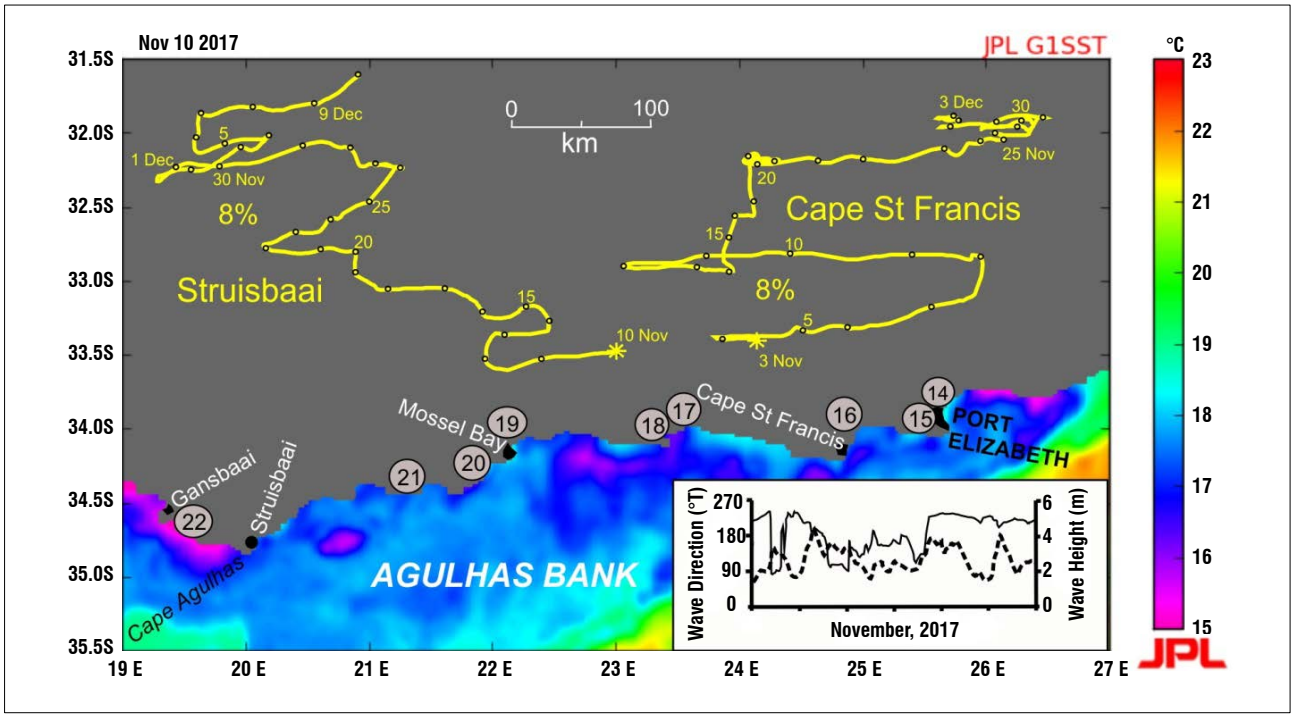

Image courtesy of the NASA Jet Propulsion Laboratory (JPL).

Figure 5: A satellite image for 10 November 2017, depicting sea surface temperatures (scale on right) off South Africa's south coast. Sites listed in Table 1 of public reports of nurdles on beaches are shown. Progressive vector diagrams discussed in the text are shown, with day starts indicated by circles and day numbers in November and December. In the bottom right-hand corner, the hindcast wave direction and height (dotted) are given for 33°S and 23°E.

Wind, ocean structures and nurdle movement

The movement of nurdles is divided into three sections with different wind and ocean regimes: these are north and south of Durban and then along the east and south coasts.

North of Durban

The strong southwesterly storm winds that caused the damage in Durban Harbour were also responsible for dispersing the nurdles out of the harbour and into the adjacent ocean. The situation is depicted in a satellite image taken on 11 October showing offshore SST structures (Figure 3). Of particular importance is the warm Agulhas Current in a typical position offshore of the KZN Bight and then moving closer to the coast some distance south of Durban; ocean currents and waves at the time are also shown.

The wind data from King Shaka International Airport were used to model nurdle movement, with four different wind drift percentages applied, namely 3%, 5%, 8% and 10%. The strong winds meant that the nurdles were rapidly moved out to sea; however, the different surface wind drift percentages show remarkably different results.

Four days are depicted, with most movement happening on the first day, 10 October. The 3% and 5% drifts did not transport the nurdles more than 30 km offshore, essentially just within the variable flow in the KZN Bight. On the other hand, the 8% drift would have taken the nurdles into the inshore shear zone, while only the 10% drift would have taken nurdles well into the Agulhas Current. Higher drifts would have been even more effective in transporting the nurdles farther offshore.

The actual movement of the nurdles over the days following the spill would have encompassed all of these movements, as it is clear from the results of Laxague et al.[24] that the dispersion and movement of the nurdles would have depended critically on their position in the water column. Those nurdles in the upper 10 mm of the ocean would have separated very quickly from those nurdles even a few centimetres deeper. As such, after a day or two, some nurdles will have been swept away southwestwards by the Agulhas Current, while others will have entered the quieter waters to the north in the KZN Bight.

The Stokes Drift associated with the waves from about 120 °T prevalent on 11 October would have acted against the offshore movement of the nurdles. However, the relatively small amplitude (2.1 m) waves would not have had a substantial impact. Later waves were mainly from the south, increasing northward movement of surface waters.

A 5% wind drift from King Shaka International Airport is also shown from 11 October (Figure 3 in yellow). The winds were more southerly, and the movement of nurdles was northwards close to the coast and into the KZN Bight; the period up to 19 October is shown.

Also depicted is the 5% drift using wind data from Richards Bay starting on 18 October, when the winds were variable and generally nearly parallel to the coast. These winds would have retained the nurdles within the KZN Bight, and the large number of reported sightings through to 10 December confirms that the nurdles remained in the area (Table 1).

Until December 2017, there were no reported nurdle sightings north of Richards Bay, probably because the continental shelf narrows to within 5 km of the coast and the southwestward flow of the Agulhas Current is correspondingly closer to the coast, inhibiting movement northwards. However, as indicated in Table 1, on 1 December nurdles were reported at the border of the iSimangaliso World Heritage site, some 70 km north of Richards Bay.

A PVD from Richards Bay over the period 21 November to 1 December indicates that from 22 to 28 November there were consistent southerly winds, which could have swept nurdles northwards more than 100 km. An inspection of satellite imagery at the time shows that the Agulhas Current was also not well defined off the coast, indicating that currents were probably slack: this would have allowed nurdle movement northwards.

Nurdles were reported at Bhanga Nek, situated at 27°N and more than 200 km north of Richards Bay on 4 December, and indicates that nurdle movement continued northward (Table 1).

South of Durban

Nurdles that reached the Agulhas Current would have been taken southwestwards at speeds of up to 2 m/s in the core. As discussed earlier, the Current typically moves closer to the coast with the narrowing shelf farther south, and nurdles on the inshore boundary would have taken 4 days or more to reach this area some 140 km south of Durban. Nurdles were reported in the Southbroom area from 21 October (Table 1 and Figure 3).

The recirculation flow northwards associated with the Durban cyclonic eddy[13] is evident on 20 October, and Figure 3 also depicts a PVD using wind data from Margate. It is clear that from around 16 October a southerly wind would have carried nurdles northward, and their presence was reported at Winkelspruit immediately south of Durban on 25 October. It is therefore likely that the nurdles found there would have followed a much longer path than immediately out of the harbour southward on 10 October.

Figure 4 shows the situation for those nurdles that were taken southwestwards by the Agulhas Current after exiting Durban Harbour. It is surmised that the majority that beached were on the inner boundary of the Current, as it is likely that those that reached the core would have been taken into the Southern Ocean.

Substantial numbers of nurdles must have been located on this inner boundary or closer to the coast, with reported sightings spread over the approximately 350 km from Port Edward to East London from 27 October to 4 November. The waves on 28 October were from the southwest with reasonably long periods (13 s) and moderate amplitudes (3 m), and would have facilitated the onshore movement of nurdles.

The PVD using wind data from Port St Johns over the period 25 October to 4 November shows a variable wind regime and little net movement. As expected, most of the winds were aligned more or less parallel to the coastline. Roberts et al.[13] have also described a small quasi-permanent cyclonic eddy off Port St Johns which would have been effective in retaining nurdles in the area; moreover, Table 1 shows that they were sighted well into November.

Farther south, at East London and Port Alfred, substantial easterly winds were present from 28 October to 4 November (yellow PVDs in Figure 4). In the ocean, two black PVDs are depicted where inshore southwestward Agulhas Current currents are combined with the 8% wind-driven surface nurdle movement. At the offshore position just north of East London, the initial current speed was assumed to be 1 m/s southwestward, decreasing until 2 November when no currents were included. Off Port Alfred, the initial position is closer to the coast and the current was assumed to be 0.8 m/s, decreasing until no currents were included from 1 November. Wave directions over this period were from the east, which would have assisted nurdle movement westward.

The added effect of the Agulhas Current is substantial, compared with the 8% movement from only wind. Under these conditions, nurdles would have been carried out of the Agulhas Current and into Algoa Bay and, correspondingly, nurdles were reported in the area at the end of October and beginning of November (Table 1). Southwesterly-component winds also commenced at Port Elizabeth from around 4 November, which would have retained the nurdles in the area.

South Coast

Figure 5 depicts the next stage in nurdle movement along the South African coast, from the end of October and into December 2017. No current structures are given in the figure because of the day-to-day variability on the wide continental shelf area of the Agulhas Bank.[18]

The PVDs for Port Elizabeth in Figure 4 and Cape St Francis in Figure 5 show that southwesterly winds prevailed until about 8 November. Thereafter there was a 4-day period during which time strong easterly

winds would have taken nurdles over 200 km westward with an 8% wind drift. Subsequent winds were mainly from the south and west.

Figure 5 shows marked upwelling at the prominent capes, as a result of the easterly winds.[18,26] The dynamics associated with such upwelling produces westward currents at the coast, assisting the movement west. The wave directions were predominantly from the south but with an admixture of easterly waves at times; from about 20 November this changed to being predominantly from the south-southwest.

As a result, nurdles were found along the whole of the south coast from 20 November and into December. The PVD for the weather station at Struisbaai has a different orientation, with a marked northeasterly trend over the whole period. This indicates that once around Cape Agulhas, the nurdles would have moved consistently west along the coast and, for this analysis, culminated at Gansbaai on 5 December.

Discussion

The analyses presented here reconstruct the conditions and factors at play in the dispersion of nurdles along about 2000 km of the South African east and south coasts in a relatively short (8-week) period after a spill in Durban Harbour. Where microplastic pollution has received attention in the past in the context of effects on the environment and bioaccumulation[25,27], only recently has attention focused on the mechanisms of movement and eventual fates of these particles[28,29].

Existing knowledge of conditions along various sections of the coast is used, together with satellite imagery, coastal wind data, satellite altimetry based geostrophic currents and hindcast wave data to explain the dispersion of the nurdles. The results are dependent on the effect of wind on objects floating in the surface layers of the ocean, and the results of Laxague et al.[24] have justified the use of a percentage wind drift greater than the commonly accepted 3% of the wind speed. Indeed, it is apparent that the good agreement between where nurdles were found and their proposed trajectories is dependent on such higher values.

However, it is important to recognise the variation in wind drift speed over the upper layers of the ocean, and that nurdles in the upper 10 mm will have been moved much farther than those even 1 m deeper. With the turbulence present in the ocean surface and a consequent spread of nurdles with depth, it can therefore be expected that they would have been dispersed widely, and the trajectories presented here are representative of only some of the many routes that would have been taken. In particular, these routes use an average value of 8% wind drift to explain where nurdles were found by members of the public.

The analysis also sheds some light on the sporadic manner in which such surface drifters can be dispersed by the wind. Along many coastal sections, winds vary in both direction and speed almost on a daily basis, and under such conditions the drifters can oscillate in position without an overall substantive movement. It is then that the periods of sustained winds are important, that is, when the drifters can be moved hundreds of kilometres in one direction over a few days. This is evident in all three figures (Figures 3–5), where there are periods when drifters would have remained within sections of the coast, and others when they would have been moved substantial distances.

Additionally, this study adds insight to environmental and ecological aspects of ocean dispersion. Microplastics, of which nurdles form a component, are found in the water column in all coastal/marine, estuary and river environments.[30-32] Understanding the movement of such particles can add insight into the location of long-term deposition sites e.g. on beaches, in beach sediments or even in the deep ocean floor when they have, through various processes, sunk to the benthic layer.[33]

Microplastics (100 nm – 5 mm in diameter, e.g. fragments, particles, fibres, pellets) and their marine prevalence are an increasing focus of study as they can be directly ingested by biota across trophic levels from fishes to mammals, turtles and seabirds.[34] Even at developing larval stages, ingestion has been documented and assertions made as to the health and developmental risks.[35] Fish larvae have been found to have high levels of microplastic pollution in coastal seas – an area where both biological and pollutant particles are highly concentrated.[35] A new consideration is trophic transfer whereby plastic is moved up the food chain by predation on fauna that have ingested or have associated plastic. Similar to biomagnification of chemical pollutants up the food chain, particles can be further concentrated in top predators.[34] These are examples of individual organism-level health risks. Recent indications suggest that microplastics could also manifest at the population level, with population shifts, altered behaviours and changes in ecological function.[36]

Understanding the fate of passive particles is further useful in the study of contaminants. Ogata et al.[25] studied the pollutant concentrations of nurdles found beached round the world relative to ambient levels and residence times in waters related to circulation patterns. Off the South African coast (south of Durban), nurdle contamination indicated recent use of an organochlorine, persistent organic pollutant – Lindane – at levels representing orders of magnitude higher than any other global study site.[25] Microplastics interact with persistent organic pollutants and contaminate marine biota when ingested.[34]

Nurdle movement also mimics passive biological particles such as drifting eggs, larvae or even adult invertebrates. Many marine species have small, pelagic early life history stages. Population connectivity of these species necessitates understanding the origin and routes of dispersing eggs and larvae between subpopulations.[37] Understanding the dispersal routes and processes during the early life history stages of fishes with respect to adult spawning grounds, preferred nursery and feeding habitats, is still relatively poorly understood.

Opportunities to study marine larval movement in the context of population connectivity are vital for both benthic species that use the planktonic larval stages to connect sessile populations[38] and for the management and conservation of fished species that require regional management efforts[39].

Acknowledgements

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Authors' contributions

E.H.S.: Original formulation; design of methodology; creation of models; data collection; data analysis; validation; writing – the initial draft; writing – revisions; project management. C.F.M.: Data collection; validation; data curation; writing – revisions; project management. N.A.S.: Original formulation; writing – revisions; project management.

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Historical and projected trends in near-surface temperature indices for 22 locations in South Africa

Motivated by the risks posed by global warming, historical trends and future projections of near-surface temperature in South Africa have been investigated in a number of previous studies. These studies included the assessment of trends in average temperatures as well as extremes. In this study, historical trends in near-surface minimum and maximum temperatures as well as extreme temperature indices in South Africa were critically investigated by comparing quality-controlled station observations with downscaled model projections. Because climate models are the only means of generating future global warming projections, this critical point comparison between observed and downscaled model simulated time series can provide valuable information regarding the interpretation of model-generated projections. Over the historical 1951–2005 period, both observed data and downscaled model projections were compared at 22 point locations in South Africa. An analysis of model projection trends was conducted over the period 2006–2095. The results from the historical analysis show that model outputs tend to simulate the historical trends well for annual means of daily maximum and minimum temperatures. However, noteworthy discrepancies exist in the assessment of temperature extremes. While both the historical model simulations and observations show a general warming trend in the extreme indices, the observational data show appreciably more spatial and temporal variability. On the other hand, model projections for the period 2006–2095 show that for the medium-to-low concentration Representative Concentration Pathway (RCP) 4.5, the projected decrease in cold nights is not as strong as is the case for the historically observed trends. However, the upward trends in warm nights for both the RCP4.5 and the high concentration RCP8.5 pathways are noticeably stronger than the historically observed trends. For cool days, future projections are comparable to the historically observed trends, but for hot days noticeably higher. Decreases in cold spells and increases in warm spells are expected to continue in future, with relatively strong positive trends on a regional basis. It is shown that projected trends are not expected to be constant into the future, in particular trends generated from the RCP8.5 pathway that show a strong increase in warming towards the end of the projection period.

Significance:

- Comparison between the observed and simulated trends emphasises the necessity to assess the reliability of the output of climate models which have a bearing on the credibility of projections.
- The limitation of the models to adequately simulate the climate extremes, renders the projections conservative, which is an important result in the light of climate change adaptation.

Introduction

Background

Global warming, as a result of increased concentrations of greenhouse gases (GHGs), poses a considerable risk to a sustainable present climate regime. In this context, a number of studies have previously been conducted to investigate historical trends in near-surface temperatures in South Africa, including extremes.[1-4] Most of these studies agree – indicating a general, but spatially variable, warming over recent decades. Mean temperatures show trends of less than 0.04 °C/decade for some stations in the interior, but higher than 0.20 °C/decade in the southwestern and northeastern parts of the country. Trends in temperature extremes also reflect warming, also with stronger warming in the southwest and northeast.[1]

A number of modelling studies have already been conducted to identify the most possible future near-surface temperature scenarios over southern Africa[5-8], e.g. the Climate Change Reference Atlas produced in 2017 by the South African Weather Service, with support from the South African Water Research Commission (available online at www.weathersa.co.za/climate/climate-change-reference-atlas). The latter is based on previous dynamical downscaling modelling done under the auspices of the Coordinated Regional-climate Downscaling Experiment (CORDEX).[9] The simulations of nine coupled Atmosphere-Ocean General Circulation Models (AOGCMs), which were included in the Inter-Governmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)[10], were used as inputs for a 1951–2095 simulation downscaled to a resolution of 0.4° x 0.4° using the Rossby Centre Regional Model Version 4 (RCA4) regional climate model (RCM)[11]. The main parts of the publication considered in this study are future projections of the average near-surface temperature for two 30-year periods, i.e. 2036–2065 and 2066–2095.

In the light of observed global warming as a result of increased concentrations of GHGs, various future GHG concentration based projections have been produced, known as Representative Concentration Pathways (RCPs).[10] These RCPs have been defined according to the anthropogenic contribution to atmospheric radiative forcing projected for the year 2100 as a result of the projected increases in GHGs. The medium-to-low concentration RCP4.5 (a pathway

that stabilises radiative forcing at 4.5 W/m^2 in 2100 without ever exceeding that value) and the high concentration RCP8.5 (which projects a radiative forcing of 8.5 W/m^2 in 2100 – also known as 'business as usual') GHG projections are the most commonly used in climate change projections and were also used in this study[12].

Assessment of agreement between model simulations and observed trends

The availability of both observed and climate change simulated near-surface temperature data provide the opportunity to validate the consistencies of model simulated trends against the associated observed trends. Such an analysis could create a better understanding of how to eventually interpret future projections.

Regional climate model outputs contain systematic errors (also known as biases) when compared to observations. It is therefore not advisable to use raw climate change projection data, but rather to express change in terms of future anomalies relative to the historically simulated climate. In the case in which change in actual values is required, an assessment of the historical performance of the model output becomes essential, and if needed, the calibration of the model output through the application of bias correction methods.[13,14] Systematic errors or biases generated by climate models can be determined through a model evaluation process, i.e. an assessment of inconsistencies between historically simulated results and the associated observations, e.g. the CMIP5 model evaluation exercise for Australia[15], and the comparison study between regional climate model simulations of daily near-surface temperatures and observations[16]. In general, biases in climate model outputs can greatly affect the estimation of the future effects of climate change in climate-reliant sectors, such as agriculture[17], if not adequately addressed.

It is also important to consider that an acceleration in future surface temperature trends is highly possible, primarily as a result of a projected acceleration in future GHG emissions. The concentration of CO_2 has increased from its pre-industrial levels of about 280 ppm in the 1880s to 395 ppm recently[18], while the RCP4.5 pathway considers an increase to 560 ppm by 2100.

In this paper, we aim to provide insight into systematic biases or errors between CORDEX model simulated and observed daily maximum and minimum temperatures at 22 locations in South Africa, over the period 1951–2005. Despite differences in the internal variability between model and observations, which influences the degree of correspondence with observations[19], the period over which the comparisons are made in this study is deemed sufficiently long to compare long-term trends. In addition, trends in temperature extremes according to the indices developed by the Expert Team on Climate Change Detection and Indices (ETCCDI)[20] are considered in the analysis.

Data and methods

Near-surface temperature data

Homogenised daily near-surface temperature data, recorded at 22 climate stations in South Africa (Figure 1) over the period 1951–2005, were used for the comparison between trends in the observed and associated model data, to quantify systematic errors in the model output for both the multi-model mean (mmm) and each of the nine model ensemble members. The measured temperature data, presented in Table 1, is a subset of the data used in the study by Kruger and Nxumalo[1], and underwent a thorough process of quality control and subsequent homogenisation to be deemed sufficiently reliable to use for the estimation of historical long-term temperature trends in South Africa.

The RCA4 RCM[11] ensemble member data comprise daily maximum and minimum near-surface temperature values generated by forcing the RCM across its lateral boundaries by output from nine AOGCMs (see Table 2) over the historical period 1951–2005 (representative of observed atmospheric composition and variability), and the future period 2006–2095 (representative of responses as a result of RCP4.5 and RCP8.5 GHG increases). In the CORDEX-Africa simulations, AOGCM output fields were dynamically downscaled to a resolution of 0.44° x 0.44°. From the grid of the RCA4 model output, the values at the positions of the 22 observation stations were estimated using a trigonometrical estimation method, to coincide as closely as possible with the positions at which the measurements were made.

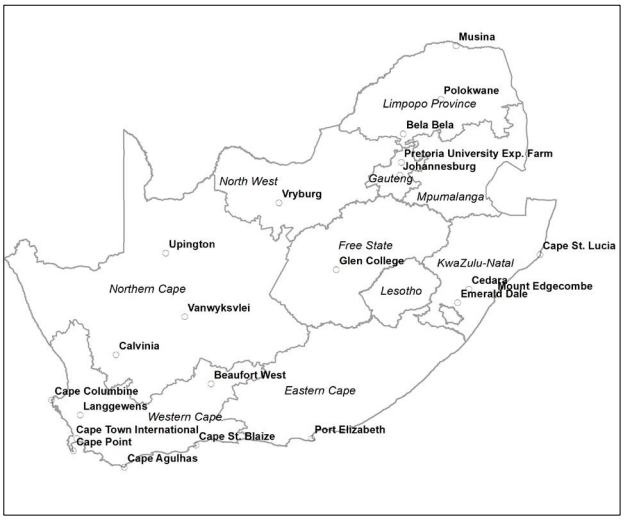

Figure 1: Positions of climate stations with provincial names in italics.

Table 1: List of stations with homogenised time series used in the study, with mean positions and height ranges

Climate station	Approximate latitude (°)	Approximate longitude (°)	Approximate height (m)
Cape Agulhas	-34.83	20.02	8
Cape Point	-34.35	18.50	208–227
Cape St. Blaize	-34.18	22.15	60–76
Cape Town International	-33.98	18.60	42–46
Port Elizabeth	-33.98	25.60	59–60
Langgewens	-33.28	18.70	175
Cape Columbine	-32.83	17.85	63
Beaufort West	-32.35	22.60	857–902
Calvinia	-31.48	19.77	975–980
Vanwyksvlei	-30.35	21.82	962
Emerald Dale	-29.93	29.95	1189
Cedara	-29.53	30.28	1076
Mount Edgecombe	-29.70	31.05	91
Glen College	-28.95	26.33	1304
Upington	-28.45	21.25	793–841
Cape St. Lucia	-28.50	32.40	3–107
Vryburg	-26.95	24.63	1234
Johannesburg	-26.13	28.23	1676–1695
Pretoria University Experimental Farm	-25.75	28.27	1372
Bela Bela	-24.90	28.33	1143
Polokwane	-23.87	29.45	1230–1311
Musina	-22.27	29.90	525

Table 2: Nine Atmosphere-Ocean General Circulation Models used in this study for downscaling with the Rossby Centre Regional Model Version 4 (RCA4) regional climate model (RCA4 RCM)

Model	Institute (country)	Reference
A. CanESM2m	CCCMa (Canada)	25
B. CNRM-CM5	CNRM-CERFACS (France)	26
C. CSIRO-Mk3	CSIRO-QCCCE (Australia)	27
D. IPSL-CM5A-MR	IPSL (France)	28
E. MICRO5	AORI-NIES-JAMSTEC (Japan)	29
F. HadGEM2-ES	Hadley Centre (UK)	30
G. MPI-ESM-LR	MPI-M (Germany)	31
H. NorESMI-M	NCC (Norway)	32
I. GFDL-ESM2M	GFDL (USA)	33

The model outputs were not bias-adjusted. While bias-adjustment has a large effect on modelled trends of absolute-threshold indices, it is found not to be the case for percentile-based indices[21], on which the extreme temperature trend analysis is focused in this paper.

Extreme near-surface temperature indices

Ten relevant maximum and minimum extreme temperature indices, as developed by the ETCCDI[22] and listed in Table 3, were considered. As demonstrated in previous studies[1,3], some of the ETCCDI indices cannot be deemed to be wholly relevant to the South African climate. Particularly, some of the absolute-threshold indices were omitted as the index values from different locations in South Africa are not directly comparable, because of the country's complex climate[23], but also because of the possible bias in the model outputs[21].

Table 3: Relevant extreme temperature indices, developed by the World Meteorological Organization's Expert Team on Climate Change Detection and Indices, use in this study

Index	Definition	Units	Description
TX90P	Annual number of days when TX > 90th percentile	days	Annual number of hot days
TX10P	Annual number of days when TX < 10th percentile	days	Annual number of cool days
TXx	Annual maximum value of TX	°C	Annual daytime hottest temperature
TXn	Annual minimum value of TX	°C	Annual daytime coolest temperature
WSDI	Annual number of days with at least six consecutive days when TX > 90th percentile	days	Annual longest hot spell
TNx	Annual maximum value of TN	°C	Annual nighttime warmest temperature
TNn	Annual minimum value of TN	°C	Annual nighttime coldest temperature
TN90P	Annual number of days when TN > 90th percentile	days	Annual number of warm nights
TN10P	Annual number of days when TN < 10th percentile	days	Annual number of cold nights
CSDI	Annual number of days with at least six consecutive days when TN < 10th percentile	days	Annual longest cold spell

Trend analysis

For historical average minimum and maximum temperatures, trends in the time series of the observed data were compared to the nine RCM ensemble member data time series, to identify any consistent biases in individual ensemble members. For the extreme temperature indices, the trend results of the observed and the mmm were compared. All the estimated trend values are linear and the statistical significance is based on the *t*-test at the 5% level. Firstly, the correlation coefficient *R* was calculated. To establish whether the value of the correlation coefficient is significant, the test statistic was calculated:

$$r = \frac{t}{\sqrt{n-2+t^2}} \qquad \text{Equation 1}$$

where n is the number of pairs of observations/measurements and t is the value in the *t*-table corresponding with the selected level of significance. If $R>r$ then R is statistically significant at the selected level of significance, in this case 5%. It can be shown that with statistical testing of historical climate trends, little difference in results is found between when linearity is assumed and when not.

Results

An initial screening of the RCA4 RCM output shows projected deviations (2036–2065 minus 1976–2005 averages) in the near-surface temperature median, under conditions of the RCP4.5 pathway, to be between +1 °C and +1.5 °C for the South African coastal regions, +1.5 °C and +2 °C for most of the interior, and +2 °C and +2.5 °C in isolated parts in the northwestern interior. An increase of +1.5 °C to +2 °C over a 60-year period equates to about +0.25–0.35 °C/decade, substantially higher than the observed historical trends, which vary to a maximum of just over +2 °C/decade.[1] Furthermore, model results from the RCP4.5 pathway for 2066–2085 show an acceleration of trend for most of South Africa of about +0.25–0.35 °C/decade, but +0.3–1 °C/decade in the northwestern parts. For the RCP8.5 pathway, temperature trends are, as expected, much stronger, with most of South Africa experiencing a mean temperature increase of about +2 °C to +3 °C in 2036–2065, compared to 1976–2005, equating to a trend in excess of +0.3 °C/decade.

Historical trends (1951–2005)

Annual average minimum and maximum temperatures

On average, the RCMs underestimate the observed annual average minimum temperature trends by about 0.05 °C/decade, compared to the observations (Table 4). While the average RCM trends range from +0.10 to +0.16 °C/decade, the range in trends in the observed time series is much larger, from insignificantly small to very large trends of more than +0.4 °C/decade. It can be argued that in some, but not all, cases of large positive trends, urbanisation might have played a role, e.g. Pretoria[1].

For the annual average maximum temperature, there is on average little difference between the trends captured by the RCM (+0.12 °C/decade) and the observations (+0.14 °C/decade). However, on closer inspection, as with the minimum temperature, the range of the RCM average trend (+0.09 to +0.17 °C/decade) is much smaller than that of the observed trend (-0.12 to +0.36 °C/decade).

The annual average temperatures also show the range of the RCM trends (+0.10 to +0.15 °C/decade) to be much smaller than those of the associated observed trends (-0.02 to +0.38 °C/decade). The results indicate that no RCM ensemble member consistently simulates the observed trends better than others. It is also noteworthy that the RCM ensemble members are mostly unable to simulate strong observed warming trends. The models that in general simulate localised strong warming better, do not perform as well in those areas with less observed warming, e.g. the central interior of South Africa.[2,3]

ETCCDI index trends

Diurnal temperature range

The differences in diurnal temperature range between the observations (obs) and mmm are apparent, in that for the mmm very small trends are shown, which are not statistically significant (Figure 2). In contrast, the obs show highly variable results, both in space and magnitude, which vary from negative trends less than -0.25 °C/decade to small positive trends up to +0.15 °C/decade. The observed trend magnitudes vary over relatively short distances, which could indicate influences of local or microscale effects on the change in differences between minimum and maximum temperatures.

Table 4: Observed trend of annual average minimum temperature (°C), as well as trend deviations of each one of the nine regional climate model (RCM) ensemble members (A–I as in indicated in Table 2) from the observed trend. The mmm trend and trend deviation are also given. Trends (°C/decade) were calculated over the period 1951–2005.

Climate station	Observed trend	RCM ensemble trend deviation from observed trend										
		A	B	C	D	E	F	G	H	I	Mmm trend deviation	Mmm trend
Cape Agulhas	**0.18**	0.03	-0.10	-0.12	0.03	-0.08	-0.15	-0.06	-0.05	-0.04	**-0.06**	**0.12**
Cape Point	**0.25**	-0.11	-0.17	-0.19	-0.04	-0.14	-0.23	-0.12	-0.10	-0.12	**-0.14**	**0.11**
Cape St. Blaize	**0.12**	0.03	-0.04	-0.07	0.11	-0.01	-0.08	0.01	0.02	0.03	**0.00**	**0.12**
Cape Town International	**0.33**	-0.18	-0.25	-0.26	-0.14	-0.22	-0.32	-0.19	-0.17	-0.18	**-0.21**	**0.12**
Port Elizabeth	**0.46**	-0.28	-0.38	-0.41	-0.23	-0.35	-0.45	-0.33	-0.30	-0.29	**-0.34**	**0.12**
Langgewens	**0.17**	-0.00	-0.09	-0.08	0.04	-0.05	-0.17	-0.02	0.01	-0.00	**-0.04**	**0.13**
Cape Columbine	**0.07**	0.07	0.00	0.00	0.13	0.04	-0.06	0.06	0.09	0.07	**0.04**	**0.11**
Beaufort West	**0.27**	-0.07	-0.17	-0.22	-0.03	-0.16	-0.22	-0.10	-0.10	-0.08	**-0.12**	**0.15**
Calvinia	**-0.02**	0.17	0.12	0.03	0.25	0.12	0.04	0.18	0.22	0.17	**0.14**	**0.12**
Vanwyksvlei	**0.10**	0.11	0.00	-0.04	0.12	0.02	-0.04	0.08	0.08	0.11	**0.04**	**0.14**
Emerald Dale	**0.09**	0.08	0.01	-0.06	0.08	-0.02	-0.02	0.07	0.07	0.02	**0.03**	**0.12**
Cedara	**0.21**	-0.05	-0.11	-0.20	-0.05	-0.15	-0.15	-0.07	-0.06	-0.09	**-0.11**	**0.10**
Mount Edgecombe	**0.31**	-0.16	-0.21	-0.29	-0.14	-0.25	-0.20	-0.17	-0.18	-0.27	**-0.20**	**0.11**
Glen College	**0.09**	0.11	0.03	-0.01	0.12	0.02	-0.05	0.06	0.04	0.12	**0.05**	**0.14**
Upington	**0.33**	-0.08	-0.21	-0.26	-0.10	-0.23	-0.26	-0.18	-0.13	-0.09	**-0.17**	**0.16**
Cape St. Lucia	**0.18**	-0.03	-0.06	-0.17	-0.02	-0.12	-0.07	-0.01	-0.06	-0.08	**-0.07**	**0.11**
Vryburg	**0.07**	0.15	0.07	0.02	0.16	0.03	-0.02	0.07	0.12	0.15	**0.08**	**0.15**
Johannesburg	**0.18**	0.00	-0.05	-0.16	0.02	-0.08	-0.14	-0.02	-0.03	0.00	**-0.05**	**0.13**
Pretoria University Experimental Farm	**0.44**	-0.26	-0.31	-0.42	-0.24	-0.35	-0.40	-0.28	-0.29	-0.26	**-0.31**	**0.13**
Bela Bela	**0.09**	0.12	0.08	-0.09	0.11	0.01	-0.04	0.07	0.09	0.12	**0.05**	**0.14**
Polokwane	**0.14**	0.05	-0.04	-0.14	0.04	-0.03	-0.08	0.06	-0.03	0.04	**-0.01**	**0.13**
Musina	**0.22**	-0.01	-0.11	-0.22	0.01	-0.11	-0.15	-0.01	-0.09	-0.03	**-0.08**	**0.14**
Average	**0.17**	0.0	-0.08	-0.14	0.02	-0.08	-0.13	-0.03	-0.03	-0.02	**-0.05**	**0.12**

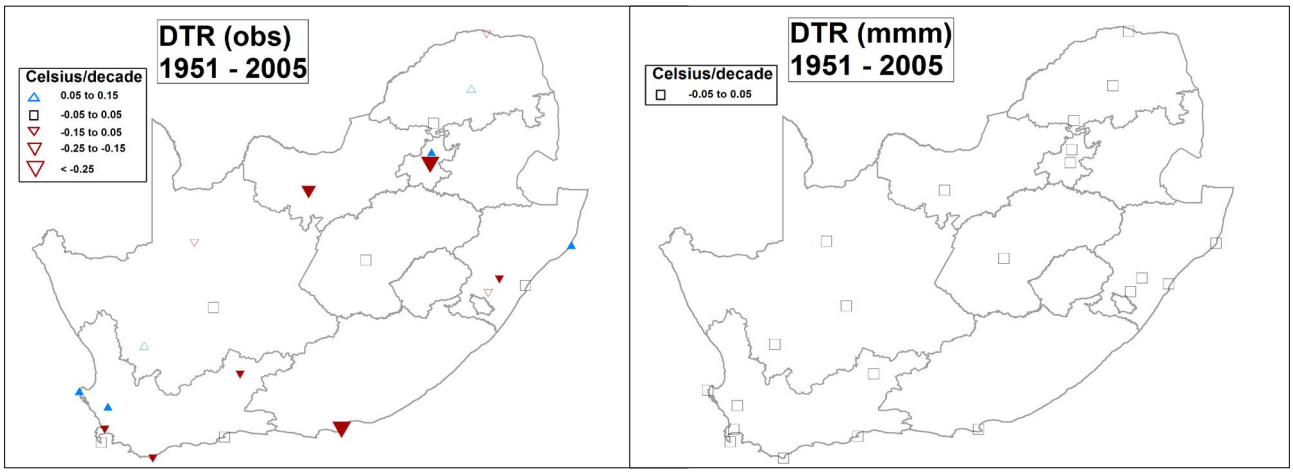

Figure 2: Trends in annual mean diurnal temperature range (DTR) in °C per decade, for the period 1951–2005, from the observations (obs) and multi-model mean (mmm) data sets, as indicated. Filled triangles denote significant trends at the 5% level.

Cold and warm nights

Both the obs and mmm show the number of cold nights decreasing (Figure 3a). Evident from the obs are larger decreases in the number of cold nights along the coastal regions (mostly <-2.5%/decade) compared to the interior (mostly -1.5 to -0.5%/decade). With the exception of Calvinia (Western Cape Province), all observed cold night trends were significantly negative. The mmm shows more consistent trends, at all locations in the range -1.5 to -0.5%/decade.

Trends in warm nights (Figure 3b) show larger spatial variation of warming in comparison to cold nights. For the obs, most stations in the central interior of the country show non-significant trends but, as is the case for cold nights, signs of stronger warming along the coast and in the Gauteng Province area. Similarly to cold nights, the mmm shows more consistent trends (+0.5 to +0.15%/decade) for most stations but, as is the case for the observations, stronger trends around the Gauteng Province (+1.5 to +2.5%/decade).

Cool and hot days

Figure 4a presents the trends in cool days. A general decrease in the number of cool days is observed, but with a stronger decrease at some of the coastal stations with trends lower than -1.5%/decade. In contrast, some stations in the southern interior show almost no observed trend. For the mmm, the trends are again, as in the discussion in the previous section, spatially more consistent, mostly in the order of -0.5 to -1.5%/decade.

The trend results for the number of hot days (Figure 4b) indicate general increases, but again the obs results are spatially more variable, with trend magnitudes ranging from negative to greater than +2.5%/decade. For the mmm, most locations show statistically significant trends of +0.5 to +1.5%/decade.

Extreme minimum and maximum temperatures

Most previous studies have shown that long-term trends of annual extreme minimum and maximum temperatures are mostly not significant, and vary spatially relatively more than the extreme indices that are not based on only one value per year.[1,3] For the coldest night (Figure 5a) it is, however, noticeable that for the obs most coastal stations show relatively large positive trends, mostly greater than +0.2 °C/decade. In contrast, all locations from the mmm results show small non-significant trends of -0.1 to +0.1 °C/decade.

For the obs, trends in warmest nights (Figure 5b) are mostly small and non-significant, but significantly positive trends are shown mostly along the coast and the Gauteng Province. This is, however, not the case for the mmm, for which most significant trends are in the central to northwestern interior and Gauteng.

Extreme maximum temperatures, indicated by the hottest and coldest day indices (not shown), show consistently small trends, mostly increases, for the mmm. However, for the obs, while the results are mostly statistically insignificant, four stations show significant warming for both the hottest and coldest day indices.

Cold and warm spells

It is evident that cold spells in general decreased over the analysis period. Significant decreases are isolated in the northern parts of South Africa, both for the obs and mmm. In contrast, general increases in warm spells are found. For the obs, most stations in the western half of the country show significant increases. For the mmm, in contrast, the significant increases are found in the northern and northeastern interior.

Future trends (2006–2095)

In this section the results of the RCM generated trends of the ETCCDI indices over the period 2006–2095, under conditions of the RCP4.5 and RCP8.5 pathways, are compared, with warming trends expected to be stronger under RCP8.5 than under RCP4.5.

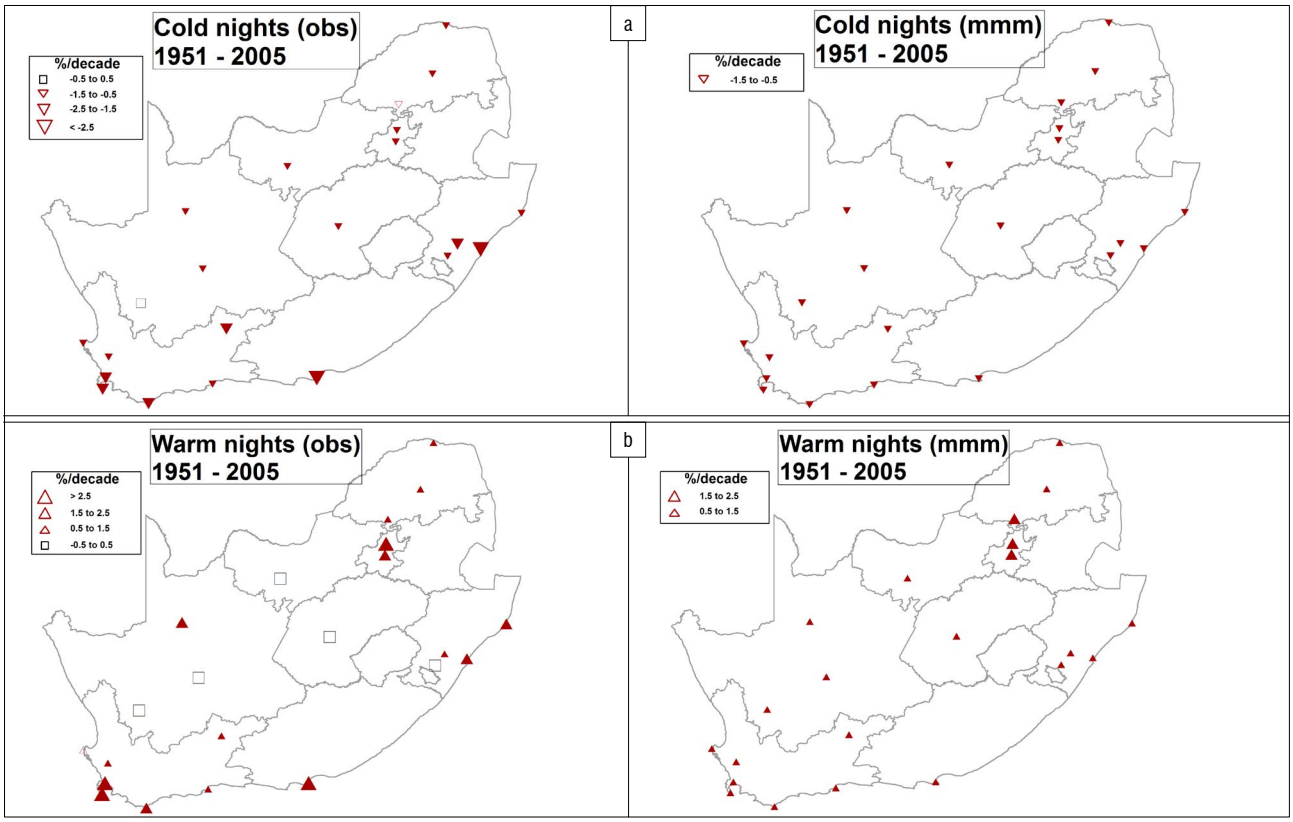

Figure 3: Trends in annual number of (a) cold nights (TN10P) and (b) warm nights (TN90P), in % per decade, for the period 1951–2005 from the observations (obs) and multi-model mean (mmm) data sets. Filled triangles denote significant trends at the 5% level.

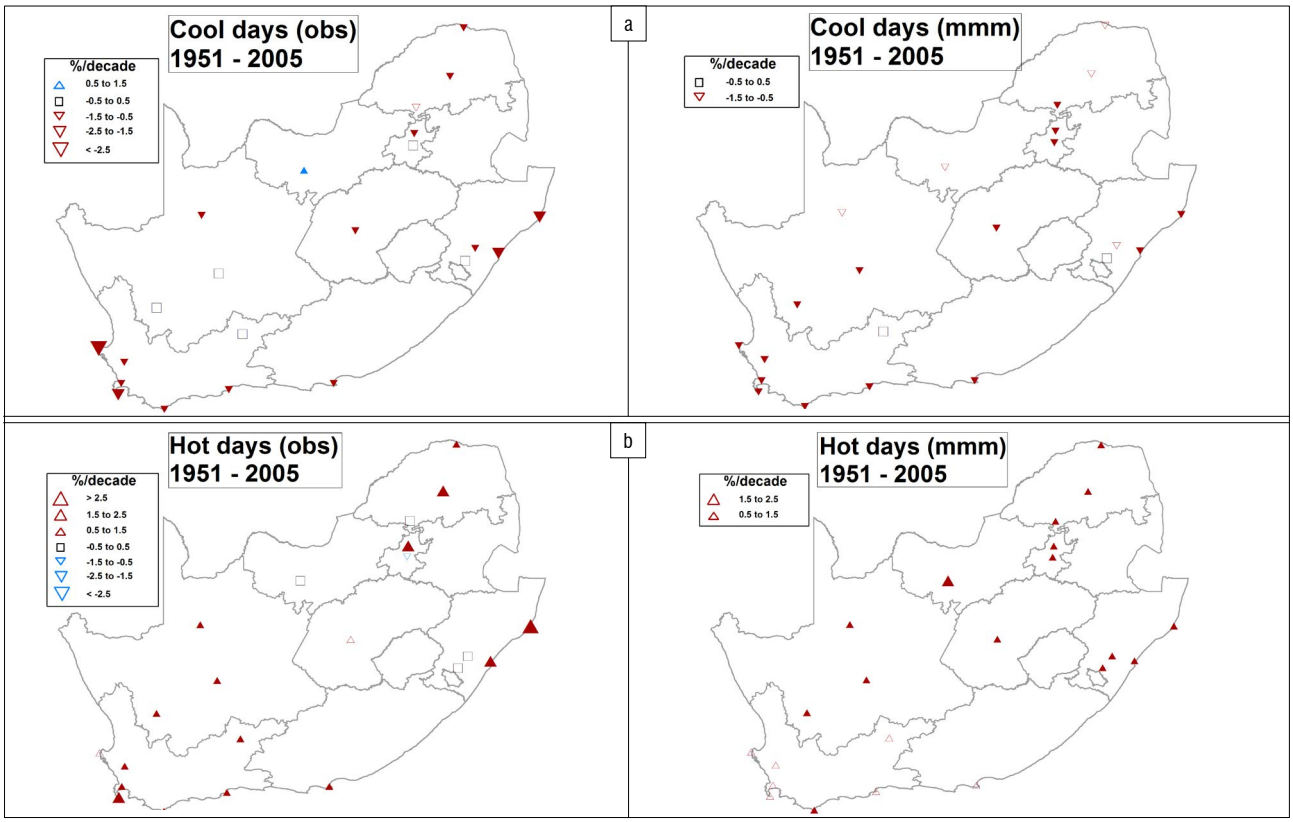

Figure 4: Trends in annual number of (a) cool days (TX10P) and (b) hot days (TX90P), in % per decade, for the period 1951–2005 from the observations (obs) and multi-model mean (mmm) data sets. Filled triangles denote significant trends at the 5% level.

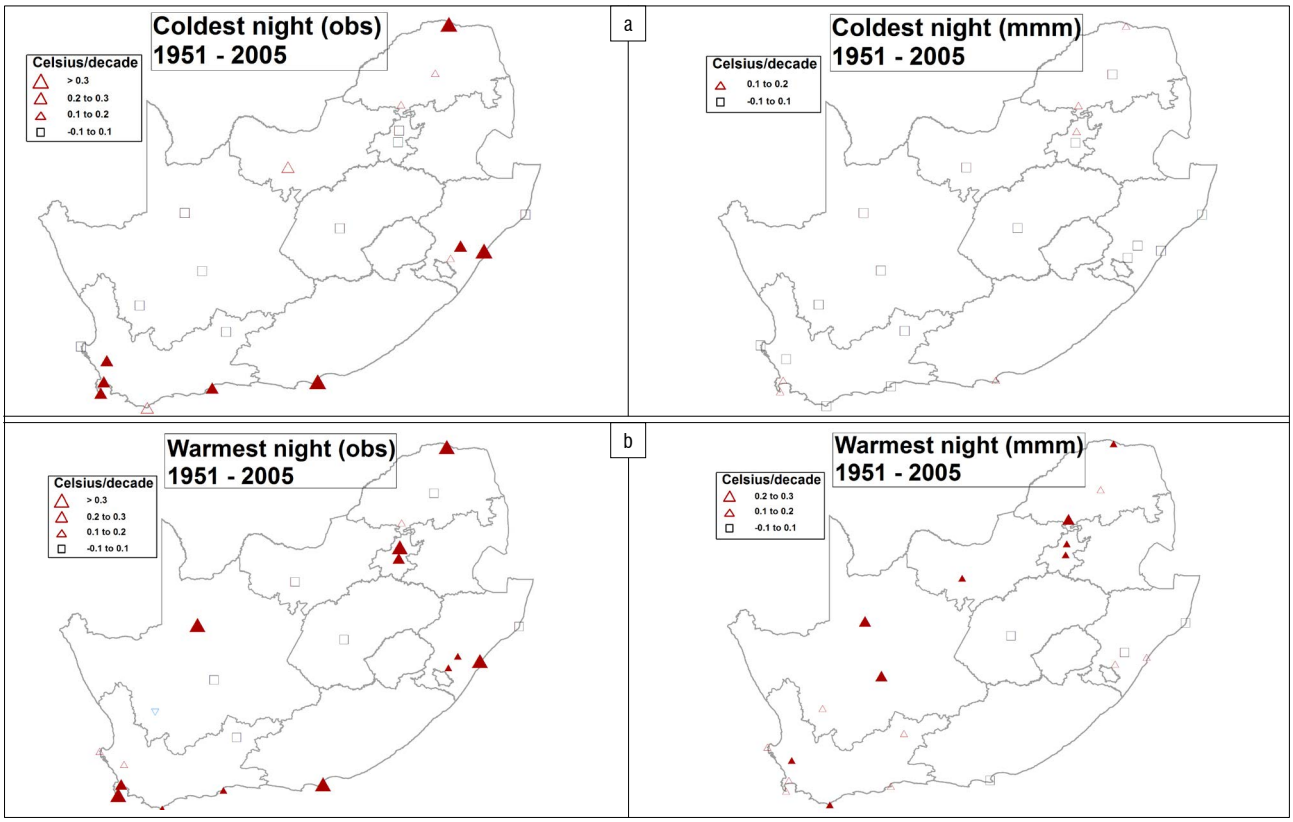

Figure 5: Trends in annual extreme minimum temperatures: (a) coldest nights (TNN) and (b) warmest nights (TNX), in °C per decade, for the period 1951–2005 from the observations (obs) and multi-model mean (mmm) data sets. Filled triangles denote significant trends at the 5% level.

Diurnal temperature range

The trends of diurnal temperature range under RCP4.5 are almost zero, similarly with the historical RCM trends. However, in the case of RCP8.5, some stations show significant, albeit very small, positive trends in the interior and negative trends for two of the coastal stations.

Cold and warm nights

Figure 6 presents the future trends in the number of cold nights under RCP4.5 and RCP8.5 conditions. Both pathways show a general warming trend, with the number of cold nights decreasing. While the RCP4.5 pathway shows trends of -0.5 to -1.5%/decade, and non-significant trends for some stations in the interior, the RCP8.5 pathway shows trends of -1.5 to -2.5%/decade, which are statistically significant at all locations.

Trends in warm nights (not shown) for the RCP4.5 conditions indicate increases in the number of warm nights from just over +1%/decade to more than +2.5%/decade, with the amount of warming unevenly distributed across the country. The RCP8.5 pathway shows trends in excess of +2.5%/decade for all stations.

Cool and hot days

A general decrease in the number of cool days is observed (Figure 7a) for most stations of -1.5 to -0.5%/decade under conditions of the RCP4.5 pathway and mostly -1.5 to -2.5%/decade under RCP8.5.

The trend results for hot days (not shown) indicate generally stronger warming than with cool days, with most stations in the interior under RCP4.5 showing increases of +1.5 to +2.5%/decade, and under RCP8.5 in excess of +2.5%/decade.

Extreme minimum and maximum temperatures

Trends in the coldest night of the year (Figure 8) under RCP4.5 conditions are non-significant at some locations in the interior, to more than +0.3 °C/decade along the south and east coasts and the far north at Musina (Limpopo Province). Under RCP8.5, trends are also lower in the interior, but mostly +0.1 to +0.2 °C/decade, and higher than +0.3 °C/decade along the coast and northern interior.

For the warmest night of the year (not shown), the northern half of the country shows significant trends of higher than +0.2 °C/decade and +0.3 °C/decade under RCP4.5 and RCP8.5 conditions, respectively.

For the hottest day of the year, trends from just higher than +1 °C/decade are shown in the south to more than +0.3 °C/decade in the north (Figure 9) under RCP4.5. Under RCP8.5, all stations show trends higher than +0.3 °C/decade.

Trends in the coldest day are somewhat lower than those for the hottest day under RCP4.5, but for RCP8.5 are still higher than +0.3 °C/decade for all stations.

Cold and warm spells

General increases in warm spells are evident, but less so in the southeast of the country. Most stations in the remainder of the country show trends of more than +0.6 days/decade under RCP4.5 conditions. Except for the south coast, all stations showed trends in warm spells in excess of +0.6 days/decade.

The results for the future trends in cold spells are spatially quite variable under RCP4.5 conditions. However, under RCP8.5, a picture emerges in which decreases in cold spells are more pronounced in the central and northern parts (decreases lower than -6 days/decade).

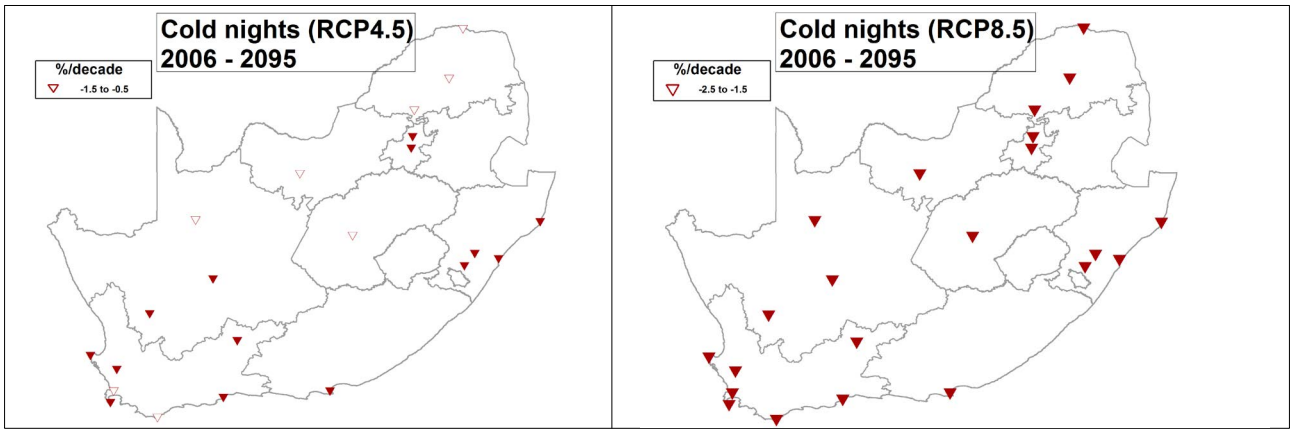

Figure 6: Trends in annual number of cold nights (TN10P) in % per decade, for the period 2006–2095 for the RCP4.5 and RCP8.5 scenarios, as indicated. Filled triangles denote significant trends at the 5% level.

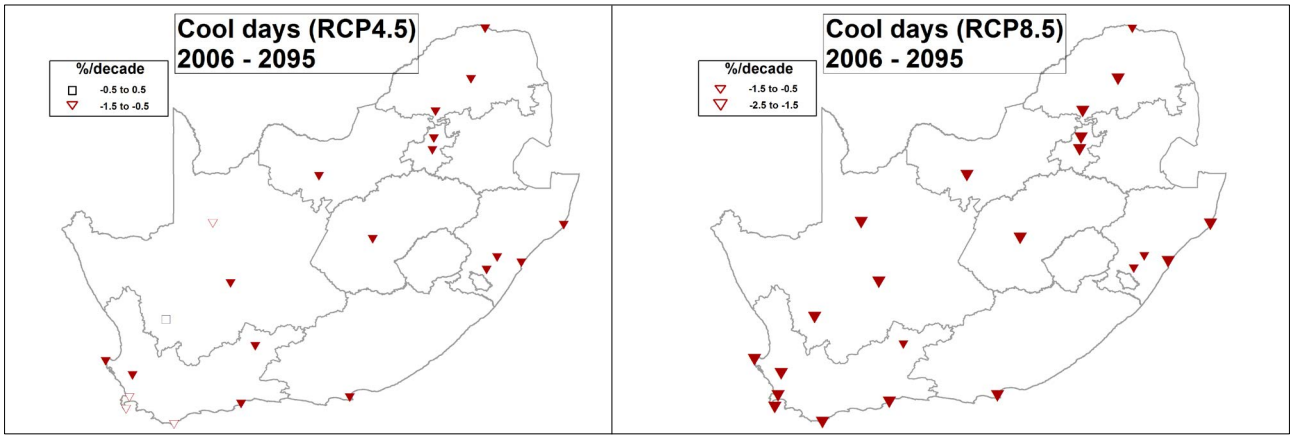

Figure 7: Trends in annual number of cool days (TX10P) in % per decade, for the period 2006–2095 for the RCP4.5 and RCP8.5 scenarios, as indicated. Filled triangles denote significant trends at the 5% level.

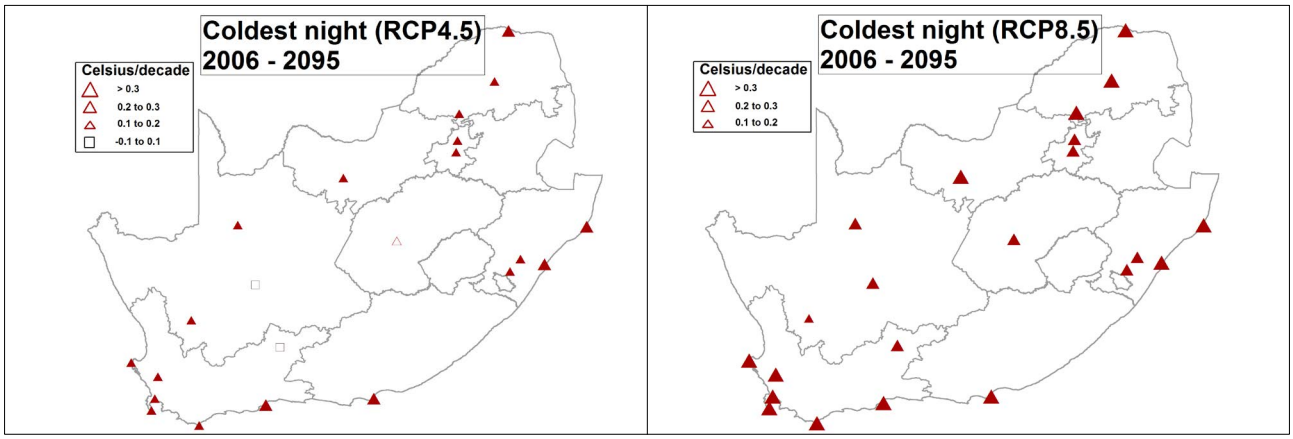

Figure 8: Trends in coldest nights (TNN) in °C per decade, for the period 2006–2095 for the RCP4.5 and RCP8.5 scenarios. Filled triangles denote significant trends at the 5% level.

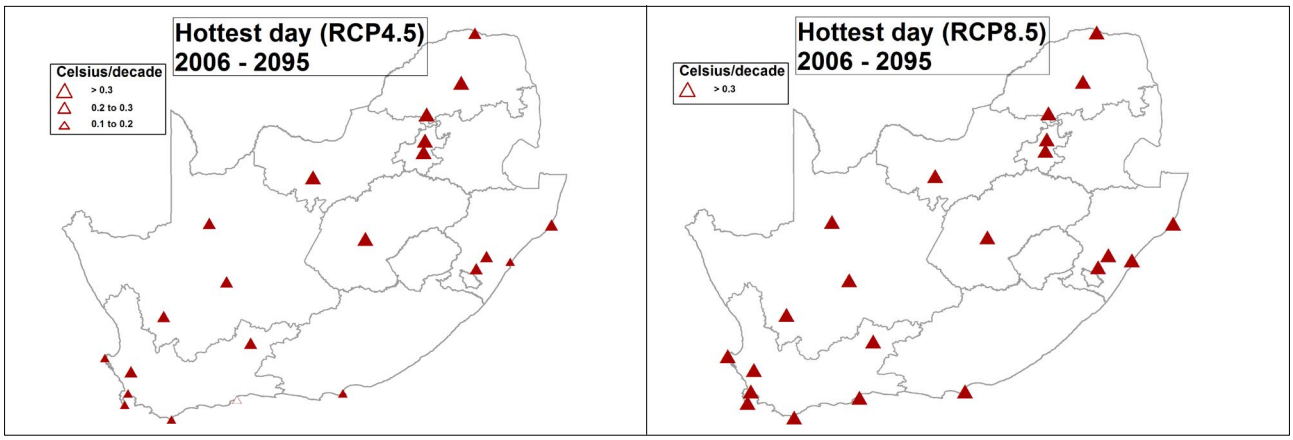

Figure 9: Trends in hottest days (TXX) in °C per decade, for the period 2006–2095 for the RCP4.5 and RCP8.5 scenarios, as indicated. Filled triangles denote significant trends at the 5% level.

Discussion and conclusion

The impact of present and future global warming on South African near-surface temperatures has been investigated by conducting a detailed and critical point station analysis on climate change model performance and projections. Overall, the results from both station observations and RCM-generated mmm confirm the findings of previous studies that over recent decades significant warming took place in most of South Africa.[1,2] The results generated by the RCA4 RCM downscaling largely confirm findings from observed temperature data analyses. However, it is apparent that the mmm trend exhibits less variability, both spatially and in magnitude. Here it should be emphasised that the RCM outputs do not reflect the exact interannual variability of the observed climate, but rather reflect the general state of the climate over an extended period, and more efficiently so over longer periods. Despite this, the RCM outputs were still able to reflect the general climatic trend over the 1951–2005 historical period of analysis. For the annual means of the maximum and minimum temperatures, and the mean thereof, the mmm show for all three cases, average trends very close to the trends from the observed data. One can infer that the general difference between obs and mmm results is that the mmm is not able to simulate larger trends effectively. There can be various causes for this ineffectiveness, e.g. the length of the analysis period and urbanisation, which is not considered in the modelling.

As expected, modelled trends under RCP8.5 show stronger warming than under RCP4.5, and for both pathways the warming trends in extreme temperatures are on average stronger than the historical trends. Here it is interesting to note the temporal constancy of the modelled future trends. The general result for all stations and extreme value indices is illustrated here with Figure 10, which presents the ensemble mean projection of the TN90P index at Cape Agulhas. Under RCP8.5, one can clearly see an acceleration of trend, especially in the second half of the future period, while the trend under RCP4.5 shows more constancy. It would seem that similar near-linear trends for both pathways can be assumed for the next few decades, but a second-order polynomial is probably a more realistic way to represent the index trends in the far-future under RCP8.5.

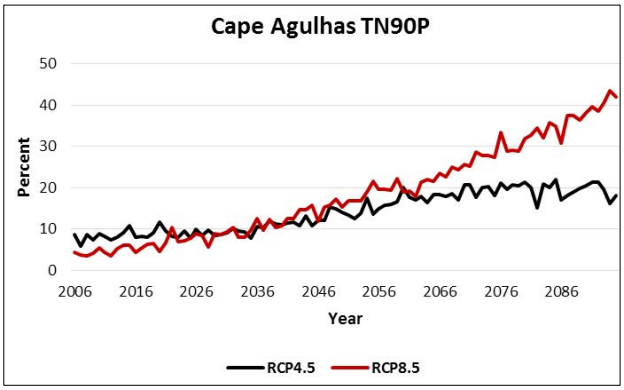

Figure 10: Ensemble mean simulation of TN90P (in % with basis period 2006–2035), under the RCP4.5 and RCP8.5 emission scenarios, as indicated.

Other studies, e.g. Ringard et al. for West Africa[24], indicate similarities in trends in extreme temperatures between observations and simulations and an acceleration of the trend thereafter. For the higher RCP pathways, the trends tend to remain similar throughout the 21st century with little indications of decrease. We have found similar results in that, for the

RCP4.5 pathway, warming trends tend to be close to constant and near linear. However, the RCP8.5 pathway indicates a future scenario in which the increase in surface temperatures, including extremes, accelerates, and therefore a simple linear trend will not represent these trends in a realistic manner.

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Authors' contributions

A.C.K. did most of the conceptualisation, developed the methodology, mapped the results and wrote the first draft of the manuscript. J.C.d.W.R. did the extraction and formatting of the CORDEX model data time series and assisted with the conceptualisation of the research. S.M. and S.N. did the analyses of the historical and model time series, i.e. calculations of index values and trends. T.E.M. assisted with the background literature review, specifically that relevant to the analysis of CORDEX model data.

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The meaning and practice of stewardship in South Africa

Stewardship offers a means of addressing social-ecological sustainability challenges, from the local to the global level. The concept of stewardship has had various meanings attached to it over time, and the links between the theory and practice of stewardship are not well understood. We sought to characterise the practice of stewardship in South Africa, to better understand the relationship between theory and practice. We found that practitioners' understandings of stewardship coalesce around two core notions: the idea of stewardship as 'responsible use and care' of nature, and stewardship as a 'balancing act' between stewards' use of natural resources for agricultural production and their responsibility to protect and manage the wider ecosystem. Stewardship practice in South Africa is strongly influenced by the biodiversity stewardship tool; however, many practitioners are integrating biodiversity stewardship with other approaches. These emerging social-ecological stewardship initiatives operate at landscape-level and work towards integrated social and ecological stewardship outcomes, by facilitating collaboration among diverse stakeholders. Further research is needed to better understand what is required to support these integrated, collaborative and cross-sectoral initiatives. Policy mechanisms that facilitate integrated place-based stewardship practice can contribute to expanding the practice of biodiversity stewardship in South Africa.

Significance:

- Our findings contribute to a growing understanding of what stewardship looks like in South Africa and how it is put into practice.
- We show that biodiversity stewardship is a prevalent understanding of stewardship practice in South Africa and is often combined with other approaches for sustainable landscape management.
- A broader understanding of stewardship, for example through the concept of social-ecological stewardship, can enable more integrated, collaborative approaches to landscape management, addressing the wide range of environmental and social development challenges faced in rural landscapes across South Africa.

Introduction

Stewardship has been put forward as a means of minimising human impacts on ecosystems and calls for stewardship abound in the literature.[1-4] If stewardship is considered a significant part of the solution to ecosystem degradation, and key to sustainability of social-ecological systems, how can it be achieved in practice? A challenge in answering this question is that the links between the theory (knowing) and practice (doing) of stewardship are underdeveloped.[4,5] Moreover, heightening this challenge, there is a variety of interpretations of the concept.

Recent research in South Africa indicates that while the practice of stewardship in the country is dominated by a fairly narrow biodiversity conservation focus through the 'biodiversity stewardship' tool (described below)[6,7], there is also evidence of a diversity of more holistic, integrated practices emerging[8]. The diversity of meanings attached to stewardship, the specific local practices, and on-the-ground stewardship practitioners' perspectives have, however, not been explored. In this study, we respond to the need to bridge the knowing–doing gap by investigating how stewardship practitioners apply theoretical ideals of stewardship in practice in South Africa. We do this by investigating the meaning and practice of stewardship, and by exploring the links between how stewardship is understood in theory and the ways in which it is actually put into practice.

A review of the theory of stewardship in the literature reveals stewardship as a complex, ever-changing concept with a diversity of understandings which have emerged over time[9,10] (Figure 1). The changing meanings of stewardship mirror shifts in environmental ideologies[5,11,12] and do not have distinct start and finish points in time. Consequently, a variety of meanings still persist, to a greater or lesser extent, in the present day. In all these conceptualisations, stewardship is a metaphor which describes a distinct kind of human–nature relationship.[13] Over time understanding of stewardship has largely shifted towards one which incorporates concerns for social justice, democracy and pluralism, and which provides a broad and deep ethical basis from which human responsibility and care for nature arises.[14-16] The more recent interpretations indicate a shift in discourses and ideologies towards more integrated, systemic understandings of the relationship between humans and nature (for example through the metaphor of social-ecological systems) – different from previous interpretations based on a more dualistic relationship (Figure 1). Of course, a plethora of understandings of stewardship also exist among diverse indigenous groups across the world.[17,18] However, these indigenous understandings are poorly documented and not well represented in English-language academic literature. Therefore, while recognising the importance of exploring these, for the purpose of this study we focus on recent definitions from the literature to capture the essence of recent stewardship theory.

We acknowledge and make use of several recent definitions of stewardship to provide the conceptual framing for this study. An important distinction that sets these selected definitions apart from other interpretations of stewardship, is that stewardship is largely a collaborative endeavour, bringing together multiple, diverse stakeholders.[8,19,20] As such, and with its applicability to a broad range of environmental concerns, the concept has appealed to

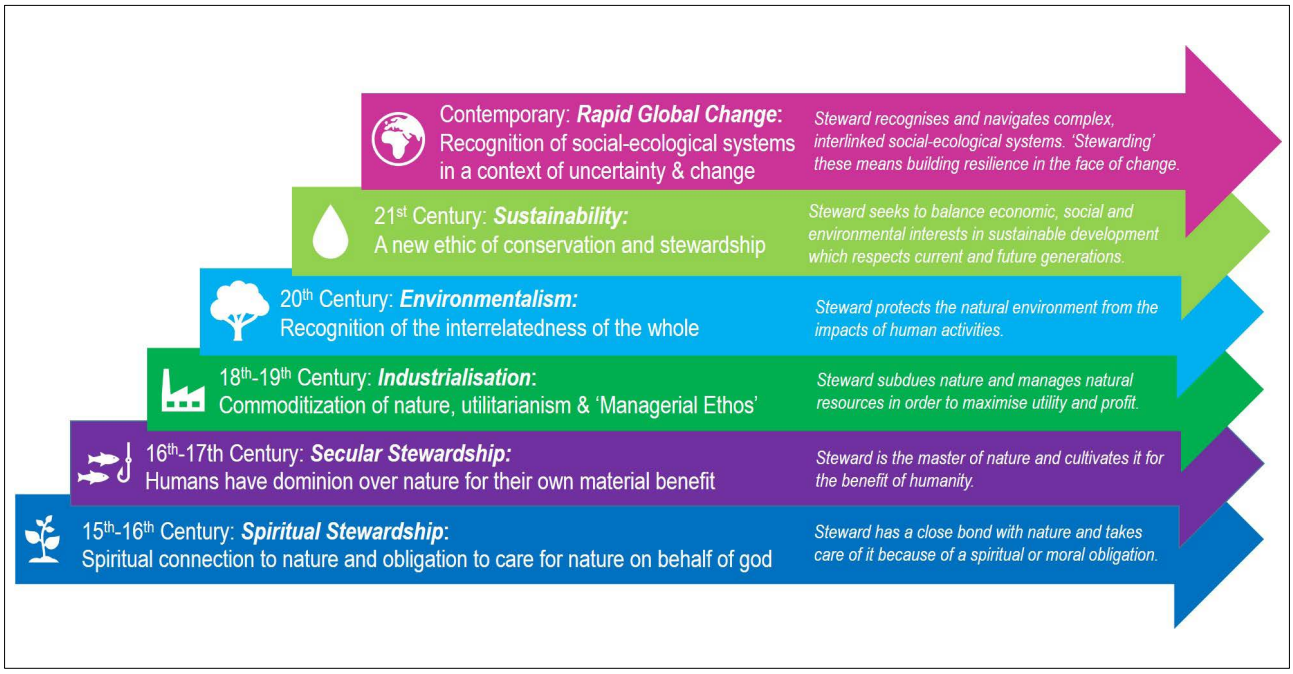

Figure 1: The changing meanings of environmental stewardship in Western history (adapted from Worrell and Appleby[5], Berry[11] and McArthur[12]).

the sustainability sciences and social-ecological systems fields[3,4,9,21], despite widely debated critiques of the concept[11,14,17].

Firstly, as a starting point we recognise the term 'environmental stewardship' proposed by Welchman[14] which captures the classical moral-ethical root of stewardship, whilst remaining relevant in the contemporary context. Welchman defines environmental stewardship as the

> *responsible management of human activity affecting the natural environment to ensure the conservation and preservation of natural resources and values for the sake of future generations of human and other life on the planet, together with the acceptance of significant answerability for one's conduct to society.*[16(p.303)]

Secondly, we use the concept of *ecosystem stewardship*, along with key principles which set it apart from other definitions and illustrate its roots in resilience thinking and social-ecological systems research.[21,22] Ecosystem stewardship is a specific management-oriented example of the most recent understandings of stewardship, and is defined as

> *a strategy to respond to and shape social-ecological systems under conditions of uncertainty and change to sustain the supply and opportunities for use of ecosystem services to support human well-being.*[2(p.241)]

Key principles of ecosystem stewardship include[2,17]: a management approach underpinned by resilience thinking[22]; recognition of ecosystems which provide diverse ecosystem services rather than single resources; stewardship which recognises stewards as an integral part of the system they manage and the inherent responsibility they hold; the need for stewards to work collaboratively with multiple stakeholders; and the need for stewards to anticipate and respond to social-ecological change and shape it for sustainability to avoid loss of future options for the system.

Thirdly, we use the term 'social-ecological stewardship' as a broad umbrella term to refer to the most recent understandings of stewardship, to encapsulate the classical interpretations of stewardship and recent links to the social-ecological systems concept.[23]

What about the practice of stewardship? We use the term 'practice' as it is defined in the Oxford English Dictionary: 'The actual application or use of an idea, belief, or method, as opposed to theories relating to it'[24]. Thus, the practice of stewardship is the actual, practical application of the concept of stewardship in a particular place or context. Worldwide, the concept of stewardship is put into practice in a diversity of ways.[4,5,9] One of the key features that stewardship practices have in common, despite the diversity of understandings, is volunteerism, and a focus on the actions and participation of local people in natural resource management.[4,25] Stewardship initiatives focus on engaging the efforts, time and resources of local people who utilise natural resources, and on facilitating their ability to steward, or to take care of, natural resources at the local level.[4,16,25] Such locally oriented stewardship activities have emerged across a variety of sectors, including fisheries, agriculture, forestry, protected areas, wildlife, ecosystem services and water management, and span rural and urban environments.[4] Thus, putting stewardship into practice is both about the practical application of the theory or ideals of stewardship, and about moving from the ethic of stewardship held by individuals, to tangible actions based on that ethic.[4,5]

In this study we focus on stewardship initiatives practised in rural landscapes in which agriculture is one of multiple land use activities, i.e. in multifunctional landscapes.[26] Such landscapes face particular challenges and opportunities for integrating social-ecological stewardship outcomes and are a commonly practised form of stewardship in South Africa.[27] Globally, stewardship practice in landscapes includes policy-driven private land conservation tools such as conservation easements and land trusts in the United States of America[28], and the biodiversity stewardship programme in South Africa[7,19]. This particular approach to stewardship in policy and practice in South Africa, is defined as follows:

> *Biodiversity stewardship is an approach to securing land in biodiversity priority areas through entering into agreements with private and communal landowners, led by conservation authorities.*[7]

Agri-environmental tools are also forms of stewardship practice and are similar to private land conservation initiatives. They include Agri-environmental and Countryside Stewardship Schemes in Europe and the United Kingdom[29,30], the Environmental Farm Plan Programme in Canada[20] and Land Care initiatives in Australia[31]. Stewardship is also put into practice in landscapes through watershed or catchment management

initiatives focused on improved land use management for catchment health[32,33], and through integrated landscape approaches[34,35] which vary across the spectrum from formal to informal. Another means of realising stewardship in practice in landscapes, which varies from policy-driven to informal bottom-up initiatives, is through a variety of informal community-based, common pool resource management initiatives in a diversity of contexts.[25,36,37]

These stewardship-in-practice initiatives vary according to a number of features (comparable to conceptual frameworks of stewardship recently proposed by Bennett et al.[4] and Peçanha Enqvist et al.[38]) which include their approach, objectives and stewardship actions. We use these features as a means of exploring stewardship practice in South Africa. These initiatives also vary in their alignment with the notion of social-ecological stewardship. We adopt this term here as an umbrella term for the most recent understandings of stewardship, using it as a lens to investigate how recent stewardship theory is put into practice in the South African context.

Working in the context of these landscapes, our study builds on recent global literature[4,9,16,23,38], and specifically extends Barendse et al.'s[8] study of South African stewardship initiatives that contribute toward sustainability and conservation outcomes by offering detailed, localised, practice-based understandings and insights from stewardship practitioners working in rural multifunctional landscapes. We explore three key areas: (1) the meanings of stewardship held by stewardship practitioners who are implementing stewardship at the local level; (2) how they are putting stewardship into practice; and (3) whether there is evidence of the more recent concept of social-ecological stewardship being applied in practice in the context of multifunctional landscapes.

Methods

Data collection

We collected data through a countrywide survey of stewardship practitioners.[39] We define stewardship practitioners as professionals from a variety of organisations working with local land owners and land users (or stewards) to bring about improved stewardship,[4] i.e. they facilitate stewardship in rural landscapes. We drew participants from the stewardship practitioner community across South Africa working in rural landscapes, making a concerted effort to reach out to people working in relevant sectors other than conservation (which is a well-represented sector in the biodiversity stewardship community), such as agriculture, rural development and water management. Almost half the sample worked with approaches other than biodiversity stewardship (see 'Respondents' stewardship context' below). To do this we employed a purposive snowball sampling approach.[40] Participants were recruited at workshops and conferences, and by email and telephone. Barendse et al.'s[8] list of stewardship initiatives provided a useful benchmark for sample completeness.

The survey questionnaire was fully structured and included 27 questions, both open- and closed-ended questions[39] (see Appendix 1 in the supplementary material). The survey was divided into three parts: (1) the context of the participants' project or initiative; (2) what environmental stewardship meant to them (open-ended questions); and (3) environmental stewardship practices in their projects. The following questions were used to generate insights on 'stewardship practices': (1) What kind of approach or model is employed in your project? (2) What is the primary objective of your project? (3) What kind of stewardship actions are expected from stewards? We use these categories to structure the results section on stewardship practice.

To increase the response rate, we administered the survey through a variety of avenues[39] including survey interviews (in person or telephonically) and self-administered survey questionnaires (hand written and web-based, using Google Forms). To reduce potential variability across means of administration, an identical form was used across all media. We piloted the survey questionnaire with five practitioners and refined the questions based on this experience. The survey ran for 11 months from August 2015 until June 2016; 95 practitioners from across South Africa participated.

Data analysis

We analysed the quantitative data using descriptive statistics.[39] We coded qualitative data from open-ended questions using inductive, open coding through a two-step coding process.[41] The first step was to identify themes of similar responses per question from the data, resulting in a long list of themes (about 15–20 per question). In the second step, we narrowed this list of themes down to a shorter list of overarching categories based on similarity in meaning.[42] We labelled the categories as much as possible using 'in vivo' codes (i.e. using respondents' wording) to stay true to the meanings expressed in responses.[41] For most questions, we also quantified the number of responses per category coded from qualitative data.

We coded the practical application of the concept of 'social-ecological stewardship' in the initiatives (Objective 3) out of the qualitative data according to a pre-determined coding framework, using the following three criteria[23]: The initiative had to: (1) be working at landscape-level (i.e. beyond the individual farm or village level); (2) be working towards multifunctionality, i.e. towards multiple, integrated social-ecological stewardship outcomes; and (3) have an explicit focus on collaboration among multiple stakeholders and stewards (or farmers) must be active participants in a collaborative multi-stakeholder process. These criteria characterise initiatives which are putting the concept of social-ecological stewardship into practice in landscapes.[23]

Respondents' answers to the question about what kind of stewardship actions they expected from stewards generated a large number and variety of responses, and we therefore treated them as free-list data.[43] We quantified the 'stewardship actions' data by counting the frequency of mention of each action across all respondents. We used word frequency counting (a form of content analysis[44]) on the textual survey data (full data set) to identify and quantify instances of key terms from the recent theoretical stewardship literature (drawing on the principles of ecosystem stewardship described above[21]). To avoid reductionist interpretations of counts, we interpreted these in the context of their usage, by analysing them together with the qualitative results.[44]

Ethical considerations

We adhered to the guidelines of the Rhodes University Ethical Standards Committee Handbook[45] which include the following key principles: respect and dignity of research participants (including obtaining free and informed consent and ensuring anonymity); transparency and honesty in all aspects of research; accountability and responsibility of researchers; and integrity and academic professionalism of researchers. Research feedback was provided to participants via email, in a magazine article[46], and through presentations at relevant events. The study was given ethical clearance by the Department of Environmental Science Ethics Sub-committee in August 2015.

Results

Respondents' stewardship context

Participants represented all nine provinces of South Africa and worked in a variety of organisations. The largest proportion of respondents (44%) worked for national non-governmental organisations (NGOs). The next biggest group worked for provincial government agencies (23%), followed by local NGOs (14%), private sector organisations (8%), national government (4%), research institutes (4%), and local government (2%). Considering the importance of the biodiversity stewardship tool in South Africa[8], we also categorised participants by their involvement with this approach: 33% worked solely with the biodiversity stewardship tool, 27% combined it with other approaches, and 40% exclusively used other approaches. We also asked participants whether they would characterise the work or purpose of their project as 'stewardship': 82% said 'Yes', 16% said 'Maybe or Partly', and 2% said 'No', confirming that a large proportion of the sample self-identify as stewardship practitioners.

Table 1: Practitioner understandings of the meaning of stewardship ($n=95$)

Meaning	Frequency	Explanation	Illustrative quote
Responsible use and care	42%	The steward needs to use and care for nature or natural resources in a responsible manner, taking an inter-generational approach.	'Responsible use of natural resources for the benefit of current and future generations.'
Stewardship = Biodiversity stewardship	20%	The term 'stewardship' is considered to mean the same as the term 'biodiversity stewardship' (i.e. the two are conflated) (see Table 1).	'Private land owners signing their properties into a conservation protection class and managing this land for the benefits of biodiversity.'
Sustainable use and management	20%	Use and management of nature and natural resources whilst implementing the principles of sustainability, i.e. balancing social, economic and ecological needs.	'Looking after or managing your natural resources in a sustainable manner – protecting and improving natural resources while you produce.'
Preserving and conserving	11%	The role of the steward is to conserve and protect nature and natural resources from human impacts, taking an inter-generational approach.	'Landowners and beneficiaries safeguarding the land, its ecosystem services for now and future generations, sustainably.'
Ethical or moral imperative	5%	This meaning focuses on the ethical or moral implications of stewardship: the role of the steward is to take care of nature and natural resources because of an ethical or moral duty, for the greater good.	'Stewardship is an ethic that embodies the responsible planning and management of resources.'
Holism and human–nature connectedness	2%	In this meaning of stewardship, the interconnectedness of humans and nature is emphasised. Stewardship is a human response to recognising this interconnectedness and acting in a certain manner because of it.	'…it is important not to view humans as separate from the landscape … but stewardship implies a responsibility on humans to take care of the life that supports us.'

Meanings of stewardship in practice

Practitioners held diverse understandings of the meaning of stewardship, yet these coalesced around the ideas of 'taking care of nature' and 'stewards performing a balancing act between protecting nature and supporting their own agricultural livelihoods' (Table 1). Just under half of the respondents understood stewardship to mean 'responsible use and care'; for example, stewardship is the 'responsible use of natural resources for the benefit of current and future generations'. A total of 20% of respondents conflated stewardship in general with the biodiversity stewardship tool specifically (Table 1: 'Stewardship = Biodiversity stewardship'). For example, one respondent expressed confusion regarding what they understood about the term:

> *…for me the word 'stewardship' is confusing due to what the word actually means and what is happening in reality. For me the word means taking responsibility for managing one's own natural resources. In reality it seems more like a process to extend protected areas status onto private lands.*

Another 20% of respondents described stewardship as 'sustainable use and management' (Table 1), for example: 'Looking after or managing your natural resources in a sustainable manner – protecting and improving natural resources while you produce'. This meaning is distinguished from 'responsible use and care' by its explicit use of the term 'sustainability' (Table 1). The remaining 18% of respondents' understandings of stewardship included notions of 'preserving and conserving nature', an 'ethical or moral imperative', and 'holism and human-nature connectedness'.

The different terms used by respondents to define stewardship and describe how they put it into practice also give insight into what stewardship means to them, and what discourse is dominant in stewardship practice. For example, the terms 'conservation', 'environment' and 'biodiversity' were the three most frequently used terms in definitions given by participants and also in the entire data set (Table 2). Terms from the more recent literature on stewardship in social-ecological systems such as 'ecosystem services', 'resilience' and 'social-ecological systems' were used far less frequently by respondents in their answers (Table 2).

Table 2: Word frequency counts from the responses of stewardship practitioners of key terms in the recent stewardship literature (aligned with '21st Century' and 'Contemporary' stewardship literature and understandings described in Figure 1)

Term from the literature (or root of term)	Overall frequency† in data set	Respondent frequency‡ in overall data set	Respondent frequency‡ in 'meaning of stewardship' responses
conserv- (conserve, conservation, conservancy)	434	84	30
environment- (environment, environmental, environmentally)	359	87	20
biodiverse- (biodiverse, biodiversity)	321	80	25
sustain- (sustain, sustainable, sustainability)	159	56	13
ecosystem (excluding ecosystem services)	85	41	4
ecosystem services	32	19	6
resilien- (resilient, resilience)	13	13	0
social-ecological, socio-ecological	8	4	1

†*'Overall frequency' = how many times the item was mentioned throughout the data set*

‡*'Respondent frequency' = the number of respondents who mentioned the item (n=95)*

Practice of stewardship

Stewardship approach

A diversity of approaches to facilitating and implementing stewardship are being practised in South Africa (Table 3), with similar approaches, objectives and activities as described for stewardship initiatives worldwide

(see Introduction). The most dominant approach is the biodiversity stewardship tool; however, a similar proportion of respondents are involved either in approaches which combine biodiversity stewardship with other approaches, or in integrated landscape or catchment approaches to stewardship. Overall, 60% of respondents are involved to a greater or lesser extent in implementation of the biodiversity stewardship tool (Table 3). The combination of the biodiversity stewardship tool with other approaches indicates its applicability in a variety of contexts, beyond the narrow focus of achieving biodiversity conservation targets. Practitioners are integrating this tool within broader sustainable land management initiatives. For example:

> *My project is quite varied with a habitat rehabilitation aspect, a more scientific based monitoring aspect and then a stewardship aspect. The monitoring functions to track the progress of rehabilitation work and to identify new threats that need to be addressed and biodiversity stewardship is used as a tool to secure high priority habitats for conservation.*

The combined use of the biodiversity stewardship tool with other approaches (often those focused on sustainable utilisation or production) (Table 3) also illustrates that for many practitioners, stewardship is about balancing protection and use of multiple ecosystem services. For example, balancing the protection and management of biodiversity, or regulating and supporting ecosystem services such as water, with the production-oriented use of land for commercial or subsistence agriculture, livestock grazing or other natural resources (provisioning ecosystem services). Seeking to strike the balance can bring sectors into conflict with one another but can also lead to new partnerships. For example, one respondent commented that:

> *For stewardship to work it is important that we are able to 'align with our enemies' e.g. I am working for a conservation agency, but I sit in the agriculture office.*

The characterisation of stewardship practice according to these different approaches (Table 3) reveals that sectoral focus areas seem to drive approaches to stewardship. The biodiversity conservation sector currently dominates stewardship practice through the biodiversity stewardship tool; however, catchment management and sustainable land management, which are represented for example by the Departments of Water, Agriculture and Land Affairs/Rural Development, are also important sectors for stewardship.

Objectives of stewardship

Despite focused biodiversity stewardship approaches only accounting for 33% of the sample (Table 3), biodiversity conservation was the primary objective identified most frequently by respondents (57%, Figure 2). Ecological objectives were by far the most cited primary objective, followed by sustainable agriculture and catchment management (Figure 2).

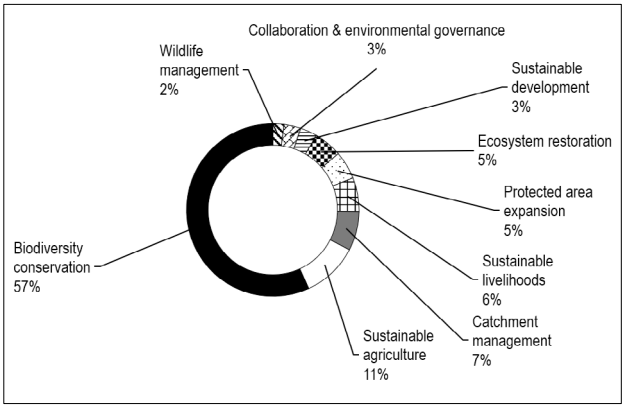

Figure 2: Primary objectives of stewardship initiatives (n=95).

The quotes below illustrate some of the more multifaceted objectives expressed by many respondents, illustrating that practitioners are working with farmers towards balancing the needs of production activities

Table 3: Stewardship approaches or models applied in respondents' projects (n=95)

Approach	Frequency	Description
Biodiversity stewardship tool	33%	'Biodiversity stewardship is an approach to securing land in biodiversity priority areas through entering into agreements with private and communal landowners, led by conservation authorities…The objective of Biodiversity Stewardship is to conserve and manage biodiversity priority areas through voluntary agreements with landowners.'[7] This tool is driven by policy and legislation in South Africa and is one of the means by which the country seeks to reach its protected area expansion targets. It is also considered a form of Private Land Conservation.[19]
Biodiversity stewardship tool combined with other approaches	27%	Practitioners often combine the biodiversity stewardship tool with other approaches, for example, they will work with landowners to declare a portion of their land as a Protected Environment or as a Nature Reserve, whilst also supporting farmers in the implementation of agricultural 'Better Management Practices' (BMPs) on the cultivated areas of their farms.
Integrated landscape and catchment approaches	26%	These are initiatives which often operate at levels above the individual farm or village, take an integrated approach to land management by working towards multiple objectives, and focus on stakeholder collaboration as a key process in their work.[34,35] The project goals are usually broader than, for example, only biodiversity conservation or only sustainable agriculture, and consider the land-based livelihoods occurring in the landscape in an integrated way. These initiatives often have a catchment approach which recognises the important ecosystem services related to water production. Biosphere Reserves (UNESCO Man and the Biosphere Programme) are an example of a landscape-level approach.[52]
Sustainable production or utilisation	9%	Initiatives which focus on sustainable production or utilisation are usually focused on the agricultural production activities occurring on the land. The starting point is to support the economically and ecologically sustainable use of land-based resources for agricultural production. This use includes commercial agricultural production and subsistence farming or grazing on communal rangelands. These initiatives focus on balancing the economic needs of stewards with long-term ecological functioning of the land. They are often implemented through development of guidelines for agricultural BMPs, and may be linked to market-based incentives to secure premium markets or prices for agricultural products which are adhering to such sustainable use guidelines. These sometimes incorporate short-term contractual agreements with farmers to ensure compliance to management guidelines or BMPs, which may make provision for financial incentives or compensation through schemes such as payments for ecosystem services.
Other environmental stewardship approaches	5%	This is a small category of initiatives which do not fit into the above four types. It includes, for example: local initiatives around water stewardship with citizen scientists; local volunteer-driven biodiversity monitoring initiatives; or alien plant clearing initiatives which are not part of a broader stewardship project like the ones described above.

(or provisioning ecosystem services), with management and protection of regulating or supporting ecosystem services in the landscape:

> *Sustainable land use, continual provision of ecosystem services, biodiversity conservation, ecosystem-based adaptation, improved access to markets for produce.*
>
> *Ensuring an ecologically functional environment where people can farm, live and thrive happily alongside biodiversity assets for multiple generations.*

Stewardship actions expected from stewards

The stewardship actions expected from stewards (Figure 3) align with the primary objectives identified by practitioners (Figure 2), confirming that stewardship practice in South Africa is primarily about engaging with ecological concerns. The most frequently expressed categories of stewardship actions focus on dealing with ecological aspects such as species, ecosystems, habitats, natural resources and biodiversity (Figure 3). However, several categories also illustrate the role of stewardship as balancing both ecological protection or management (e.g. for regulating and supporting ecosystem services), and production or livelihood outcomes (e.g. for provisioning ecosystem services). This role is reflected in statements such as: 'utilise resources sustainably' and 'implement agricultural best management practices'. Actions relating to social learning and collaborative processes were also mentioned, including 'participate in knowledge-sharing and education', 'participate in research and monitoring' and 'participate in collaborative initiatives', although these were reported far less frequently (Figure 3).

Evidence of 'social-ecological stewardship' in practice

Further insights into the nature of stewardship practice and the alignment of initiatives with the most recent meanings of stewardship in theory (i.e. social-ecological stewardship) are revealed through the following key features: 65% of initiatives operate at landscape-level and therefore involve multiple stakeholders; 47% of initiatives are working towards multiple, integrated social-ecological outcomes; and 67% of initiatives have an explicit focus on building collaboration among stakeholders. Of the initiatives, 41% showed all three of these features of social-ecological stewardship, suggesting that, in many initiatives, putting stewardship into practice is about more than simply working towards ecological objectives (Figure 2) and implementing ecological management actions (Figure 3).

Although 60% of initiatives are implementing the biodiversity stewardship tool (33% solely, and 27% in combination with other approaches (Table 3), our findings show that in many cases the tool is being implemented within a more integrated overall approach in which biodiversity conservation is one of many potential outcomes of improved stewardship.

We also investigated whether any initiatives were explicitly applying the resilience-based principles of ecosystem stewardship.[2,21] In defining the meaning of stewardship, none of the respondents used the term 'resilience', only 6 of 95 respondents mentioned the term 'ecosystem services' in their definition of stewardship (Table 2), and the term 'social-ecological' was used only a total of eight times (Table 2). These three terms are core to the principles of ecosystem stewardship described in the introduction. In contrast, the word root 'sustain-' (i.e. sustain, sustainable, sustainability) was used by 13 respondents in their definitions of stewardship and was mentioned overall in the full data set by 56 respondents (Table 2). The lack of uptake by practitioners of the most recent jargon from the stewardship literature is not surprising, especially considering that these are also recent concepts in the literature, and that there is a well-known gap between theory and practice in this field. What is striking, however, is that when one looks beyond the language, meanings and discourse to the actual practice of stewardship, there is evidence of social-ecological stewardship, as described above.

Discussion

Our study provides insights into the practice of stewardship in South Africa, revealing how local practitioners are working towards achieving stewardship outcomes on the ground, thus shedding light on the links between theory and practice. We begin by discussing concerns and opportunities raised by the prevalence of the biodiversity stewardship tool in the practice of stewardship in South Africa. We then turn to two new perspectives on stewardship in practice revealed through this study. Firstly, the findings on the meanings and practice reveal insights into the contemporary role of local stewards working in multifunctional landscapes, where they are expected to care and share. Secondly, despite the dominance of the biodiversity stewardship tool in South Africa, the practice of stewardship appears to be shifting to align with the most recent social-ecological understandings of stewardship in the literature – practitioners may not be 'talking the walk' (aligned with stewardship theory), but they do seem to be 'walking the walk' (putting stewardship into practice).

Concerns and opportunities for stewardship practice

There are concerns about the dominance of stewardship practice by one sector through the biodiversity stewardship tool. The prevalence of biodiversity stewardship is perhaps to be expected given the institutionalisation of the approach in South African policy[8], and its relative success within the conservation sector[6,47]. This institutionalisation

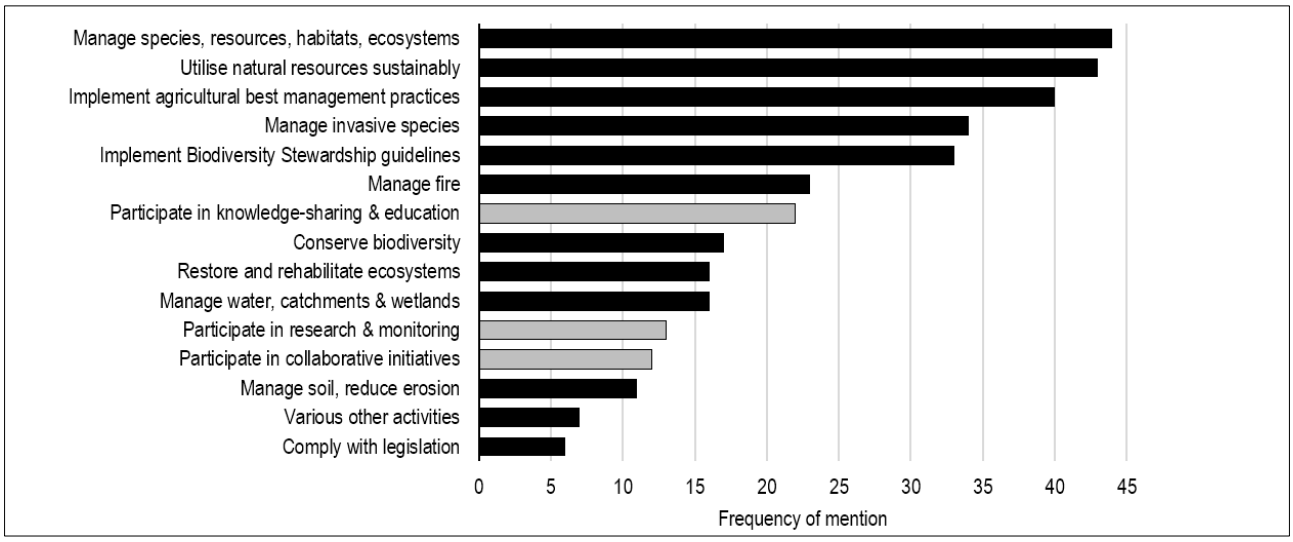

Figure 3: Stewardship actions which practitioners expect stewards to implement. Black bars indicate stewardship actions focused on ecological outcomes; grey bars indicate stewardship actions related to social outcomes (n=95).

demonstrates that both local and global policy play a strong role in shaping the understanding, discourse and practice of stewardship in South Africa – possibly more so than global theory (Figure 1) and practice. For example, the Protected Areas Expansion Strategy from which the biodiversity stewardship tool emerged, is a response to South Africa's commitments for protected area expansion to the international Convention on Biodiversity.[48]

The strong focus of biodiversity stewardship on conservation outcomes may hinder opportunities for other diverse forms of stewardship (Figure 1), and the narrow focus on 'high-value' biodiversity priority areas within the biodiversity stewardship approach means large areas of the country are excluded from the potential positive impacts of stewardship.[8] Possibly in response to such concerns, some national NGOs in South Africa have adopted more holistic and integrated interpretations of stewardship[8] aligned with the notion of social-ecological stewardship or 'Earth Stewardship'[1]. This adoption indicates recognition among the practitioner community that more integrated, holistic approaches to stewardship may be more suitable to addressing the complex social-ecological challenges faced in South Africa.

Another concern relates to associations between biodiversity stewardship and the problematic history of biodiversity conservation in the country. Because of its strong ties with biodiversity conservation in South Africa, there is a risk that stewardship is associated with the social injustices which were historically enacted in the interests of conservation.[49] Tellingly, a respondent in our survey commented that 'there is a perception that stewardship is for rich white people'. Policymakers and practitioners of biodiversity stewardship in South Africa would do well to continue working on ensuring that implementation of the biodiversity stewardship tool in no way infringes on local people's voice, rights to equal access of benefits of ecosystem services, and other social justice concerns. This consideration is especially relevant considering critique in the literature about the concept of stewardship and its historical association with paradigms that have perpetuated exclusive religious and chauvinist ways of engaging with nature.[14,15,17] Moreover, recent debates in South Africa around land reform and expropriation without compensation[50] and resulting land tenure uncertainty among private landowners, raise important questions about the long-term sustainability of the current model of biodiversity stewardship as the primary tool for conservation outside of state-owned protected areas. The conservation community needs to earnestly engage in the realities of land redistribution. Stewardship policies and practices need to be agile and flexible enough to accommodate changing land tenure arrangements.

The strong position of biodiversity stewardship is also positive in many ways. Certainly, within the conservation sector in South Africa, this approach is considered a success story for biodiversity conservation and protected area expansion.[6,47] It is viewed as a cost-effective tool for securing protected areas on non-state land, and is considered a valuable means of securing commitment and investment from private and communal land users into long-term stewardship.[6] Through binding contractual agreements with landowners, practitioners can also potentially secure fiscal benefits for farmers (for example through tax rebates), supporting stewards to off-set the costs of voluntary stewardship actions on their land.[51] There is also recognition that integrating the biodiversity stewardship tool with other approaches to sustainable natural resource management could help South Africa to work towards its National Development Plan and the Sustainable Development Goals.[19,47] Examples of these include the integrated landscape-level initiatives identified here, but also market-based incentive schemes, and rural development and environmental education initiatives, which were not identified in our findings but have been recognised as important forms of stewardship.[8]

There is an opportunity to leverage the effectiveness and success of the biodiversity stewardship tool to achieve more integrated outcomes[47], as practitioners are already beginning to do (Table 3). To successfully implement the ideals of stewardship informed by a social-ecological view, a cross-sectoral policy framework which supports or mandates cooperative governance and creates an enabling environment for multistakeholder collaboration is necessary. Existing landscape-level stewardship initiatives such as, for example, the Man and the Biosphere Reserve Programme and Catchment Management Forums, are promising candidates for such a framework, and require more support to realise their potential in South Africa[52].

In practice, stewards are expected to care and share

Our findings on the meanings of stewardship in practice reported here clarify what kind of role local stewards are expected to play by practitioners. Despite a diversity of understandings of stewardship in practice which mirror to some extent the diversity in understandings represented in the theory[38] (Figure 1), the meanings attached to stewardship coalesce around two core themes: (1) 'responsible use and care of nature and natural resources' and (2) the idea of 'stewardship as a balancing act' between utilisation of natural resources for agricultural production and protection of nature (Table 1). Therefore, according to practitioners, the role of the steward is to use natural resources responsibly and carefully by balancing the use of natural resources for their own agricultural production needs and objectives (e.g. crop or livestock production) with a responsibility to manage and protect natural resources for the good of the ecosystem, and for the greater good of society. This aligns with the more classical definition of stewardship proposed by Welchman[14], and with the sustainability-informed conceptualisations of stewardship in theory (Figure 1). Furthermore, in the literature 'care' has been identified as a fundamental concept underpinning many diverse stewardship understandings, and our findings from practitioners support this relationship.[16,38]

Although practitioners in this research did not mention the concept of ecosystem services much (despite its prominence in the literature on ecosystem stewardship[21]), interpreting the role of the steward through the lens of ecosystem services reveals an interesting feature of their role. The role of stewards could hence be re-formulated as: *to interact with ecosystems responsibly and carefully by balancing the use of provisioning ecosystem services for their own direct needs, with the societal and ecological needs of a broader, more diverse suite of ecosystem services, such as regulating, supporting, and spiritual and cultural ecosystem services*. This means that they are in effect stewards of the multifunctionality of the landscape and are expected to act as stewards of an interlinked social-ecological system, reinforcing the notion of stewardship as a relational concept.[16] Consequently, stewardship, even at the individual farmer level, is about balancing or managing trade-offs among multiple types of ecosystem services.[53] If a steward is to be responsible in their interactions with nature and to take care, then they have an obligation to collaborate with others, i.e. to share, across the landscape, to negotiate ecosystem services trade-offs.[54] A competent steward is expected to care, and to share. Collaboration therefore becomes an imperative of stewardship practice[23], and a relational approach to understanding and practising stewardship is necessary[16].

In seeking to achieve the 'balancing act' of the benefits of diverse ecosystem services from multifunctional landscapes, stewardship initiatives hold the potential to address the long-standing conflicts between agriculture and conservation.[55] According to the practitioners in our study, successful stewards are expected to be able to manage species, habitats and ecosystems, whilst also utilising ecosystem services sustainably (Figure 3). Managing this balance is similar to the role expected of stewards in other countries, for example in the Australian Land Care programmes[25,31] and in agri-environmental schemes in Britain and Europe[30]. Land-use conflicts between agriculture and conservation are of increasing concern[56], and approaches like stewardship, which seek to address conservation, agricultural and social concerns on a single piece of land – or even at landscape-level – are necessary[57]. Given that most stewards (at least in South Africa) are practising stewardship in a voluntary capacity with minimal or no financial incentives or subsidies (which are provided elsewhere, for example, through agri-environmental schemes in Europe[58]), these would be high expectations. Incentivising policies and funding mechanisms, as well as platforms for collaboration and negotiation, which create enabling conditions for stewards to fulfil this important role in society, are needed. At present, different land uses, or beneficiaries of different types of ecosystem services, are represented by different, often competing, sectors (e.g. water vs conservation vs

agriculture) which brings them into conflict with one another and makes it difficult for stewards to become competent in this important role.

Practitioners 'walking the walk, not talking the talk'

Many stewardship initiatives in South Africa conform to some extent to the contemporary theoretical ideas of social-ecological stewardship (Table 3), confirming that this is being applied in practice. Whilst the meanings of stewardship (Table 1) and the language used by practitioners (Table 2) align with less recent understandings of stewardship in the literature (Figure 1), the practice is shifting towards more integrated approaches. This seems to indicate that the language and discourse may in fact be obscuring the more contemporary and innovative practice, i.e. that practitioners are 'walking the walk', even if they are not 'talking the talk'. Although these social-ecological stewardship practices are similar to many approaches elsewhere in the world (see description of global stewardship practice in the Introduction), we consider their emergence in the South African context to be an institutional and practical innovation in the face of traditionally siloed approaches to conservation and natural resource management.[8] Practitioners appear to be responding to the complex challenges they face in multifunctional landscapes by implementing more integrated, social-ecological stewardship initiatives.

The practice of social-ecological stewardship in South Africa signals an opening for greater dialogue between practice and theory, to counter the usual underlying assumption that theory should inform practice.[59] For example, whilst stewardship practitioners may not have adopted the most recent language of stewardship theory in their discourse, they are putting social-ecological stewardship into practice, as concluded by Barendse et al.[8] Practice-based environmental knowledge is gaining increasing recognition[60], and researchers in the social-ecological systems field are calling for place-based research and comparative case studies of local stewardship initiatives[23,61]. South African stewardship practice is therefore an opportunity to conduct this kind of grounded research, whereby practice can inform theory.

Conclusion

Practitioners' understandings of the meaning of stewardship vary, mirroring to some extent the diversity of understandings prevalent in stewardship theory. However, the themes of responsibility, care for nature and balancing multiple demands on ecosystems were common threads. Hence, the primary role of the steward is to interact with ecosystems responsibly and carefully by balancing the use of provisioning ecosystem services for their own direct needs, with the societal and ecological needs of a broader, more diverse suite of ecosystem services. In the context of multifunctional landscapes, stewards therefore have an obligation to collaborate with other stakeholders across the landscape to negotiate trade-offs around a diverse suite of ecosystem services. Recognising collaboration as a key process for stewardship highlights that stewardship is fundamentally a relational concept. Investigating the stewards' perspective on their role and responsibilities would be valuable follow-up research, as they are likely to experience challenges in this balancing act, and in working collaboratively with others across landscapes.

The policy-driven biodiversity stewardship tool is a prevalent feature of stewardship practice in South Africa, and many practitioners are integrating this tool with other approaches. Practitioners' understandings of stewardship are strongly influenced by the sustainability discourse, and there is limited evidence in the language of practitioners of the most recent conceptualisations of stewardship in the social-ecological systems literature. However, despite this slow uptake of the recent theory, there is evidence of social-ecological stewardship emerging in practice. Practitioners' use of more classic stewardship language to talk about their work appears to be masking more innovative, contemporary practice which is responding to complex, multifaceted realities on the ground. These innovative social-ecological stewardship initiatives work at landscape-level and work towards integrated social and ecological stewardship outcomes by facilitating collaboration among diverse stakeholders. Innovative policy mechanisms and further research are needed to support these integrated, collaborative cross-sectoral initiatives.

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Authors' contributions

All four authors jointly conceptualised and developed the methodology for the study. J.C. was the lead researcher of the study, collected and analysed the data and wrote the initial draft of the article. G.C., S.S. and M.R. assisted with data analysis and revisions of the written draft. Significant conceptual and editorial input into writing of the article was provided by G.C. and S.S. G.C., S.S. and M.R. supervised the research as part of J.C.'s PhD research. G.C., S.S. and M.R. assisted in acquiring funding to support the study.

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Anthropogenic disturbances of natural ecohydrological processes in the Matlabas mountain mire, South Africa

Matlabas is a mountain mire in Marakele National Park, located within the headwaters of the Limpopo River in South Africa. This mire consists of a complex of valley-bottom and seepage wetlands with small elevated peat domes. The occurrence of one decaying peat dome, which has burnt, and desiccated wetland areas with terrestrial vegetation has raised concerns. The aim of this study was to understand the mire features and water flows in order to identify the potential drivers causing wetland degradation. Wells and piezometers were installed to monitor the hydraulic head and collect water samples for analysis of ion composition, ^{18}O and ^{2}H stable isotope content, and $\delta^{13}C$ and ^{14}C isotope content for radiocarbon dating. Moreover, peat temperature profiles were measured and peat deposits were also dated using radiocarbon. Results indicate that the Matlabas mire developed in the lowest central-east side of the valley by paludification at the onset of the Holocene. During the Mid-Holocene, peat development was extended laterally by autogenic and allogenic processes. Three types of water flows driving peat development were identified – sheet flow, phreatic groundwater flow and deep groundwater flow – two of which are surface or near surface flows. The recent occurrence of decaying peat domes and desiccated wetland areas is possibly related to loss of exfiltrating deep groundwater flows that have resulted from drainage by the head-cut channels in the mire and interception of near surface water flow by an access road, respectively. Interventions should be undertaken to prevent further degradation of the mire.

Significance:

- This study is the first, as far as we are aware, on the ecohydrology of an inland mountainous mire in southern Africa.
- The results highlight the importance of the current wetland management (including rehabilitation) initiatives in South Africa.
- The integrative ecohydrological methods can be applied in other headwater wetlands in southern Africa.

Introduction

Peatlands play a crucial role as carbon sinks in the regulation of atmospheric CO_2 concentrations, which in turn influence climate.[1] Peatlands also provide ecosystem services like carbon sequestration, water storage and nutrient cycling.[2] Over the past two centuries, the health of peatlands and their ecosystem functions have been affected by direct and indirect use of these systems, e.g. use of peat for fuel, agriculture and groundwater extraction for drinking water.[2,3] Hence, there is growing attention on the assessment, conservation and restoration of peatlands on a global scale.[4] Mires are peatlands that are still actively accumulating peat, and this process is controlled by climate, hydrology and vegetation.[2] While near-natural mires are still widespread in the northern hemisphere – such as in Canada, Russia, Siberia and Finland[5] – they are relatively scarce in the southern hemisphere[2]. Nevertheless, the southern hemisphere's peatlands play an important role in the global carbon cycle.[6]

Pristine peatlands are rare in South Africa.[7] The best examples of pristine peatlands here are found along the eastern coast and in the central mountain areas. Two-thirds of South African peatlands occur along the northeastern seaboard of the Indian Ocean, known as Maputaland, in KwaZulu-Natal Province.[7] Maputaland contains both the largest peatland, the Mkuze peatland complex at 8800 ha, and the oldest mire, Mfabeni at 48 000 years.[8-11] The Matlabas mire, however, is situated in Marakele National Park in Limpopo Province, and is part of the Central Highlands Peatland Eco-Region.[12] Matlabas is one of the largest and least impacted spring mires known to exist in South Africa. The mire falls within the reaches of the Limpopo River, which suffers events of severe drought.[13] While the mire is largely in a good state, some signs of erosion were observed during a wetland inventory project undertaken in the park in 2008.[14] These signs included head cuts and gully erosion. Previous land-use practices (cattle farming) and road construction (see results), which took place in the 1960s up to the early 1980s, may have affected the mire's natural processes.[15] However, it is not known whether this erosion is increasing or what has caused it. These head cuts and gully erosion are expected to further increase peat drainage in the future, which could result in the loss of large sections of the mire. In the present study, we aimed to determine how the Matlabas peatland developed over time in relation to the principal water flows and recent changes in land use, as this knowledge will serve as a strong basis for effective conservation and rehabilitation planning.

Study area

Figure 1 shows the location of the Matlabas mire in the Waterberg Mountains, within Marakele National Park (an area of approximately 290.5 km^2). The altitude of the Matlabas mire is around 1200 m above sea level (a.m.s.l.), and it has a total surface area of 64 ha, only 14 ha of which have peat accumulation. It has been managed as a national park since 1988 but was only officially proclaimed a national park on 11 February 1994. Before 1988, the area was used for agriculture, with both farming of crops and cattle grazing.[15]

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The mire can be divided into two sides: a western side (6 ha) and an eastern side (8 ha). The western side of the mire drains from west (from 1621 m a.m.s.l.) to east along a slope of 4%, while the eastern side of the mire drains primarily to the north (from 1614 m a.m.s.l.) along a slope of 5%.[16] Two seepage wetlands upslope of the mire were intersected in the late 1960s by a road that runs along the southern edge of the mire. The mire is located close to a watershed within a major east to west stretching valley.

Matlabas is underlain by sandstone bedrock of the Aasvoëlkop Formation, part of the Matlabas Subgroup in the Waterberg Supergroup (with shale and mudstone), and the Sandriviersberg Formation, part of the Kransberg Subgroup also in the Waterberg Supergroup.[17] The formations developed on the parent materials range from shallow to deep sandy soils on sandstone and clayey soils on diabase dykes and mudstone.[15] Wetlands in the Waterberg Mountains mainly occur in the valleys, and are arranged in a prominent kite-like pattern as a result of the diabase dykes intruding along faults striking west-northwest to east-southeast and northeast to southwest into the Waterberg Supergroup sandstones.[16]

Average daily ambient temperatures range between a high of 19.5 °C and a low of 5.1 °C, with the maximum daily temperature reaching 22.8 °C and minimum night temperature reaching -1.7 °C. The average annual ambient temperature was 17.6 °C during the period 2011–2013.[16] Average rainfall during the same period was around 1000–1200 mm/year, with an average daily rainfall of about 5.5 mm/day during the hot and wet season, which takes place from October to April.[16]

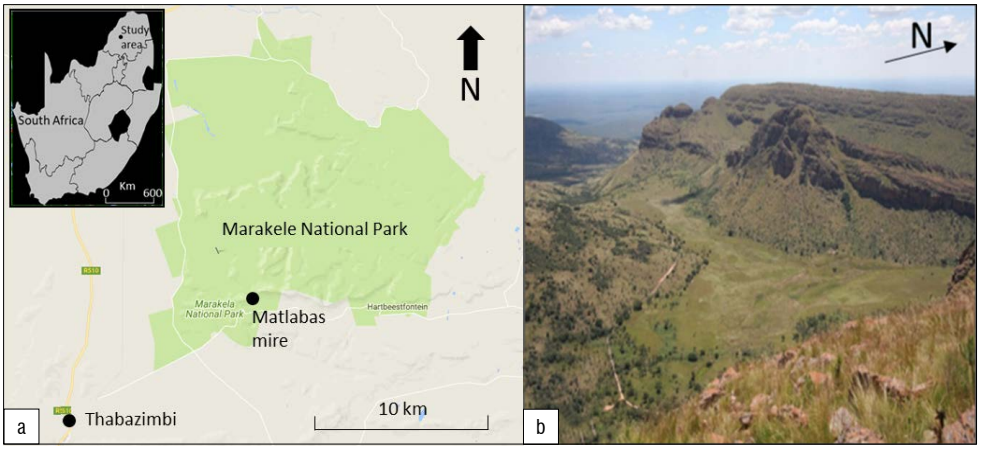

Figure 1: (a) Location of the Matlabas mire in Marakele National Park in South Africa (24°27'33.24"S, 27°36'1.28"E). (b) Overview of the Matlabas mire from a high plateau in the east.

Methods

Surface elevation and channel tracing

Elevations were determined with a differential GPS method, using a network of fixed, ground-based reference stations to broadcast the difference between the positions as indicated by the GPS and a known fixed position to obtain accurate contour lines at 50-cm intervals. Data for 290 points were obtained in February 2012 by F.J. Loock Surveyors Inc. from South Africa. The data were calibrated to height above sea level (a.m.s.l). Channelled surface water flows in the mire were recorded in the field by a hand-held GPS, visually plotted using aerial imagery and classified as either permanent or intermittent. Moreover, historical aerial images of the mire surface taken in 1956 and 1972, i.e. before and after road construction, were visually analysed.

Vegetation description

The different plant communities present in the area were mapped to determine their spatial spread as an indication of the inundation patterns. The Braun-Blanquet approach was followed to describe the vegetation.[18] Using aerial images, the area was divided into homogeneous units, in which a total of 54 sample plots (4x4 m) were placed in a randomly stratified manner per unit.[19] Plant species within the sample plots were identified and cover abundance values were assigned using the modified Braun-Blanquet scale.[20] Thereafter, a modified TWINSPAN was performed to classify the different plant communities present.[21] These vegetation patterns were used as environmental indicators to locate the zones of hydrological changes, and, therefore, to identify the most prominent sampling targets.

Peat thickness and dating

The thickness of the peat in the mire was recorded along four south-to-north running transects (A, B, C and D) covering the eastern side and at five points (W1 to W5) covering the western side (Figure 2). A Russian peat auger was used to sample peat cores, at 50-cm increments at a time, down to the top of the mineral soil.

A total of 14 peat samples (at a thickness of 1 cm) were collected for radiocarbon (^{14}C) dating to estimate the age at the bottom of the peat (at five locations) and to determine accumulation rates along two vertical profiles at points B3 (3 samples, a to c), B4 (6 samples, a to f) and C (2 samples, a and b). Samples from the vertical profiles were taken at the observed boundaries of facies change, e.g. degree of peat decomposition. Also, $\delta^{13}C$ content in the peat was measured to estimate the type of plant remnants forming the peat, i.e. C3, C4 or CAM (crassulacean acid metabolism) plants.[22] Each plant type has a different photosynthesis process, which leads to different $\delta^{13}C$

values as a result of the isotope fractionation.[23] C3 plants indicate wetter conditions with $\delta^{13}C$ values ranging from -22 to -25‰, and C4 plants indicate dry conditions with $\delta^{13}C$ values ranging from -11 to -14‰.[22,23] The colour and texture of each peat sample were described according to the Von Post Humification Scale,[24] and then the sample was sealed in a plastic bag. The samples were sent to the Centre for Isotope Research at the University of Groningen in the Netherlands for analysis.

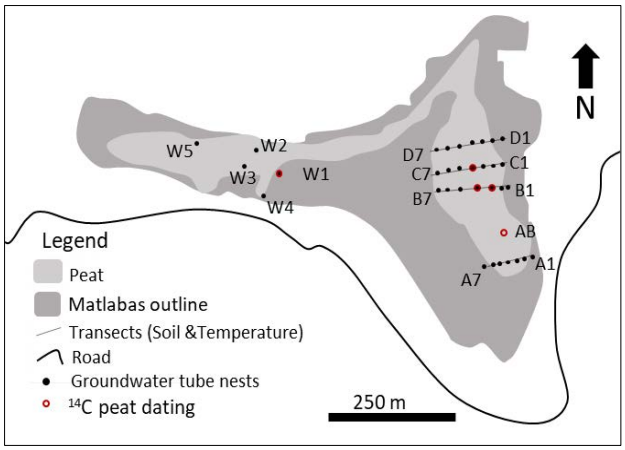

Figure 2: Location of sites used for soil description, radiocarbon peat sampling, groundwater wells for head measurement and groundwater samples for analysis of ion composition, stable isotopes and radiocarbon dating.

All the samples were treated using the acid-alkali-acid method to remove any contaminating material.[25] Then the $^{14}C/^{13}C$ content was measured by atomic mass spectrometry at the facility.[25] Most of the ^{14}C measurements were reported in before present (BP) units,[26] except for the samples with bomb effect backgrounds ($^{14}C>100\%$), while the $\delta^{13}C$ values were reported in permil (‰). The results in BP were calibrated to calendar age (CalBP) using the OxCal calculation model.[27] The calibration curve used for most of the samples was SHCAL13 for zone 1–2.[28] For the samples with ^{14}C content >100%, the calibration curve accounting for the bomb effect was used.[29]

Groundwater flow

Phreatic and piezometric water levels

Polyvinyl chloride (PVC) groundwater tubes were installed to measure phreatic and piezometric water levels at various depths. Phreatic groundwater levels were measured using wells, with perforated screens placed along the entire tube, at a depth of 60–80 cm, in the peat layer. Piezometric water levels were measured using piezometers, with a 20-cm screen at the bottom of the tube placed in the underlying mineral soil. Observation nests, each consisting of one well and two piezometers, were installed at transects A, B, C and D on the east side and at points W1 to W5 on the west side (Figure 2). The 20-cm screens of the piezometer were inserted at two depths: the first was at a shallow depth of 60–80 cm in the peat layer (referred to as 'a' in the code) and the second in the mineral soil beneath the peat ('b'). Supplementary table 1 shows the depths of all the groundwater tubes. Water levels within the wells and piezometers were monitored manually on a monthly basis from 2011 to 2013 to obtain 24 months of consecutive readings.

Peat temperatures

Peat temperatures were measured to identify the direction of the groundwater flows in the peat layer.[30] They were measured using a 2-m-long steel probe along the four transects on the eastern side (A, B, C and D) at 20-cm depth intervals. The measurements were carried out at each transect during a cold and dry period in June 2011, with ambient air temperatures around 12 °C.

Ion composition

Water samples were collected from piezometers during a wet summer season in October 2011 and a dry winter season in June 2012, with 54 samples taken for each season. Another sampling round was added in October 2017, but there were only 29 samples because many piezometer tubes had been burnt by a natural fire. All piezometers were emptied with a hand pump one day before sampling to replenish the water before sampling. The sampled water was then stored in PVC bottles in volumes of 100 mL and 50 mL for cation and anion analyses, respectively, and kept in the dark at a temperature of 4 °C.

These water samples were analysed at the Agricultural Research Council laboratory in Pretoria, South Africa. The samples were passed over a 0.45-mu membrane vacuum filter to remove sediments and impurities. Water pH was measured by titration, and ion composition of Ca, Cl, NO_3, SO_4, PO_4, HCO_3, Mg, Na and K were measured by inductively coupled plasma mass spectrometry. In the third round of sampling, Fe and SiO_2 ions were also measured. The results were checked for deviations in ionic balance, and samples with deviations higher than 20–30% were disregarded in further analyses.

$^{18}O/^{2}H$ stable isotopes

In March 2014, 22 water samples were collected to measure the stable isotopes of oxygen and deuterium (^{18}O and ^{2}H) in the water (Figure 2, Supplementary table 2). These water samples were collected in dark glass bottles of 50 mL and 30 mL and stored in the dark at a temperature of 4 °C. Later, they were analysed at the Centre for Isotope Research laboratory by dual inlet isotope ratio mass spectrometry (DI-IRMS). The sampling was repeated in October 2017 (29 samples), and these samples were analysed at the Environmental Isotope Laboratory of iThemba LABS at the University of the Witwatersrand, South Africa. The stable isotope ratios in the samples ($\delta^{18}O$ and $\delta^{2}H$) were reported in ‰ w.r.t. VSMOW, i.e. the reference used was the Vienna convention material.[31]

Carbon isotopes

The radiocarbon content of water samples is an indication of the residence time of groundwater in the soil.[32] Six water samples were taken, using 500-mL dark glass bottles, from the piezometers in the sand layer at the end of the dry season in October 2017 to measure the radiocarbon content. Five points were selected on the eastern side at transects A, B and D (A2, B4, B6, D4 and D5) and one point on the western side of the mire at W5 (Figure 2). These samples were analysed for their carbon isotope content ($\delta^{13}C$ and ^{14}C) at the Centre for Isotope Research laboratory. $\delta^{13}C$ values of the samples were analysed using DI-IRMS and reported in ‰ w.r.t. VSMOW, similarly to the stable isotopes. The ratios were then used to infer whether there had been dilution of the ^{14}C values as a consequence of infiltration through the peat layer, which is indicated by $\delta^{13}C$ values lower than -16‰.[32]

Results

Elevation and peat thickness

The peat soils in Matlabas cover a total of 14 ha, which is only 22% of the larger wetland area of 64 ha. Peat depth varied from 30 cm at the steep slopes to almost 5 m in the central parts of the eastern side of the mire, while average peat thickness was 1.5 m. Hence, the estimated volume of the peat layer was around 150 000 m^3. Most of the peat layers were fibrous, and they were interrupted by clay and sand layers at the bottom, where some layers of gravel occurred, e.g. at B4.

Six channels with concentrated surface water flow were identified (Figure 3). Two of these are permanent water flow channels on the eastern side. A third channel starting from the western side also has a permanent flow. The permanent channels are incised about 40–50 cm into the peat. Surface water drains the mire in a northerly direction.

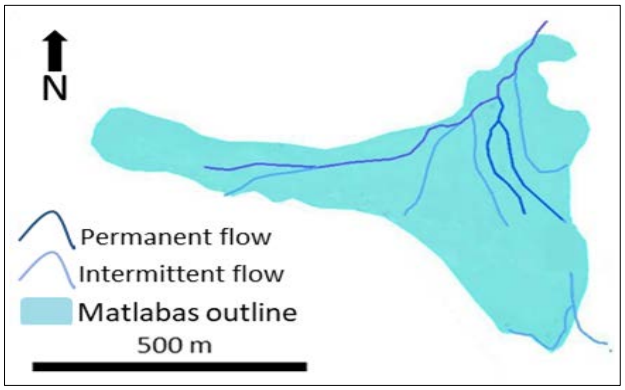

Figure 3: Map of water flow channels.

Aerial images taken in 1956 and 1972 show the mire before and after the road was built. These images show that some channel formation was already apparent in 1956 (Figure 4a). Since the construction of the road in the late 1960s, however, channel formation in the eastern section of the mire had increased in number and volume by 1972 (Figure 4b). Furthermore, the extent of two seepage wetlands visible on the 1956 images south of the later constructed road are largely reduced in the 1972 images.

Moreover, the mire has developed a series of elevated peat domes, with heights of approximately 1 m above the surrounding landscape and widths between 3 m and 9 m (Figure 5a). Most domes are situated along a fault line in a northwest-southeast direction, shown in a geological map of the area,[17] but some are also aligned in an east-west direction (Figure 5b).

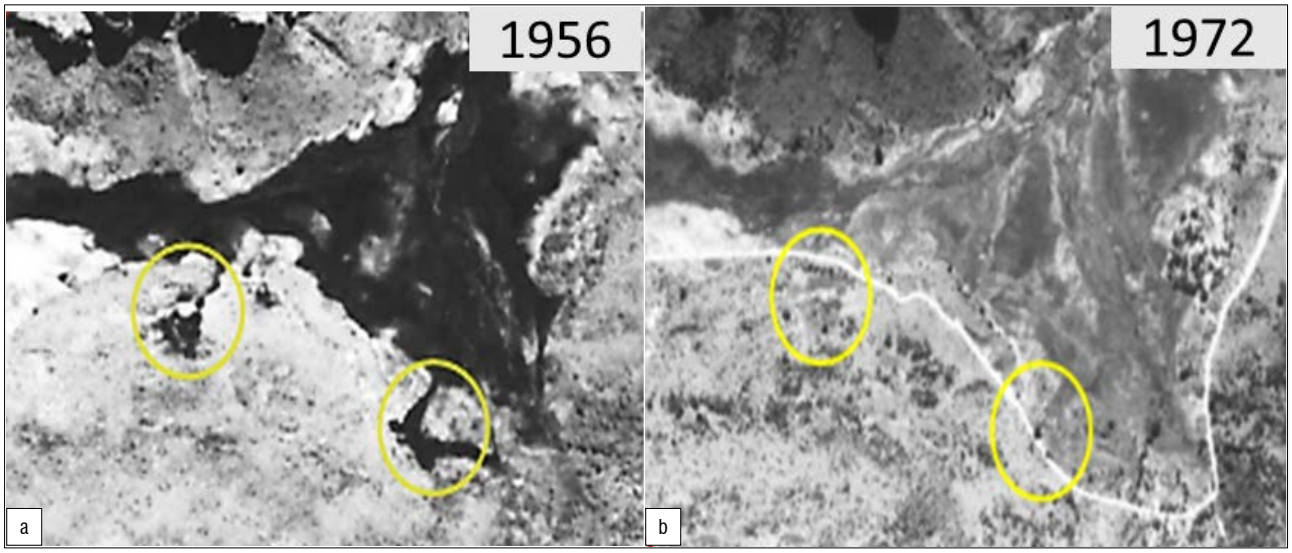

Figure 4: Aerial images of the Matlabas mire taken in (a) 1956 and (b) 1972. The yellow circles show the location of seepage wetlands, which appear to have been significantly reduced after construction of the road, thus indicating changes to the hydrological processes of the mire.

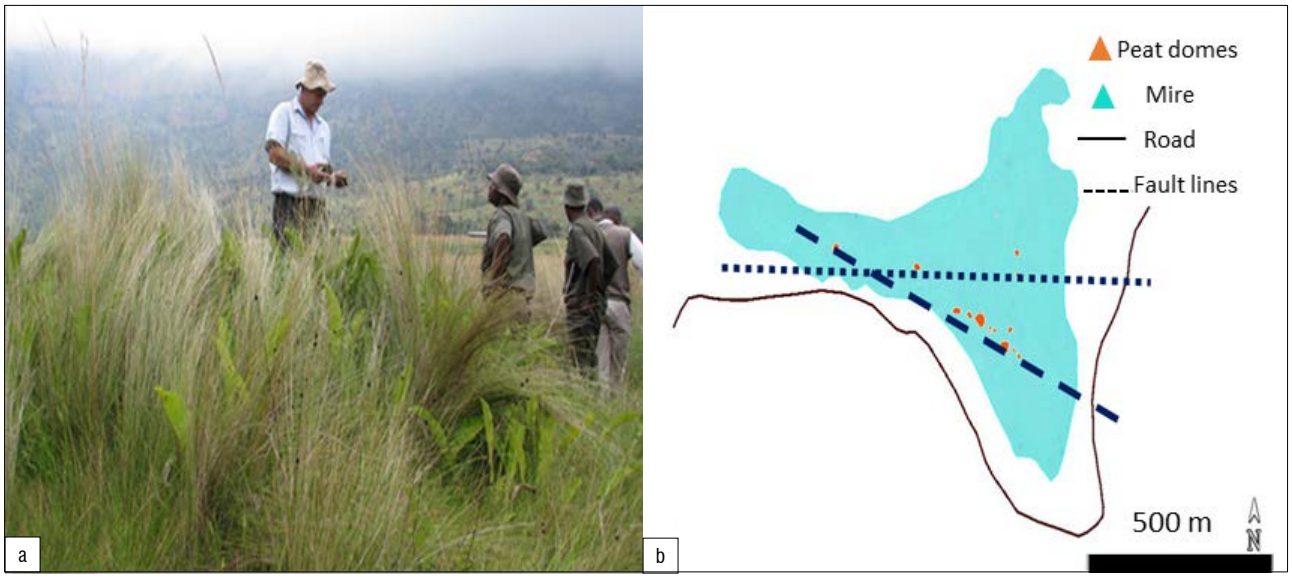

Figure 5: (a) Photograph of one of the small peat domes. (b) Peat dome occurrences and their alignment: NW-SE direction along a previously identified fault line (dashed line) and E-W direction that might indicate another fault line (dotted line).

Vegetation description

From the TWINSPAN analysis, three major plant communities were identified (Figure 6). The three major communities are briefly described below:

1. *Andropogon eucomis–Aristida canescens* community. Most of the elevated peat domes were covered with this vegetation community. This vegetation community contained the largest number of species, with common wetland species as well as species generally associated with drier conditions.
2. *Kyllinga melanosperma–Miscanthus junceus* community. This community occurred in the wettest part of the mire and was closely associated with peat deposits. A stand of *Phragmites australis* reeds on transect B at B3–B4 was found in this vegetation community.
3. *Pteridium aquilinum* community. This community occurred along the edges of the mire and is characterised by species-poor patches dominated by the fern *Pteridium aquilinum*.

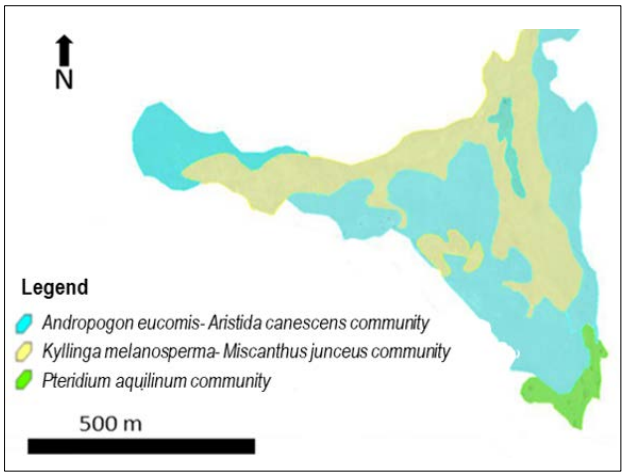

Figure 6: Vegetation map of the mire showing the three dominant vegetation types.

^{14}C dating

Table 1 lists the results of the radiocarbon dating of the 14 peat samples, their $\delta^{13}C$ content and descriptions of the depth intervals; the ages are given as median calibrated age. The mire's oldest basal peat sample, with a radiocarbon age of 11 160 CalBP, was taken from point B4f, which is the second lowest point in altitude. The valley flank basal peats all had younger ages, ranging between 5120 CalBP on the southeastern side (AB), 3860 CalBP on the western side (W1) and 690 CalBP on the northeastern side (C3b). Modern dates with bomb values were observed at point B4a (-55 CalBP) and point C3a (-6.5 CalBP), while point B3a dated to 130 CalBP. The $\delta^{13}C$ values show that C3 plants were limited to the top layer in core B4 (point B4a), whereas the rest of the samples had values indicating C3 plants.

Groundwater flow

The groundwater phreatic head in the peat layer showed a decrease from east to west along transect B (Figure 7a). At transect C, however, there was a downward direction of the phreatic head isohypse with most of the flow being directed to point C5, which is at the head of a permanent channel. The channel at C5 was shown to be draining from points C4 and C6, which had higher phreatic heads (Figure 7b).

Differences between the piezometric head and the phreatic head were + 0.01 to 0.04 m at B2 and B3, respectively. Such differences indicate potential seepage of groundwater, in line with the depressions visible on the ground surface. The head differences were largest at B4, where differences in the sand piezometric head and peat phreatic head equalled 0.14 m. Similar differences in head were observed along transect C, with the highest piezometric head found under one of the peat domes at point C4. In contrast, the piezometric heads in the sand were lower (c. 0.03 m) than those in the peat further west from B4 and C4 at both transects. At C5, the head difference was also significantly lower at 0.4 m.

Lastly, the water levels in the peat domes were found 30–50 cm below the surface. This depth is different from that of other parts with no dome structures, where the water levels were close to the surface. In the south to north direction, the phreatic head decreased northwards following the height gradient of the mire surface and the drainage direction of the surface water channels.

Peat temperature

Peat temperature showed an increase with depth, with the temperature gradients generally following the gradient of the peat surface slope. However, the discharging groundwater at B4 showed input of warmer water about 1.5 m from the surface: >14 °C when the ambient temperature was 10 °C (Figure 8). These measurements were taken at night during the dry and cold season in August 2013. Such patterns were also found along transects A and C, where warmer temperatures appear to be associated with discharging groundwater flows.

Table 1: Results of ^{14}C dating of the peat samples taken from transects A, B, C on the eastern side and point W1 on the western side

Code	Sample depth (cm)	Altitude (m a.m.s.l)	Sample description and Von Post scale (H1–H10)	$\delta^{13}C$ (‰)	Median age (CalBP)	Thickness (m)	Accumulation rate (mm/year)
W1	200	1590.4	Peat with gradual increase of clay content with increasing depth in the 50-cm core, low water content	-12.22	3860	–	–
AB1	250	1584.65	Decomposed peat (H8)	-13.26	5120	–	–
B3a	37	1579.7	Decomposed peat (H6)	-11.62	130	1.00	1.56
B3b	136	1578.03	Peat with high clay content (>H6)	-10.33	590	0.72	0.61
B3c	208	1577.31		-11.43	1780	–	–
B4a	35	1577.63	Red amorphous peat (H1–H3)	-25.88	-55	0.46	1.31
B4b	79	1577.17	Recomposed peat (H6)	-12.29	295	1.42	1.76
B4c	227	1575.75	Radicel peat (H1–H3)	-13.31	1100	0.62	0.66
B4d	282	1575.13	Radicel peat (H1–H3)	-14.46	2040	1.18	1.37
B4e	399	1573.95	Peat with clay and sand interval at 415–425 (>H6)	-15.92	2900	1.00	0.12
B4f	499	1574.95		-13.97	11 160	–	–
B5	155	1575.31	Peat with high clay content (>H6)	-11.53	1225	–	–
C3a	80	1575.52	Decomposed peat (H6)	-10.07	-6.5	1.15	1.65
C3b	195	1574.37	Peat with high clay content (<H6)	-12.96	690	–	–

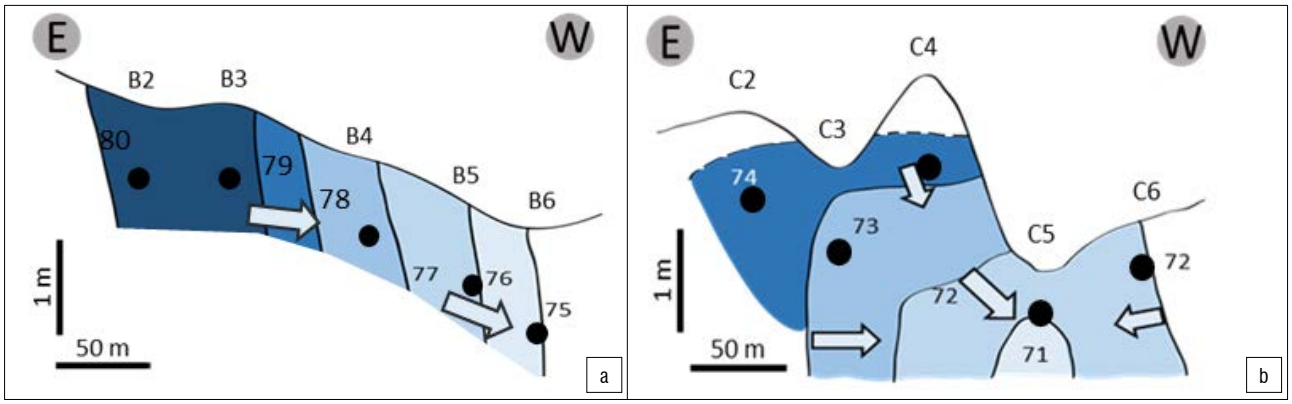

Figure 7: Groundwater phreatic head isohypse in March 2012 along (a) transect B and (b) transect C.

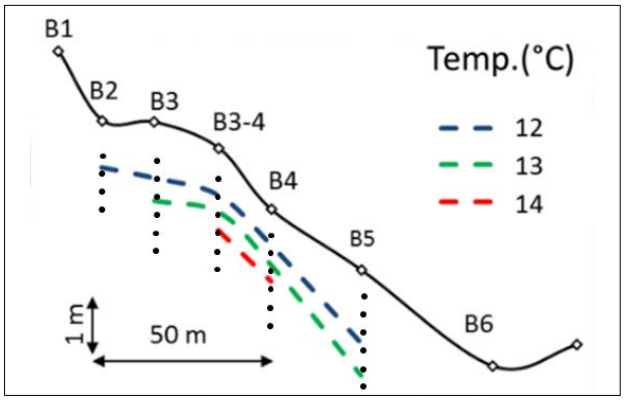

Figure 8: Peat temperature patterns along transect B measured in August 2013.

Ion composition

Chloride ion concentrations changed by three- to fourfold with season in the top 1–2 m of the peat layer. In deeper layers, the changes in concentration were smaller and less than onefold, e.g. at the sand piezometer at B4 (Figure 9a to c). Calcium ion concentrations also increased in the dry seasons, with magnitudes of change similar to patterns in the chloride ion. Calcium values increased by more than threefold within the top 2 m, while it remained one- to twofold higher in the deeper parts, except for B6 which showed higher calcium values in the deeper layers (Figure 9d to f).

In transect C, the calcium-rich and chloride-poor groundwater remained in the deeper soil layers. In the central peat dome, relatively large changes in ion composition occurred. During the wet season the calcium values were low under the peat dome (point C4), while in the dry season the calcium values were higher. There was also an increase in nitrate concentrations (0.73 mg/L relative to the average of 0.16 mg/L) in the

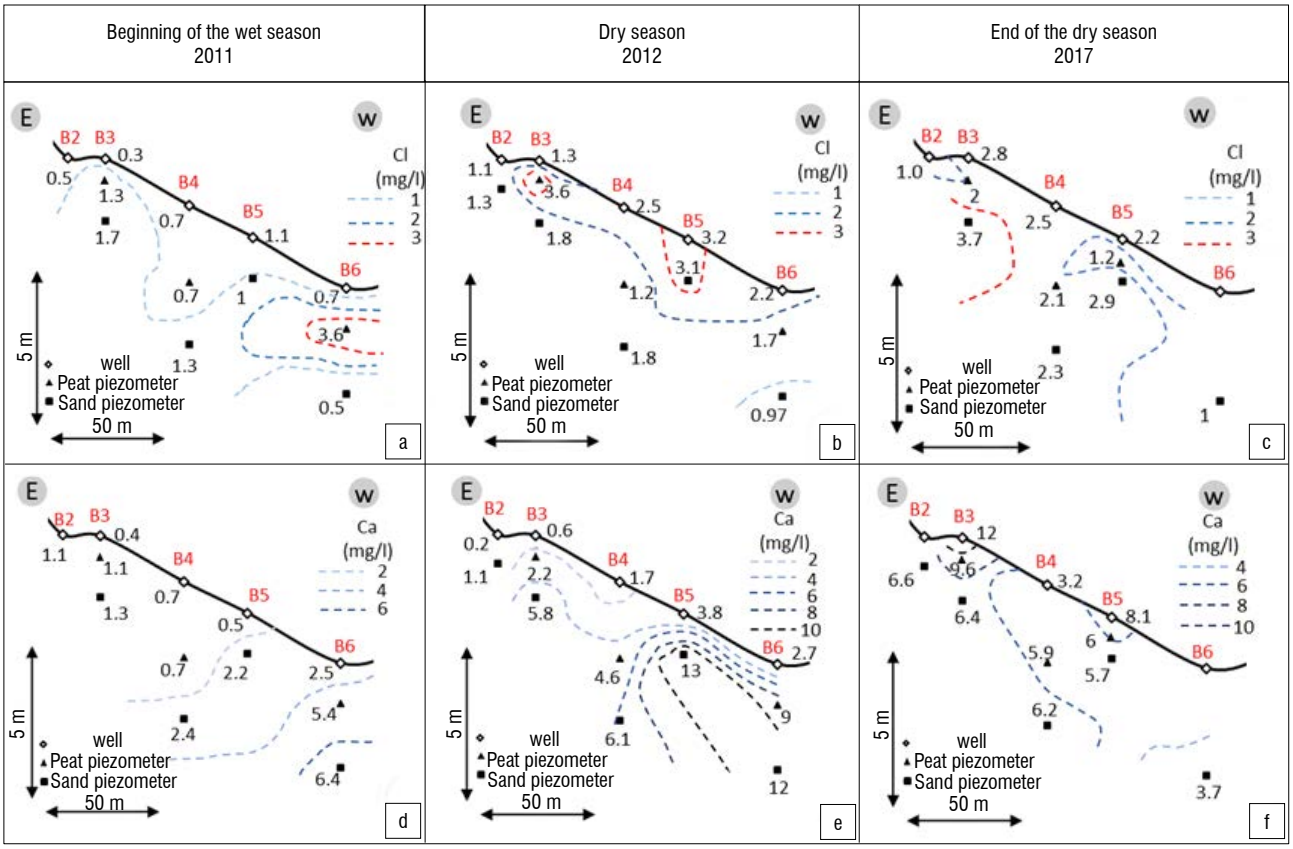

Figure 9: Ion tracers in transect B: (a) chloride at the beginning of the wet season in October 2011, (b) chloride during the dry season in June 2012, (c) chloride at the end of the dry season in October 2017, (d) calcium at the beginning of the wet season in October 2011, (e) calcium during the dry season in June 2012, and (f) calcium at the end of the dry season in October 2017.

groundwater below the peat domes at points C2 and C4 during the wet season (Supplementary table 1).

Stable isotopes

The stable isotope content in the water sampled in March 2015, which was at the end of the hot summer season, was significantly enriched compared with that of the water sampled in October 2017, which was at the end of the cold winter season (Figure 10). The samples from March 2015 had $\delta^{18}O$ values ranging from -4 to -6‰ and $\delta^{2}H$ values ranging from -20 to -30‰, while the samples from October 2017 had $\delta^{18}O$ values ranging from -4 to -3‰ and $\delta^{2}H$ ranging from -10 to -20‰. Samples from the western side of the mire appear to be mostly below the global meteoric water line, with more indications of enrichment.

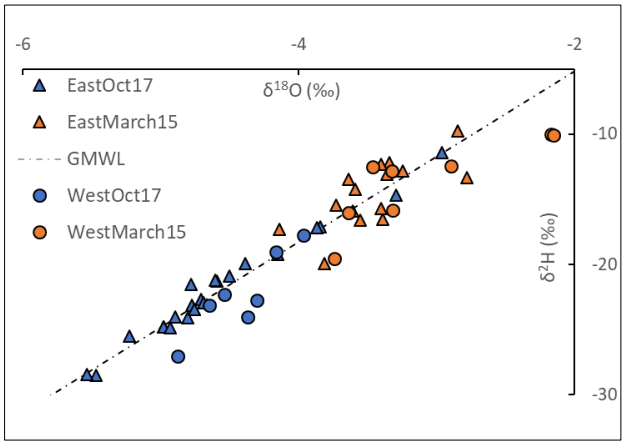

Figure 10: Stable isotope content in water samples from Matlabas. There were 22 water samples taken in March 2015 and 29 water samples taken in October 2017. These samples are labelled according to the side of the mire from which they were sampled: west samples and east samples.

Carbon isotopes

Table 2 shows that four water samples (A2b, B6b, D4b and W5b) had uncorrected ^{14}C values above 100%, indicating infiltration after 1950 and short residence times. Their $\delta^{13}C$ values differed 0 to -15‰. Two samples (B4b and D5b) had $\delta^{13}C$ values around -13‰ and ^{14}C values between 95% and 100%, which indicate infiltration before 1950 and longer residence times.

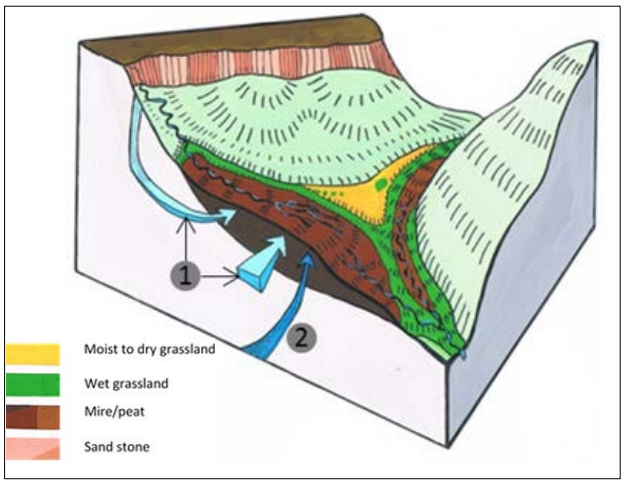

Figure 11: An illustration of the major water flows. 1) Near surface flows: 1a) lateral sheet and phreatic groundwater flow from the hillslopes and 1b) sheet flow above the peat surface during the wet season and 2) deep groundwater flow with a continuous discharge, especially dominant in the dry season.

Table 2: Radiocarbon dating content in six groundwater samples from Matlabas. The samples were taken in October 2017.

No.	Code	Lab no. (GrM)	^{14}C uncorrected (%)	Error ±	$\delta^{13}C$ (‰; IRMS)	Error ±
1	A2b	11547	104.26	0.19	-14.27	0.15
2	B4b	11548	96.42	0.18	-13.38	0.15
3	B6b	11549	104.91	0.19	-10.10	0.15
4	D4b	11550	106.3	0.19	0.43	0.15
5	D5b	11552	95.31	0.18	-13.06	0.15
6	w5b	11554	105.25	0.18	-6.31	0.15

IRMS, isotope ratio mass spectrometry

Discussion

Mire development

Based on radiocarbon dating, peat accumulation began at the lowest parts of the valley on the central eastern side during the transition from the Late Pleistocene to the Holocene. This onset was observed in the thickest peat core obtained at Matlabas, a 5-m peat layer underlain by sand and clay, which was sampled from point B4. Peat accumulation started directly over the mineral soil by paludification processes.[33] The observed sand/clay layers indicate high energy flows during the Early to Mid-Holocene, coupled with an apparently slow peat accumulation rate in the first metre of peat. This accumulation rate indicates initially unstable conditions for accumulating peat.

By the Mid-Holocene, lateral expansion of peat formation had occurred in the higher parts of the valley bottom in the south and west, possibly as a result of a mixture of both autogenic and allogenic factors.[34] Autogenic factors include the clogging effects of peat accumulation on the slope of transect B, with a low hydraulic conductivity leading to a higher water table upslope at transect A in the south and point W1 in the west. With respect to allogenic factors, expansion to the north occurred because of the shift to a wetter climate during the Late Holocene.[34]

In the current vegetation, the wettest vegetation type, which possibly contributes to peat formation, is dominated by the large tussock species *Miscanthus junceus* and also includes stands of *Phragmites australis* at B3 to B4, although *Kyllinga melanosperma* and *Thelypteris confluens* are also abundant. However, the plant remnants in the peat cores were dominated by $\delta^{13}C$ values of C4 plants, which indicates lower water availability.[22,23,35] However, the recent vegetation shows shifts to C3 plants in the best developed and wettest parts of the mire (B4). This modern shift in $\delta^{13}C$ values highlights the role that stable discharge of groundwater flow coupled with the maturity of the peat development plays in sustaining wetter conditions in the mature parts of the mire.

Natural dynamics: water origin and flow

Piezometric head data indicate that groundwater discharge is limited to the central eastern parts of the mire, e.g. at B2 to B4 and C2 to C4. Three major water flows were shown to control mire development (Figure 11).

The first water flow is sheet flow over the peat surface that occurs in the wet season when precipitation exceeds peat infiltration capacity and the peat is often already saturated. The second is the phreatic groundwater flow in the peat layer, which is often also supplied by the intermittent channel in the south that flows in the mire during the wet season with relatively high energy flows, i.e. sand deposits in the soil profiles at transects A and B. The third is the seepage discharge of deeper groundwater at certain points in the mire, e.g. B4 and C4, which is stable and shows little change over the seasons.

The ion composition indicates that the groundwater in Matlabas is generally poor in dissolved minerals, similar to the precipitation water in the Limpopo region.[36] Infiltrating water that passes through the colluvium layer at the valley slopes hardly dissolves any minerals. Hence, the water flows have low concentrations of calcium and mostly depleted stable

isotopes, especially during the wet season when the occurrence of rainwater lenses in the top peat layers increases.[37] After a dry period, higher mineral concentrations are evident as a result of concentration by evapotranspiration, particularly in the top layers.

The effects of evaporation could also be observed in the stable isotope values. The variations at the end of the wet period were minor, indicating the stable upward flow of groundwater that is not affected by evaporation. This was, however, not the case for the water flows in the western side of the mire, which has lower hydraulic conductivity in its peat layer. Hence, signs of evaporation were observed in the samples taken from its middle parts during both the hot-wet periods and the cold-dry periods, where the hillslope water enters from the sides, showing a slower flow subject to evaporation processes,[38] and follows the relief to the east side of the mire.

The observed discharges of deep groundwater flow generally had short residence times; however, they had longer flow lines and deeper origins than the phreatic ones. This deeper flow origin is indicated by the radiocarbon values of the water samples. Hence, the sources of these deep discharging groundwater flows are most likely the adjacent hillslopes, which consist of unsorted rock boulders and coarse fragments that form highly permeable layers acting as recharge areas for subsurface water flow to the mire. The groundwater discharges are diluted in the wet period by input from the phreatic and sheet flows, resulting in low calcium and chloride concentrations. However, their chemical characteristics are more nuanced in the dry period with their calcium and bicarbonate-rich groundwater moving vertically upwards, especially at point B4. This deeper groundwater differs distinctly from the shallow groundwater, and their dynamic interactions are most likely to control the vegetation zones, e.g. the *Phragmites australis* reed zone.[39]

Mire features

Geological structures and vegetation also play an important factor in regulating and maintaining the sheet flow during the wet season. The geological fault lines appear to be linked with an upward flow of groundwater, in that the alignment of the peat domes in the northwest-southeast direction resemble the position of a fault line indicated on the 1:250.000 Geological Map.[17] There is also another alignment of peat domes in an east-west direction, which could point to the presence of another fault line.

The large tussocks of the grass *Miscanthus junceus* and the thick rhizomes of the sedge and fern species appear to prevent soil erosion during storm flood events caused by the intermittent stream from the south. The large tussocks are elevated above the water surface, in some instances by as much as 50 cm. They probably reduce the flow velocity and prevent further erosion during storm flood events, with the tussocks and rhizomes dispersing surface water flow so that it does not directly flow into adjacent erosion channels. The vegetation, therefore, is exhibiting a self-organisation mechanism, providing a local positive feedback to stabilise soil against erosion processes.[40]

Anthropogenic disturbance

There are signs of desiccation and release of nutrients, e.g. nitrate concentrations in the dry season, especially in nearby peat dome areas. The desiccation seems to be related to the head cuts in the peat, e.g. at C5. The head cuts not only drain the peat but also expose soil layers to oxidation and infiltration of precipitation water, thus stimulating the presence of acid components in the soil.[41,42] The water pressure data indicate that some desiccated peat domes within the mire, one of which is burnt, have become infiltration areas that lose groundwater to the stream. Also, calcium concentrations in the groundwater below some of the drained peat domes increase significantly during dry periods. The grass *Andropogon eucomis* is a 'moisture-loving' grass. *Aristida canescens* is a hardy grass that grows in poor shallow soil, normally in degraded areas. The presence of this species on the domes can most probably be attributed to the fact that there is a variation in soil moisture on the elevated peat domes which is not suitable for all moisture-loving plant species, hence this grass has established on these elevated areas. We have noted this grass in similar areas in South Africa. It needs to be noted that there are a number of other moisture-loving species that are described in more detail in Bootsma[17]. We connected the peat domes to the fault lines, indicating that these domes have been formed by the deep groundwater exfiltration. The formation of the head-cut channels has led to draining of the mire from its water flows, not limited to the deep groundwater flow, leading to less moisture in the high areas, e.g. the domes and the elevated western side.

The desiccation can be attributed to the change in the land-use practices that have intercepted the sheet flow and the phreatic water supply during the wet seasons. The land-use role in intercepting the natural water flows is also evident from the data available from the unaffected parts of the mire, which reflect stable conditions of groundwater discharge and wetness. The constructed road is a major factor in intercepting the sheet flow at the valley flanks, which is also evident in the disappearance of the seepage wetlands in the south that have now been replaced with non-wetland plant species. The interception of the natural water flow entering the mire has taken place as the road has decreased the space of the flat area separating the hills from the mire, in addition to increased surface run-off via culverts. Another factor responsible for the head cuts is past grazing practices and the current increase in the local elephant population. The vegetation was often burnt in winter to encourage grazing, thereby leading to poor vegetation growth and higher run-off because of reduced vegetation interception of storm flows. Currently, these two factors may be coupled with the appearance of elephant walking paths towards the wet peat areas, where they make bathing pools, which is because of the increasing numbers of elephants since the area became a national park. These paths may lead to accelerated flow, resulting in the initiation of more head cuts. However, these processes require further investigation.

Conclusion

The Matlabas mire started accumulating peat during the Early Holocene; however, the accumulation rate remained very low (0.011 mm/year) until the Mid-Holocene. The maturity of peatland development drives a positive feedback on sustaining wetter conditions for higher accumulation rates. Water availability for plants seems to have shifted to more positive conditions for wetland species in the present, especially in the oldest part of the mire at transect B. Three major water flows were found to support functioning of the mire, namely phreatic groundwater combined with intermittent sheet flow and discharges of locally permanent deep groundwater. The first type of flow had higher water quality during the wet season, when ion composition was diluted by the sheet flow originating from the intermittent channel in the southeast of the mire. During the dry season, this phreatic flow increased in ion concentrations as a result of evaporation processes. The deep groundwater flow was dominant during the dry period, and areas with this type of discharge had more or less stable ion composition throughout the year, e.g. at B4. Land-use practices have had an effect on the less mature parts of the mire by intercepting water from the intermittent channel in the south through the constructed road and formation of head cuts in areas of the mire with grazing and walking paths for cattle and elephants.

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Authors' contributions

A.B.: Research design; fieldwork; writing. S.E.: Research design; fieldwork; laboratory analysis; writing. A.G.: Research design; fieldwork; student supervision; writing. P-L.G.: Research design; fieldwork; student supervision; writing. S.K.: Research design; fieldwork; writing. M.B.: Laboratory analysis; writing. L.B.: Research design; fieldwork; student supervision; writing. P.S.: Research design; fieldwork; student supervision; writing.

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The ecosystem of e-learning model for higher education

We present the ecosystem of e-learning (EeL) model, which can be applied to any higher education context, and which takes full account of all inhabitants and their interrelationships, not only the components, of the e-learning food chain. Specifically, this model was applied to our context within the University of the Western Cape, highlighting the role of the academic developer within the model. A key argument advanced in this paper is that academic developers should work to reduce complexities associated with emerging e-tools. The EeL model is used to emphasise the role of academic developers as mediators between components and relationships.

Significance:

- By the application of the EeL model, it is demonstrated that the use of e-tools and their alignment with pedagogies within any context must be sensitive to the entire ecosystem, with the recognition that this is simultaneously a top-down and a bottom-up process.
- The student must be the core focus in the adoption of emerging technologies and the learning process, but simultaneously the student can only be in focus when they are placed within their broader ecosystem – including the societal level.
- Our findings add to the debate on physics education specifically, and more broadly by providing new ways of conceptualising an e-learning ecosystem.
- It is advocated that an academic developer-mediator should step in to mediate between academics, tutors and emerging e-tools, through a structured developmental process for learning and teaching.
- The EeL model can afford an insight into the processes involved when incorporating a learning management system (and emerging e-tools) into learning and teaching in higher education institutions.

Introduction

> *Science is more than a body of knowledge; it is a way of thinking.*[1]

Globally, science has been lauded as the 'engine of prosperity' – a reflection of its importance in promoting economic growth.[2] In Africa too, the importance of a scientifically and technologically literate and innovative population has been recognised as a precondition for achieving the aspiration of a 'prosperous Africa based on inclusive growth and sustainable development', as envisioned in the African Union's Agenda 2063 Strategic Framework.[3] South Africa's National Development Plan 2030 also recognises the crucial importance of science and technology for social development, economic growth and international competitiveness, and stresses that '[q]uality higher education needs excellence in science and technology, just as quality science and technology needs excellent higher education'[4]. It is therefore disheartening that the World Economic Forum's 2016 Global Information Technology Report ranked the quality of South Africa's science and math education as the lowest out of the 139 countries surveyed.[5] The South African education system in its entirety was ranked the third lowest. This represents a critical challenge to the country's desire to overcome the legacy of apartheid and the continued inequality that pervades society.

The University of the Western Cape (UWC) was historically a disadvantaged institution under apartheid, yet it was able to achieve a 'distinctive track record as an institution which enables people from sometimes severely disadvantaged backgrounds to succeed at university and aspire to excellence'[6]. While the science and math fields are critical growth areas for the university, there is a 'shrinking pool of learners [who are] doing Science and Mathematics at school', while the quality of that education is questionable, as the World Economic Forum report suggests. One of the strategies employed by UWC is to leverage learning technologies to help meet the challenge of providing quality education to ever-increasing numbers of students, while bridging gaps in their knowledge, particularly in relation to technology. As Merkoffer and Murphy[7] note:

> [d]*eveloping countries such as South Africa face a greater challenge owing to the larger deficit of available infrastructure to build e-skills at an educational and community level,*

while it is also

> *characterised by economic disparities resulting in a wealthy and educated minority having more access to information technologies and the disadvantaged majority increasingly being left on the other side of a growing 'digital divide'.*

While this remains true today, UWC is attempting to bridge this divide through various initiatives.

Educational technologies for learning and teaching practices

The widespread adoption of learning technologies within higher education institutions (HEIs) globally has made it evident that e-learning serves a critical need, especially in developing-world contexts in which HEIs have limited resources. e-Learning in an academic context is defined here as the use of time- and space-independent application(s) designed to deliver multimedia content, such as assessments, discussions and communications to both academics and students. e-Learning can be supported by learning management systems (LMSs), other stand-alone software

applications, or both in combination. Also, numerous HEIs are adopting new online learning environments to replace the traditional pen and paper methods of subject instruction.[8] For this study, we define a LMS as a web-based application that is used for educational purposes to disseminate multimedia resources, organise resources in a chronological manner, communicate with course participants (students, teaching assistants, tutors and others), and assess students' competencies, amongst other capabilities. This assessment, for example, includes higher-order question types such as the Calculated Questions, Numeric Response, Questions Pools, and Lessons[9]. Moreover, we argue that all LMSs share the same four core functionality categories: communication, assessment, management and content.

A large variety of LMSs exists today and can be divided into either commercial software (like Blackboard and Edmodo) or open-source software (including Moodle, Canvas, Claroline and Sakai). The most preferred of these are Moodle and Sakai. According to Cigdemoglu et al.[10], 'Moodle ... is preferred by a significant number of educational institutions' which is probably because of its ability to let the user '…create powerful, flexible and engaging online experiences', according to Rice[11]. On the other hand, Caminero et al.[12] showed that out of three open-source LMSs used in their study, 'Sakai is considered the best tool because it obtains high ratings in both evaluations'. This conclusion was based on the 'large community of users...[and it is] easy to install and use, and it is kept up-to-date'. To date, some studies have been done on the use and adoption of these various LMSs within HEIs, but the use and value of an LMS within the science field, specifically physics, remains under-researched. This is especially true for the Sakai LMS (https://sakaiproject.org), which is utilised by UWC, and branded as iKamva.

Emerging learning technologies within the learning and teaching environments of physics are generally underutilised in South Africa. The need for, and use of, these e-tools is of utmost importance as national HEIs are working towards a common goal within the context of a global education transformation. The Department of Physics and Astronomy at UWC is currently making use of iKamva's various functionalities for both theory and laboratory sessions. Despite the 21st century being well underway, it is still vital to introduce both academics and students to emerging technologies to enhance their current learning and teaching practices, especially within complex developing-world contexts.

By further leveraging iKamva, learning and teaching practices within our department can be better aligned with the *Institutional Operating Plan* [IOP] *(2016–2020) White Paper* of UWC. The IOP states explicitly that '[s]trengthening the informed use of technologies in learning and teaching is a central feature of the plan', and further states that the 'use of technologies must be underpinned by pedagogical rationales which draw on their potential to transform learning and teaching, especially by facilitating the active participation of students'[6]. Furthermore, the research will also focus on aligning e-tools use within physics to the university's Charter of Graduate Attributes, thus supporting the IOP's goal of promoting learning and teaching 'as a research-led process', while further positioning e-learning as a vital role player in promoting the Graduate Attributes.[6]

Purpose

Accordingly, this conceptual study presents our ecosystem of e-learning (EeL) model, which we use as a framework for implementing emerging educational technologies within our context in the Department of Physics and Astronomy, highlighting the role of an academic developer within the model. At the same time, it helps us contextualise the incorporation of educational technologies in a way that takes full account of all inhabitants of the e-learning 'food chain' (and their interrelationships, not only the components). In this way, we argue that globalised higher education initiatives and technologies must still be viewed and applied through the prism of more local awareness. The reason we have selected an image of an ecosystem is to emphasise the notion of a living, evolving and dynamic system. Our aim is for readers to contemplate how their initiatives with educational technology fit into their specific context and if, and how, this serves the broader needs of society. Another aim is to promote the further adoption of blended learning within science.

The methodology employed in this study is a variant of qualitative action research in that it is 'a disciplined process of inquiry conducted *by* and *for* those taking the action'. Like Sagor[13], we employ the 'primary reason for engaging in action research…to assist the "actor" [such as academic developers] in improving and/or refining his or her actions'.

The e-learning ecosystem

While our concept of an e-learning ecosystem draws on similar concepts from the e-learning literature, it puts these together in new ways and expands them in new directions. As stated, a biological metaphor was explicitly chosen to emphasise themes of adaptability and evolution – necessary key features in the field of emerging learning technologies, especially in developing-world contexts where innovative approaches are required to meet complex sets of demands and challenges. Indeed, as Cavus and Alhih[14] note, the 'educational process is evolving continually, such as a living organism'. The e-learning ecosystem we envision consists of a variety of components. These are the biome, the habitat, the ecotone and ecoline. The broader ecosystem will first be deliberated before we unpack these various components. While our concept of an e-learning ecosystem has commonalities with concepts employed by other scholars, there are also notable differences. Both will be highlighted throughout the discussion.

It is useful to begin with a definition of an ecosystem, for which two interrelated aspects are observable. First, at its most basic, an ecosystem is 'a community of organisms together with their physical environment'[15]. This definition emphasises the components of the ecosystem – the organisms that form the community, and their environment. Second, an ecosystem is also characterised as 'a system of ecological relationships' in which stability within the system is upheld because 'the relationships between the different organisms is such that each member mutually supports the continued existence of the other members and of the system itself'[16]. This definition thus privileges the relationships between the components. In our conception of an ecosystem, we focus on both these aspects – the components and the relationships.

This work is similar to that of Chang and Guetl[17], who expanded on earlier vague conceptions of learning ecosystems by focusing on the 'biotic and abiotic components [of an ecosystem] and all their interrelationships in specified physical boundaries'. This approach enabled them[17] to then arrive at a definition of learning ecosystems as 'consist[ing] of the stakeholders incorporating the whole chain of the learning process and the learning utilities, the learning environment, within specific boundaries'. These authors then applied the learning ecosystem model more narrowly to e-learning, specifically in relation to training initiatives within small and medium enterprises, by focusing on (1) the learning communities – in their view the learners, along with other stakeholders such as lecturers, tutors, content providers, pedagogical experts and information technology (IT) support and management; (2) the learning utilities and technology – such as an LMS; and (3) ecosystem conditions – such as 'cultural and sociological influences' and the demands of industry or government policy.[17] More recently, Eswari[18] defined an e-learning ecosystem as consisting of 'stakeholders, e-Learning portals, ICT infrastructure and processes', while Lohmosavi et al.[19], defined it as 'all the components needed to implement an e-learning solution', including 'providers, consultants and infrastructures'. However, these definitions privilege the components rather than the relationships within an ecosystem.

While there are thus similarities between these concepts of ecosystems and our use of the term, we specifically apply it to our tertiary education environment, in our South African context. This is why our model includes all elements from the LMS, through the HEI, to the broader society in which they are embedded. It then reflects the definitions of ecosystems given above, by including the components, the environment (virtual, physical, institutional and national), and their interrelationships. Our EeL model is presented in Figure 1. While we employ a broad metaphor of an e-learning food chain (to emphasise the interrelationships), and its attendant trophic levels, we strongly emphasise that none of these levels is more important than the others. Instead, the relationships between the components of the ecosystem take the form of constant dialogue. In this way, the broader societal imperatives (for example producing more

qualified graduates in the science field) feed into the goals and plans of HEIs, and these set the context for academic developers and lecturers, ultimately filtering through to the students. These goals and needs must then be supported by any learning technologies employed within HEIs. At the same time, academic developers and lecturers must align the tools and their appropriate pedagogies with the needs of their students, in supporting the institutional goals and societal imperatives. This process is thus a continuous, fluid process that is simultaneously top-down and bottom-up, meaning that no part of the ecosystem can be privileged above another. However, we have arranged our model into a pyramid to reflect the attention and focus we place on the various components in this study. Hence, the primary component of our e-learning ecosystem that is under investigation here is the LMS.

Further focus is then placed, in diminishing order, on the academic developer and the lecturers, and how their use of the LMS lines up with the needs of students. Finally, as mentioned in the Introduction, no discussion of these can be fruitful without recognising the national and institutional context within which we operate. Importantly, however, the EeL model can be applied to, and customised for, any specific context or study (or trophic level).

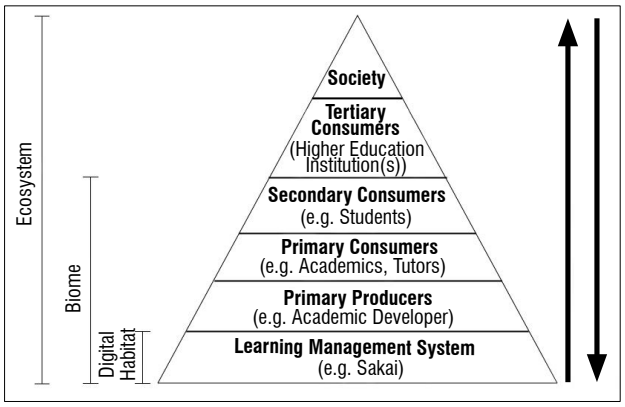

Figure 1: Ecosystem of e-learning model.

The physics biome and digital habitat

As mentioned in the Introduction, the specific learning community we focus on in our study is the Department of Physics and Astronomy at UWC. In line with the EeL model, this includes the academic developer(s), lecturers, tutors, teaching assistants and students, along with the LMS used within the institution – iKamva/Sakai – as well as the relationships between all role players. In an extension of the biological metaphor, we refer to this as our specific e-learning biome. A biome can be defined as 'a major ecological community type'[20]. In our view, while it is necessary to guard against viewing biomes as silos (by embedding them within the broader, shared ecosystem), it is still equally necessary to break this broader academic ecosystem into specific disciplinary biomes because the e-learning contexts and requirements of disciplines vary. For example, the science field is notorious for what Habibi and Habibi[21] call its 'abstract nature', which can contribute to high attrition rates, especially when combined with inadequate knowledge on the part of the educator, or unengaging or 'obsolete material'. This potentially leads to some 'students [being] forced to lose interest, motivation and passion; [and ultimately] in some cases frustration sets in and students abandon the discipline or subject matter'. This is a legitimate concern when paired with the challenges of South Africa's school system, which often leaves new students underprepared for grappling with complex and abstract concepts at the tertiary education level. Therefore, one of the challenges facing physics educators is to impart more than content knowledge, and to 'bring about scientific thinking in students' – as Carl Sagan's quote highlighted at the beginning of this paper – and this constitutes a transformed 'mindset… [that] requires students to test out, through experimentation'[21].

Achieving this transformed mindset is why we combine our specific LMS with our learning community (and its members) to form the biome, which is reflected in the specialised interrelationships within physics specifically, and how the LMS and its tools must be aligned with the needs of the department. The learning demands and challenges of each learning community will thus necessarily differ, and this must be taken into account when selecting specific tools and educational technologies, meaning that an LMS cannot be viewed in separation from the community it must serve. Martín-Blas and Serrano-Fernández[22] reinforce this notion by reflecting on the value of LMSs for physics education specifically, by highlighting the ability of LMSs to allow the use of

> *objects of many kinds such as: videos, mp3s, text documents, scanned images, links to other websites or animations which can be used to show dynamically many physical situations and concepts that are often difficult to apprehend by the students.*

This multi-modal approach is what Salihi[23] refers to as contextualisation, where 'learning takes place in real-life situations or in situations simulating real-life instances', assuming that 'the learning environment setting allows for authentic and real-life learning experiences'.

Having discussed the broader e-learning ecosystem, and our departmental biome, we now turn to the specific (digital) habitat of this biome. Our concept of habitat is in line with the work of Wenger et al.[24] While a learning community's habitat can be both physical and digital/virtual, these authors note that 'community habitats [increasingly] include technology-based connections and places in addition to physical ones', and these digital habitats can be thought of as 'the portion of a community's habitat that is enabled by a configuration of technologies'[24]. Importantly, a digital habitat thus not only consists of technological aspects, but more broadly 'reflects the practices that members have developed to take advantage of the technology available and thus experience this technology as a "place" for a community', meaning that a 'digital habitat is first and foremost an experience of place enabled by technology'[24]. Four perspectives have been proposed regarding these digital habitats, focusing on the (1) tools, (2) platforms, (3) features making the tools usable and (4) full configuration of technologies.[24] Our perspective on the digital habitat used in our departmental biome is in line with the latter, the configuration perspective, which considers the 'full technology substrate' of the habitat.[24] The fourth perspective applies to our departmental biome because, while the department and the broader institution mainly rely on the iKamva LMS, personal learning environments and other standalone software applications are also frequently used. Wenger et al.[24] elaborate on the configuration perspective as including:

> *the overall set of technologies that serve as a substrate for a community's habitat at a given point in time – whether tools belong to a single platform, to multiple platforms, or are free-standing. For communities with complex sets of activities, the full configuration often involves multiple platforms, or selected tools from different platforms combined with a main platform. Even communities that appear to only use one platform usually depend on other tools (including backchannel emails, phone calls, public web spaces, and other means of collaboration) that are not part of the 'main platform'.*

This is indeed the case for UWC. It should also be pointed out that while personal learning environments may at first glance appear, because of their individually focused nature, to be removed from the concept of 'place' for a community, they still require the same guidance and pedagogical alignment as tools within the LMS in order to meet the specified learning outcomes and objectives. It also cannot be assumed that users will automatically know how to navigate Wikis, Google Docs, blogs or other personal learning environments. Hence the need for the learning community's relationships to come to the fore, for example, through training initiatives. In line with the EeL model, we explore our digital habitat in relation to its use by members of this biome (and thus not in isolation as a mere list of affordances or features). The following

section will delve deeper into this digital habitat, specifically in relation to science education.

This focus on relationships within the biome brings to the fore the role of an academic developer as a mediator between the digital habitat and the rest of the biome. For this reason, Figure 1 depicts the academic developer as primary producer within the e-learning 'food chain' (or e-chain). Mediation, in this sense, refers to acting as a knowledgeable but impartial go-between linking the digital habitat and the rest of the biome, by helping to align the tools to both primary consumers (i.e. academics, lecturers, tutors, teaching assistants) and secondary consumers (i.e. students). This mediation requires taking into account all academic needs for learning and teaching, as well as being aware of emerging learning technologies and their affordances for physics. In turn, ultimately, this mediation can promote awareness within the broader ecosystem, specifically the rest of the institution – the tertiary consumers (i.e. other faculties and departments) – and eventually the rest of society – the apex. Thus, ideally, the academic developer-mediator ultimately serves to reduce complexity within the ecosystem and to reduce the opacity of lesser-known emerging technologies that can be of service to the primary consumers, secondary consumers, tertiary consumers and broader society.

An important caveat is that not all primary consumers within our biome are making use of the digital habitat. Most primary consumers are not using any part of the digital habitat. One of the ultimate aims of this study is thus to promote the further adoption of blended learning within the department. A critical element to this aim is that this promotion takes place from within the department itself, because both the primary producers and primary consumers within our model understand the particular needs and requirements of physics education intimately, and thus what features of the digital habitat can speak most directly to these. The role of champions among the primary producers and primary consumers must not be overlooked. Those individuals who are currently making use of the 'full technology substrate' of the digital habitat are best placed, through their experience, to model the benefits and advantages of emerging learning technologies to their colleagues. As the United Kingdom's National Health Service[25] notes:

> *e-Learning Champions work at the front line. They understand the practical issues that colleagues face but have the wherewithal to bridge the gap between desire and execution of e-Learning. They can act as intermediaries, lobbying for resources and training time with managers and encouraging colleagues to make best use of both. To do this, their role must be respected, recognised and rewarded.*

This front line can be described by another biological metaphor – the ecotone and the ecoline. An ecotone is defined as 'an area of relatively rapid change, producing a narrow ecological zone between two different and relatively homogeneous community types', and these transition areas are 'highly dynamic and usually unstable, resulting in an environmentally stochastic stress zone', resulting in 'fluctuations [that] are strong and … a time-series of strongly different, but individually relatively homogeneous, environments'[26]. Put another way, ecotones are sharp boundaries between different communities or organisms that produce tensions and uneven pockets of communities along the boundary zone. Ecolines, in contrast, are boundaries of 'more gradual, progressive change … between two systems', being a

> *response to the gradual difference in at least one major environmental factor, whilst a further factor (acting at a different scale) influences the total differences within the gradient, yet maintains all the transitional states.*[26]

These are useful analogies in the field of e-learning, including for our context, because there are boundaries present within the same biome (the department, but also for the institution as a whole) between those who are making use of emerging learning technologies and those who are not. Without champions, this boundary is more akin to an ecotone, with abrupt changes and tensions and with relatively homogeneous 'pockets' of adopters and non-adopters. While progress may be made in terms of more academics exploring and provisionally adopting emerging learning technologies in their teaching, because this zone is unstable (if there is no proper support or guidance), this change may not last. In contrast, where there is strong support from within the institution and biome, and with champions paving the way and sharing their successes with their colleagues, the boundary between adopters and non-adopters may be more like an ecoline. An ecoline thus entails more and more individuals trying out emerging learning technologies, initially on a very small scale (for instance one or two tools), but gradually gaining more experience and confidence to adopt more. Our biome is characterised by such an ecoline, and by sharing some of the work being done by champions within the department, we hope to align the biome with the digital habitat further, which is depicted in Figure 2.

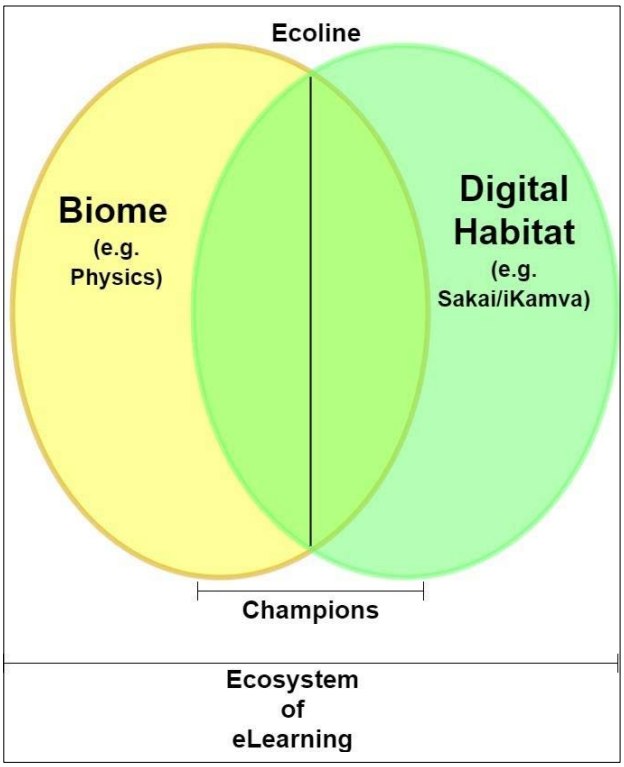

Figure 2: Representation of an ecoline within a physics education context.

The physics digital habitat

In this section, the physics digital habitat will be explored in greater depth. As mentioned, in line with the configuration perspective, this digital habitat includes more than the LMS platform. However, we will focus specifically on e-tools within the Sakai LMS that are underutilised. In the e-learning literature there is a dearth of research on the Sakai LMS platform, especially in terms of its use in the science field, and even more so in the physics education context. However, some studies have been produced concerning the utilisation of Sakai in other academic fields. One example is the work by Wannous and Nakano[27], which explored the integration of a 'stand-alone web-based laboratory (NVLab)', which they developed, into Sakai in support of computer networks online courses.

However, in the science field, and specifically in physics, studies have been done on the use of other LMSs for learning and teaching. Martín-Blas and Serrano-Fernández[22] showcased the main features of their (online) physics course, implemented in Moodle. One of the observations they make is that LMSs are valuable tools for assisting with the teaching of physics courses specifically, and science courses more generally, because, as mentioned above, successfully promoting scientific thinking depends on students 'develop[ing] the ability to solve problems that represent different (more or less complex) physical situations', while those same students may struggle 'to apply the laws and equations they have seen in the classroom'[22]. More recently,

Murakami et al.[28] proposed an LMS for physics education by 'using the internet in combination with a wide-ranging selection of learning objects with remote access experiment integrated into Moodle's … learning management system'. According to Cavus and Alhih[14], LMSs 'are considered to be largely applicable for natural sciences as they enable representation of phenomena, foster experimental study and enable the creation of models and problem solving applications', but still there is a lack of LMS within science modules, especially physics. This use of an LMS for physics education employs a further set of skills including higher-order thinking and learning, constructivist pedagogy and digital competency in the use of emerging technologies.

Conclusion

One of the goals of the primary producer (academic developer) is to incorporate e-tools within all of the physics courses within the department. This incorporation necessarily progresses at a gradual rate, as it involves a 'structured developmental process' (as Salmon[29] advocates), including phases of introducing the primary consumers to the e-tools, aligning the e-tools to their learning and teaching methodology (as well as learning theories), designing and developing with related ePedagogy and finally implementation and evaluation. Part of this process involves grappling with what Matthews[30] identifies as a 'source of inertia [among academics, namely] the need to hang on to their "personal identity affirmation"', to avoid appearing less knowledgeable in front of students. This grappling is directly related to mediating between the digital habitat and the rest of the biome, in the sense of translating pedagogy into ePedagogy, which can be defined as a 'specifically designed set of principles and practices that focus on how to deliver…content to those using technology in their learning'[31]. We summarise and illustrate these concepts of overcoming inertia within academia and mediating between the digital habitat and the biome. In doing this, we draw on the TPACK model[32] and Gartner Hype Cycle[33]. By creatively combining the three facets of knowledge, namely subject matter, e-pedagogy and technological, our TEeL model adaptation can assist in avoiding the peak of inflated expectations and trough of disillusionment.

Thus, the goal of the primary producer is to empower the primary consumers, so that they, in turn, can empower other academics not currently making use of e-tools. This empowerment is part of the effort to ensure the gradual transition linked to the ecoline concept. The EeL model outlined earlier can afford an insight into the processes involved when incorporating a LMS (and emerging e-tools) into learning and teaching in HEIs. Ultimately, this process represents advocacy of reducing the complexity for academics within HEIs, in line with our philosophy of the primary producer as academic developer-mediator. Indeed, it is often lamented how complex, emerging technologies pose a challenge to many academics, without steps being taken to showcase these technologies and their tools in a manner that is tailored for a particular digital habitat (like Sakai), biome or ecosystem. This study is thus an exercise in creating and spreading awareness ('phases of introduction' as mentioned above).

However, while a LMS possesses many positive benefits to all 'organisms' within a biome, there are also challenges. One is the lack of pedagogical progress in physics education, which is linked to the fact that not all primary consumers within our biome make use of an LMS, and thus they only contribute to traditional pedagogical achievement, but not ePedagogy. Here the academic developer-mediator steps in to mediate between primary consumers and the emerging e-tools, through a structured developmental process – for instance helping academics to align themselves with the IOP White Paper[6], which recognises the benefits of being a 'smart' university.

Today's tech-savvy students and staff prefer an interactive and engaging experience and expect flexible and secure IT tools, systems and spaces to be available to them inside and outside the classroom. Universities face a large and growing challenge to use technology creatively to meet learning, research, administrative and support goals across a broad front. UWC has embraced the challenge.

We have used the concept of the e-learning ecosystem, and the EeL model to situate our work within its broader context, and to emphasise both the components and the relationships within this ecosystem. We thus aim to contribute to both the debate on physics education specifically and more broadly to provide new ways of conceptualising an e-learning ecosystem.

By advocating the EeL model, we also argue that at all times the student must be the core focus in the adoption of emerging technologies and the learning process, but, simultaneously, the student can be the focus only when they are placed within their broader ecosystem – including the societal level. Thus, the EeL model is a promising lens to help focus future research, especially concerning the concept of the academic developer-mediator.

One of the main arguments elucidated by the application of the EeL model is that the use of e-tools and their alignment with pedagogies within any context must be sensitive to the entire ecosystem, with the recognition that this process is simultaneously top-down and bottom-up. We argue that by planting seeds within a biome through the work of the academic developer-mediator, the whole e-learning ecosystem can become empowered, leading to overall advancement in learning and teaching for all involved. As the UWC IOP White Paper notes: 'UWC is committed to a major programme of technology-enabled management and learning

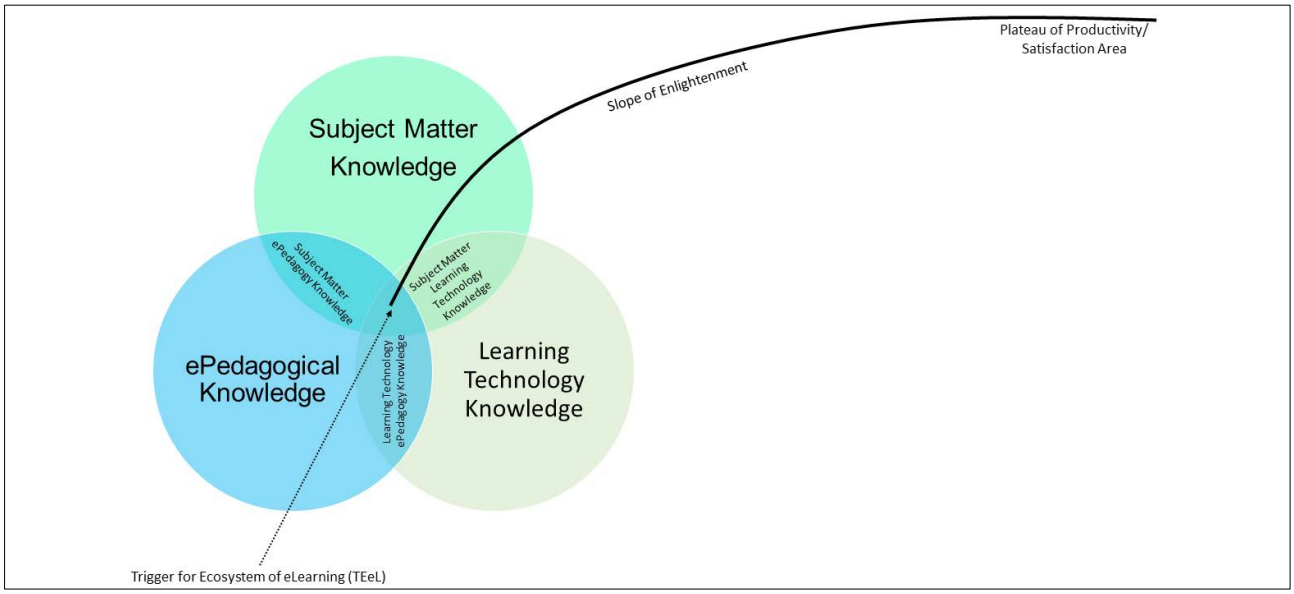

Figure 3: Trigger for ecosystem of e-learning model.

and we will systematically improve infrastructure and systems and our capacity to use them to maximal advantage'[6]. By employing the EeL model, this paper represents a contribution towards unlocking the full potential of this technology-enabled learning and teaching with our context. In this way, echoing Sagan, we emphasise the importance of the *education* of science as a way of thinking, not just a body of knowledge.

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Authors' contributions

V.v.d.H.: Conceptualisation; methodology; data collection; data analysis; writing; student supervision; project leadership; project management. A.S.: Conceptualisation; methodology; data analysis; writing; project management.

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Metatarsophalangeal proportions of *Homo naledi*

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Post-cranial differences between extant apes and humans include differences in the length, shape and size of bone elements relative to each other; i.e. differences in proportions. Foot proportions are influenced by the different functional requirements of climbing and bipedal locomotion. Phalangeal length is generally correlated with locomotor behaviour in primates and there is variation in hominins in relative phalangeal lengths – the functional and evolutionary significance of which is unclear and currently debated. *Homo naledi* has a largely modern rearfoot (i.e. tarsal skeleton) and midfoot (i.e. metatarsal skeleton). The proximal pedal phalanges of *H. naledi* are curved, but the relative lengths are unknown, because the phalanges cannot reliably be associated with metatarsals, or in many cases even with ray number. Here, we assess the lengths of the proximal pedal phalanges relative to the metatarsals in *H. naledi* with resampling from modern human and chimpanzee (*Pan troglodytes*) samples. We use a novel resampling method that employs two boundary conditions, assuming at one extreme that elements in the sample are associated, and at the other extreme that no elements are associated. The associated metatarsophalangeal proportions from digits 1 and 2 are within the 95% confidence interval of the modern human distribution. However, the associated and unassociated proportions from digits 3–5 fall above the 95% confidence interval of the human distribution, but below and outside of the chimpanzee distribution. While these results may indicate fossil preservation bias or other sample-derived statistical limitations, they potentially raise the intriguing possibility of unique medial versus lateral pedal column functional evolution in *H. naledi*. Additionally, the relevant associated proportions of *H. naledi* are compared to and are different from those of *H. floresiensis*. Both species suggest deep phylogenetic placement so the ancestral condition of the pedal phalanges in the genus *Homo* remains unclear.

Significance:

- Modern humans demonstrate straight and relatively short pedal phalanges, whereas *H. naledi* demonstrates curved phalanges of an unknown relative length. This research analyses the relative length of the proximal phalanges to the metatarsals to determine if *H. naledi* has relatively short phalanges similar to modern humans or is distinct from modern humans in both its phalangeal length and curvature.
- This analysis further develops a statistical resampling method that was previously applied to large fossil assemblages with little association between bones.
- A more comprehensive understanding of pedal morphology of *H. naledi* could provide insight into the ancestral pedal form of the genus *Homo* as the overall morphology of *H. naledi* appears to be deeply rooted in the genus.

Introduction

Evidence of hominin bipedality is obtained from multiple sources: hominin limb proportions from fragmentary post-cranial fossil evidence[1]; basicranial position of foramen magnum[2]; preserved fossil partial foot skeletons[3-6]; and footprints preserved in volcanic ash or lakeshore sediment in eastern Africa at the Laetoli and Ileret sites[7-9]. Modern humans have a robust and long hallucal ray, aligned with the lateral digits, which is morphologically and functionally distinct from those in the living great apes. The lateral digits in humans are markedly short compared to those of living great apes, and the lateral toes are much shorter in humans relative to the lengths of the metatarsals.[10-13] These traits functionally support human bipedal walking and running, including the distinctive 'toe-off' phase of the gait cycle.[14,15] Short toes eliminate some of the mechanical costs of walking[16], while a stiff and elongated midfoot (i.e. metatarsal skeleton) is thought to promote the posterior-anterior transfer of weight through the foot's medial column and from heel-strike to toe-off for a more efficient bipedal gait[11].

In addition to digit length and midfoot stability, the relative lengths of the proximal pedal phalanges are potentially informative for assessing bipedal gait efficiency. We focused on proximal phalanges because they are more readily identifiable and are thus more numerous than intermediate or distal phalanges in fossil and comparative collections. In this study, we assess proximal phalangeal lengths relative to metatarsal lengths, or the metatarsophalangeal proportions, in the fossil sample of *Homo naledi*.

Although pedal traits can be inferred for several species of hominins based on partial feet or isolated foot bones, relatively complete hominin feet in the fossil record are rare. Consequently, the pedal proportions that are characterised by the relations of multiple foot bones, such as the direct proportions of the lengths of the metatarsals and phalanges, are unknown for most hominin species. In the later Pleistocene fossil record, the Neanderthals exhibit proximal phalangeal and metatarsal lengths that are largely indistinguishable from those of modern humans.[17] Like Neandertals and modern humans, *Homo erectus* also demonstrates clear post-cranial adaptations for obligate bipedalism, meaning a commitment to terrestrial bipedalism and loss of all unambiguously climbing adaptations.[18] The metatarsal ratios of *H. erectus* material from Dmanisi are human-like in their proportions to one another; however, the lengths of the pedal phalanges are unknown for this species.[19] Evidence of *H. erectus* foot morphology has been largely obtained from the Ileret footprints in Kenya, which date to 1.5 million years ago (mya), and appear to have been produced by a more modern-appearing foot architecture than the more ancient Laetoli footprints.[8]

The Late Pleistocene *Homo floresiensis* is represented by a partial foot. This foot has curved phalanges that are longer relative to the metatarsals than the range presented by modern humans. Additionally, *H. floresiensis* is thought to have an elongated foot – partially because of its longer phalangeal length.[5]

Prior to the origin of *Homo*, the only hominin specimen that has preserved pedal phalanges in association with metatarsals is ARA-VP-6/500, the partial skeleton of *Ardipithecus ramidus.*[20] Because of damage to the distal ends of the metatarsals of ARA-VP-6/500, researchers normalised the complete phalanges from ray 4 by body size and concluded that the phalangeal lengths were closer to a mean length for *Gorilla.* Long lateral digits in addition to the evidence of an opposable hallux led researchers to conclude that the species likely had an ability to grasp large branches and support itself arboreally.[20] The preserved base of the third metatarsal suggests that *Ar. ramidus* had a more stable midfoot and this bone has a relatively slight curvature compared to third metatarsals of living orangutans and chimpanzees. The proximal phalanges of *Ar. ramidus* exhibit substantial curvature, as does the single proximal pedal phalanx, AME-VP-1/71, from the Amba East locality in the Middle Awash, Ethiopia.[21]

Some aspects of pedal morphology can be assessed in other species of hominins. However, these do not contribute to the discussion of relative proximal phalangeal length, because of the lack of pedal material preserved at many of the well-known early hominin sites. This leaves a substantial gap in our understanding of pedal phalanx proportions in *Australopithecus* and *Homo habilis*, as the OH 8 foot, representing *H. habilis* at Olduvai Gorge, Tanzania, does not retain complete metatarsals or proximal phalanges.[22]

The AL 333 locality at Hadar, Ethiopia, presents a commingled assemblage of bones representing at least 18 individuals of *Australopithecus afarensis.*[23] There is substantial debate about the morphology of *Au*. *afarensis* in terms of its locomotor adaptations; the pedal morphology is no exception.[24] No metatarsal lengths are known from this assemblage; however, it does preserve complete, strongly curved phalanges. Stern and Susman[16] noted that the proximal phalanges of *Au. afarensis* are likely long relative to the metatarsals, because they are longer relative to the diameter of the femoral head than expected for modern humans. Longer toes would require more work during the swing phase of the bipedal gait. With the assumption that a costly trait would not persist without some countervailing functional utility, they suggested that longer and curved toes probably indicate arboreal behaviour in this species.

Phalangeal curvature has taken on a substantial weight in arguments about the function of fossil feet because the curvature is thought to be a reliable indicator not only of adaptation but of use during an individual's lifetime. Phalangeal curvature is considered epigenetically sensitive, such that the repeated use of the fingers and toes in grasping is believed to influence the development of curvature.[25-29] If this is true, then the curvature exhibited by certain species is not merely a retention from arboreal ancestors but an indication of the way the foot was used.[30] Increasing the curvature of the phalanges decreases the amount of stress from the fibres of the flexor sheath, and forceful gripping/strong flexion becomes safer (i.e. mitigates the likelihood of avulsion fractures and other joint failures) at higher curvatures.[31] A similar functional response would occur in the pedal phalanges if gripping with the toes occurred throughout a lifetime.

White and Suwa[32] argued that the relevant functional parameter is not toe length, as was suggested by Stern and Susman[16], but instead overall foot length, that is, the toes contribute little to locomotor costs relative to the overall length of the foot. White and Suwa demonstrated that the relative length of the *Au. afarensis* foot to the femur was within modern human variation, ergo the length of the foot would not negatively affect the bipedal gait. Later, additional fossil remains from Hadar and from the Woranso-Mille study area of Ethiopia were recovered, demonstrating that some individuals of *Au. afarensis* had tall statures well within the range of modern humans.[33] This evidence further emphasises that the relative length of a single pedal phalanx is unlikely to indicate accurately the proportion of phalanges within a fossil species.

In South Africa, at the site of Sterkfontein, STW 573 or 'Little Foot', a specimen representing *Australopithecus africanus*, is missing the distal-most aspects of the foot and does not present pedal phalangeal lengths.[34] However, from other morphological indicators in the rearfoot and midfoot, *Au. afarensis* and *Au. africanus* demonstrate unique morphologies, which are also unique from *H. habilis*, indicating variation in pedal form in early hominins.[28]

As a consequence of variable pedal forms of hominin species in the Pliocene, the ancestral condition of the pedal phalanges in the genus *Homo* is unknown. *H. floresiensis* is a later *Homo* species, yet is primitive in its overall morphology. It is not clear whether *H. floresiensis* is phylogenetically linked to *H. erectus* or if it is more distantly related and rooted deeper in the genus *Homo* like *H. naledi*. *H. floresiensis* exhibits curved and elongated phalanges relative to associated metatarsals, which is unique to that of contemporaneous *H. sapiens.*[35] Because of the phylogenetic ambiguity, it is unclear if the *H. floresiensis* foot represents the primitive condition of the basal *Homo* foot.

The recently described species, *H. naledi*, occupies a phylogenetic position deeply rooted in genus *Homo*, yet the depositional age of the fossil bones and associated sediments within the Rising Star Cave system in South Africa is 236 kya to 335 kya[36], which implies that *H. naledi* was sharing the landscape with more derived Middle Pleistocene hominin species. *H. naledi* is presently represented by over 1700 fossil fragments in the Dinaledi Chamber, of which more than 100 are pedal elements.[37] Note that no fossils relevant to this study have been recovered from the Lesedi Chamber.[38] The Dinaledi Chamber assemblage contains the remains of at least 15 commingled individuals, including 7 adults, which appear to represent a limited time of deposition.[39] Although most of the material discovered in the Dinaledi Chamber was unassociated and commingled, a remarkably complete hand and at least one nearly complete foot were preserved in situ.[27,40] However, while this foot has an associated hallux, it lacks any clear associations of the phalanges for digits 2–5 and the lengths of the phalanges relative to the metatarsals are unknown for *H. naledi*.

The morphology of the *H. naledi* foot is similar to the hand in that it is mosaic, with modern features such as an adducted hallux and an elongated talus, while retaining ancestral features such as a minimally developed medial longitudinal arch and curved pedal phalanges.[27] With clear adaptations to bipedality in the pelvis and lower limb[37,41], and features of the upper limb that appear to reflect an enhanced ability to climb relative to that found in modern humans, Neanderthals or *H. erectus*[27,42], the *H. naledi* hominins engaged in a combination of locomotor grasping[43] and bipedal locomotion. The foot of *H. naledi* provides valuable insight into these activity patterns, in that it primarily presents derived bipedal morphology, yet retains curvature of the phalanges that reflects some degree of climbing behaviour.

The lengths of the phalanges relative to the metatarsals may provide key evidence about the timing and sequence by which the early hominin foot, with its relatively long toes, evolved toward more human-like proportions. *H. naledi* has a more human-like midfoot and rearfoot, placing its anatomical configuration much closer to modern humans and Neanderthals than to *H. habilis, H. floresiensis* or *Australopithecus*. This might suggest that *H. naledi* would also have shorter lateral digits, more similar to modern humans and Neanderthals.[44] However, the metatarsophalangeal proportions of the associated *H. naledi* Foot 1 (F1) cannot be directly assessed, because it is missing the phalanges of digits 2–5, and although the hallucal phalanges are present, the proximal hallucal phalanx is incomplete and its length cannot be estimated with certainty.[40] Yet, the *H. naledi* pedal sample contains 21 unassociated proximal phalanges and metatarsals (Table 1). Because of the unknown association among the elements, we applied two assumptions about the possible associations in the pedal sample in order to assess the metatarsophalangeal proportions of *H. naledi.* We compared the fossil proportions to the associated and resampled[45] distributions of modern humans and chimpanzees (*Pan troglodytes*), and to the associated proportions of *H. floresiensis*.

Table 1: *Homo naledi* fossil elements that were included in the pedal sample. Additional information and lengths described in the Supplementary Information of Harcourt-Smith et al.[40]

Accession number	Element	Digit	Side
U.W. 101-244	Metatarsal	1	Left
U.W. 101-1019	Metatarsal	1	Left
U.W. 101-1443	Metatarsal	1	Right
U.W. 101-1530	Metatarsal	1	Right
U.W. 101-459/461	Metatarsal	2	Right
U.W. 101-1022	Metatarsal	2	Left
U.W. 101-1458	Metatarsal	2	Right
U.W. 101-552	Metatarsal	3	Left
U.W. 101-1457	Metatarsal	3	Right
U.W. 101-269	Metatarsal	4	Right
U.W. 101-1456	Metatarsal	4	Right
U.W. 101-1439	Metatarsal	5	Right
U.W. 101-082	Proximal phalanx	1	Left
U.W. 101-1452	Proximal phalanx	1	Unsided
U.W. 101-504	Proximal phalanx	2–5	Left
U.W. 101-976	Proximal phalanx	2–5	Unsided
U.W. 101-1013	Proximal phalanx	2–5	Left
U.W. 101-1034	Proximal phalanx	2–5	Left
U.W. 101-1148	Proximal phalanx	2–5	Unsided
U.W. 101-1395	Proximal phalanx	2–5	Unsided
U.W. 101-1441	Proximal phalanx	2–5	Unsided

Materials and methods

Our procedure was similar to the procedure used by Rolian and Gordon[46] to study the manual proportions of the Hadar *Au. afarensis* material. Analogous to the *H. naledi* context, the Hadar AL 333 locality is a commingled assemblage with limited bony associations.

The modern human comparative sample was derived from plain film pedal radiographs taken during routine medical care. All radiographs were de-identified prior to measurement in compliance with the *Health Insurance Portability and Accountability Act* (HIPPA) and Institutional Review Board (IRB) regulations; acquiring such radiographs does not require interaction with patients on the part of the researchers, and because the radiographs are anonymised, they are not considered human subjects and are exempted from IRB oversight. Radiographs of skeletally immature or pathological individuals were not included in this study. Measurements of pedal phalangeal and metatarsal lengths (mm) were taken in the dorsal-plantar view using standard equipment (lightbox and calipers). The sample of 110 adults included a variety of ancestries, was mixed-sex (48 male and 62 female), and was from a habitually shod US population. Agoada[47] demonstrated that linear measurements collected from pedal radiographs are accurate depictions of pedal skeletal element dimensions in humans, therefore this study considered the radiographic measurements equivalent to an osteological pedal sample. These radiographic linear measurements were compared to fossil bone linear measurements.

The chimpanzee (*Pan troglodytes*) comparative sample included 39 individuals (17 female, 18 male, 4 indeterminate) from the skeletal collections of the American Museum of Natural History, Cleveland Museum of Natural History, and the Smithsonian Natural History Museum. Chimpanzees demonstrate more ancestral metatarsophalangeal proportions (i.e. longer proximal phalanges relative to metatarsals) than modern humans[11] so the ancestral condition can be considered in contrast to the derived modern human sample. The maximum lengths of the proximal phalanges and metatarsals were measured with calipers held flush on proximal and distal ends.

The *H. naledi* fossil sample included the maximum lengths of 21 adult proximal phalanges and metatarsals (Table 1). These phalanges and metatarsals are described further in the Supplementary Information of Harcourt-Smith and colleagues.[40] The pedal elements represent a minimum of four adult individuals, although at least seven adult individuals are known from dental remains, and there is no reason to assume the pedal material samples fewer individuals than the dentition.[37] When resampling, many researchers have emphasised the importance for modern comparative samples to match the fossil sample in the minimum number of individuals (MNI) represented by the site.[48-51] Of the two fossil MNI, we chose to resample from the larger MNI of seven because it reduced the probability that multiple comparisons in each resampled set would come from the same individual.

Distinct from the Rolian and Gordon analysis[46], the present analysis considered the relationship among the bones of the commingled sample. While assessing proportions within a commingled assemblage, one cannot assume the fossil sample is a random, independent sample of a fossil population. There is a true state among two bones in a commingled assemblage. Either these two bones belong to the same individual, or they belong to different individuals. Hence, looking at a sample of bones with unknown associations, these two possible states constitute two boundary conditions. While bones may belong to a single individual, they may alternatively all belong to different individuals. These two states provide the boundaries within which all other partial associations must fall, including when some bones belong to one individual, but other bones belong to other individuals.

In this study, we probed the two boundary conditions by carrying out two separate tests. For each digit, two different analyses were performed. In the first analysis, the procedure assumed that an association was present between two bones in the sample, meaning they belong to the same individual. The assumed associated pair of bones was compared to a distribution generated from paired bones that were each from the same individual. In the other analysis, the procedure assumed that all bones were unassociated, which means that they were all from different individuals. This unassociated sample of bones was compared to a resampled distribution generated from samples of bones that were all from different individuals.

Usually, the commingled context of *H. naledi* would prevent the comparison of the indirect proportions of *H. naledi* to the direct proportions of *H. floresiensis.* However, because this novel approach to studying commingled assemblages addresses the associations among the elements, the associated proportion of *H. naledi* and direct proportion of *H. floresiensis* can be compared. The *H. floresiensis* pedal material contains the maximum lengths of five proximal phalanges, excluding the hallucal proximal phalanx, and three metatarsals.[5,35] Jungers and colleagues[35] assigned the longest and shortest phalanges to the second and fifth metatarsals, respectively. Therefore, the proportions of second and fifth digits of *H. naledi* and *H. floresiensis* were compared to better understand the pedal morphology of two species, both thought to be primitive in their morphology.

Digit 1

The first proximal phalanx (PP1) and first metatarsal (MT1) fossils were morphologically distinguishable from digit 1. There were two PP1 and four MT1 elements in the fossil sample (Table 1). If the sample of six elements included a minimum of one associated pair of PP1 and MT1 elements, the shortest proximal phalanx and the longest metatarsal in the sample create the most conservative pairing as they generate the smallest proportion. The human data set was composed of known individuals, or associated elements; thus, all PP1/MT1 proportions were calculated for the human sample. The minimum associated proportion for *H. naledi* was then compared to the distributions of associated human proportions.

If the PP1 and MT1 elements were unassociated, a resampling procedure was required to analyse the indirect proportions. From the initial data set

of 110 modern humans, 7 individuals were randomly sampled without replacement, to equal the MNI of *H. naledi* (Figure 1, step 1). Two of the seven individuals were randomly sampled without replacement and their PP1 lengths were collected (Figure 1, step 2). To ensure no association, of the remaining five individuals (Figure 1, step 3), four were randomly sampled without replacement and their MT1 lengths collected (Figure 1, step 4). Six elements were sampled – two PP1 and four MT1, ensuring the modern sample was equivalent to the *H. naledi* sample for digit 1. The arithmetic mean proportion, or the mean length of the phalanges divided by the mean length of the metatarsals, was calculated for these six elements (Figure 1, step 5). The resampling procedure was run 100 000 times (Figure 1, step 6) then the *H. naledi* mean proportion was compared to the resampled human distribution of unassociated mean proportions.

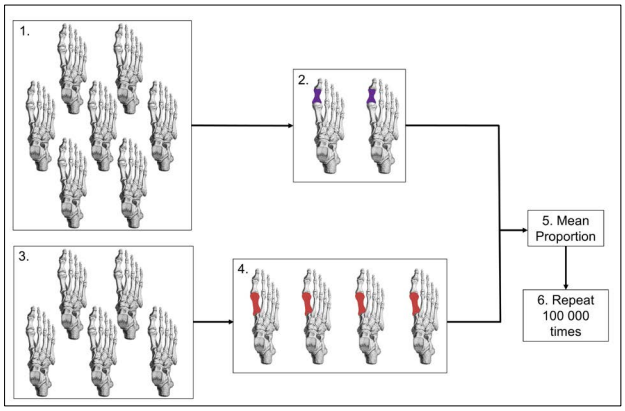

Figure 1: The resampling schematic for digit 1 if there is no association between the phalanges and the metatarsals. Step 1: Randomly sample 7 individuals from the sample of 110 modern humans. Step 2: Randomly sample two individuals from those seven and collect their PP1 lengths. Step 3: There are now five remaining individuals to sample from to assure no association. Step 4: Sample four individuals from the remaining five and collect their MT1 lengths. Step 5: Determine the arithmetic mean proportion of the mean proximal phalangeal length and the mean metatarsal length. Step 6: Repeat this sampling procedure 100 000 times to create a distribution of mean proportions represented by the human sample.

Digits 2–5

Regarding digits 2–5, the metatarsals were distinguishable from the digit, but the proximal phalanges were not. Resampling does not require complete fossils or complete data sets to perform an analysis; this provides the opportunity to study incomplete data sets and compare them to more complete extant samples. Resampling designs a scenario in which the largest possible range of ratios is generated from the available fossil material and is then compared to the resampled distributions of ratios from an equivalent number of elements representing extant taxa. Hence, digit attribution is not required for the relative length of the proximal phalanges to the metatarsals to be studied. Because the proximal phalanges of digits 2–4 were not distinguishable from each other, all proximal phalanges not assigned to digit 1 were pooled. This method of phalangeal pooling was previously performed by Rolian and Gordon[46] to assess the manual proportions of *Au. afarensis*. It was reasonable to use the approach here to assess pedal proportions because of the similar morphological ambiguity of both the manual and pedal proximal phalanges of the lateral digits. The resampling procedure will be demonstrated with digit 2, but was also applied to digits 3–5.

The digit 2 sample comprised three metatarsals (MT2) and seven pooled proximal phalanges (PP2–5; Table 1). If the sample included a minimum of one associated pair of elements, the identical digit 1 procedure was performed for digit 2. The *H. naledi* minimum proportion for digit 2 was generated from the shortest pooled phalanx and the longest MT2, with the assumption that if a phalanx from PP2–5 was associated with the MT2, it was a second proximal phalanx (PP2). This minimum fossil proportion was compared to the distribution of modern human proportions for digit 2 (PP2/MT2).

If the digit 2 PP2–5 and MT2 elements were unassociated, the modern human phalanges were pooled to mimic the fossil sample composition and a similar resampling procedure to that of digit 1 was performed (Figure 2). From the modern human sample of 110 individuals, 7 individuals were randomly sampled without replacement (Figure 2, step 1). Of those seven, three individuals were randomly sampled and their MT2 lengths were collected (Figure 2, step 2). The proximal phalanges of digits 2–5 from the remaining four individuals were pooled (16 phalanges), and the third, fourth and fifth proximal phalanges of the three individuals from whom MT2 lengths were collected (nine phalanges), for a total of 25 pooled phalanges (Figure 2, step 3). From the pooled phalangeal sample, seven phalanges were randomly sampled without replacement (Figure 2, step 4). In total, three MT2 elements and seven PP2–5 elements were sampled, equivalent to the composition of the fossil sample. The arithmetic mean proportion was calculated from the arithmetic mean of PP2–5 lengths and the arithmetic mean of the MT2 lengths (Figure 2, step 5). The resampling procedure was run 100 000 times (Figure 2, step 6) and the mean fossil proportion was compared to the resampled distribution of mean proportions. Both associated and unassociated procedures were repeated for digits 3–5.

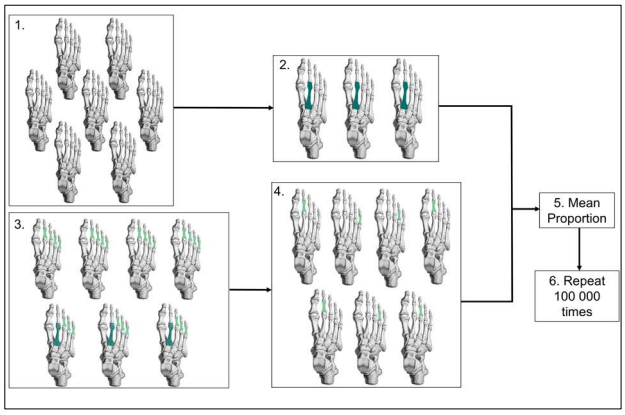

Figure 2: The resampling schematic diagram for digit 2 if there is no association between the phalanges and the metatarsals. The same procedure was applied to digits 3–5. Step 1: Randomly sample 7 individuals from the human sample of 110 individuals. Step 2: Randomly sample three individuals and collect their MT2 lengths. Step 3: Pool the phalanges from all seven individuals, excluding the PP2s from the individuals whose MT2 lengths were collected for a total of 25 proximal phalanges. Step 4: From those 25 pooled proximal phalanges, randomly sample 7 proximal phalanges. Step 5: Calculate the arithmetic mean proportion of the proximal phalanges to the metatarsals. Step 6: Repeat this sampling procedure 100 000 times to create an empirical distribution of human mean proportions.

Analysis

The analysis was performed with R software version 3.1.2.[52] Each *H. naledi* proportion was compared to its corresponding cumulative distribution function (CDF), which represented human variation for a given proportion. If a fossil value falls outside of the human distribution, it is considered significantly different. There is no associated *p*-value for the comparison. We tested the null hypothesis that *H. naledi* is not significantly different from modern humans in its metatarsophalangeal proportions. Because the assemblage is commingled, the true state of the bones is unknown, therefore both associated and unassociated states must be considered for each digit. The null hypothesis was not rejected if both assumptions failed to reject the null, meaning if both *H. naledi* proportions fell within the 95% confidence interval of their respective modern human CDF. Likewise, the null hypothesis was rejected if both assumptions rejected the null, or if both *H. naledi* proportions fell

outside the 95% confidence interval of their respective CDF. Finally, the null hypothesis was not rejected if only one assumption failed to reject the null. Both assumptions were considered equally plausible, therefore if one *H. naledi* proportion fell within the 95% confidence interval of its respective CDF, it could represent the true state of the bones so the null hypothesis cannot be rejected.

If the fossil value fell within the upper 97.5% of the human distribution, meaning that the fossil proportion was larger than modern humans, the fossil proportion was compared to a chimpanzee distribution to test if the fossil proportion was more similar to the ancestral condition of longer phalanges in relation to metatarsal length. If the null hypothesis was rejected for a given digit, the associated and unassociated fossil proportions for that digit were compared to the corresponding chimpanzee CDFs. The chimpanzee distributions were generated using the same methods described above.

Results

If at least one association between the elements was assumed to be present in the fossil sample, the minimum direct proportion of digit 1 fell at the 80th percentile of the modern human CDF (Figure 3). Similarly, the minimum direct proportion of digit 2 fell within the 95% confidence interval of its respective CDF (Figure 3). Both digit 1 and digit 2 unassociated mean proportions fell outside of 95% confidence intervals. However, because both states were equally plausible, if only one assumption failed to reject the null, the null hypothesis could not be rejected. If there was at least one pair of associated elements in the *H. naledi* pedal material, we failed to reject the null that *H. naledi* resembles modern humans in its metatarsophalangeal proportions, particularly those in the medial pedal column. With the present pedal data of *H. naledi*, we conclude that the proportions of first and second digits could be similar to those of modern humans.

In contrast to digits 1 and 2, all minimum associated and unassociated proportions of the more lateral digits 3–5 fell above the 95% confidence interval of their respective modern human CDFs (Figure 3) and so we rejected the null hypothesis that the metatarsophalangeal proportion values in the lateral column of *H. naledi* are similar to those of modern humans. This could be a result of preservation bias, in which the larger proximal phalanges were more likely to be preserved than the smaller phalanges from the more lateral digits. If the smaller phalanges of lateral digits are not represented in the *H. naledi* sample, it would result in a higher metatarsophalangeal proportion value for the lateral digits compared to modern humans. This could also be a result of a biological difference between the lateral and medial pedal columns in the *H. naledi* foot. The more lateral phalanges could be longer relative to the metatarsals than in modern humans, which would generate the higher proportions seen in this study. Alternatively, the metatarsals could be shorter. Either way, the proportions of the lateral digits are different from those of modern humans and could represent different medial versus lateral pedal column development in this species.

Because the fossil proportions of the lateral digits were different from those of modern humans, we compared digits 3–5 to corresponding chimpanzee CDFs. The unassociated minimum and associated mean proportions of digits 3–5 of *H. naledi* fell below all respective chimpanzee CDFs (Figure 4). This demonstrates that although the values of metatarsophalangeal proportions are higher in *H. naledi* than they are in humans, they are not within the range of the more ancestral chimpanzee values.

Regarding the *H. floresiensis* pedal elements, both *H. floresiensis* digit 2 (0.43) and digit 5 (0.39) proportions fell outside the modern human confidence intervals provided by this study (Figure 3) and both were larger than the *H. naledi* minimum associated proportions (0.29, 0.32). This analysis demonstrates that *H. floresiensis* has different proportions from those of modern humans, which confirms the results of Jungers and colleagues[35], but also demonstrates that *H. naledi* is distinct from *H. floresiensis* in its pedal proportions.

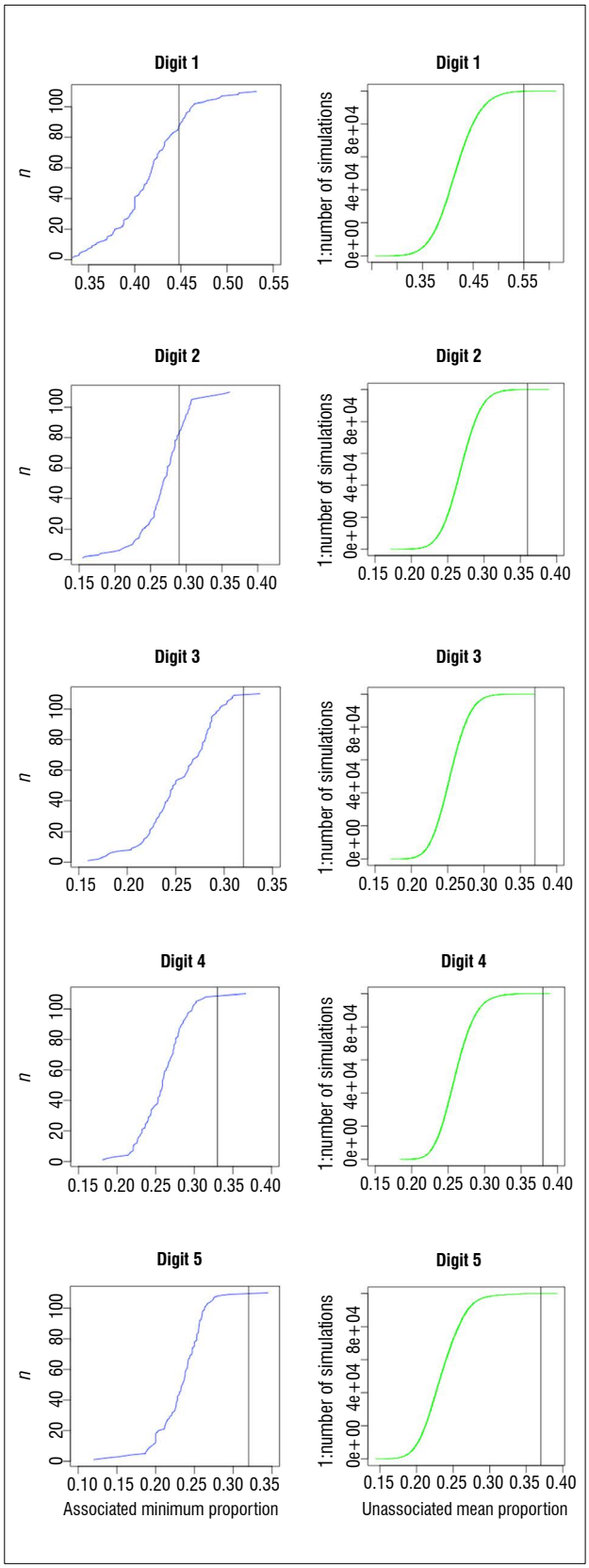

Figure 3: The associated (left) and unassociated (right) modern human cumulative distribution functions (CDFs) for digits 1–5. Each corresponding *Homo naledi* value is represented by the vertical lines in each of the CDFs. The scales of the axes differ with digit and assumption.

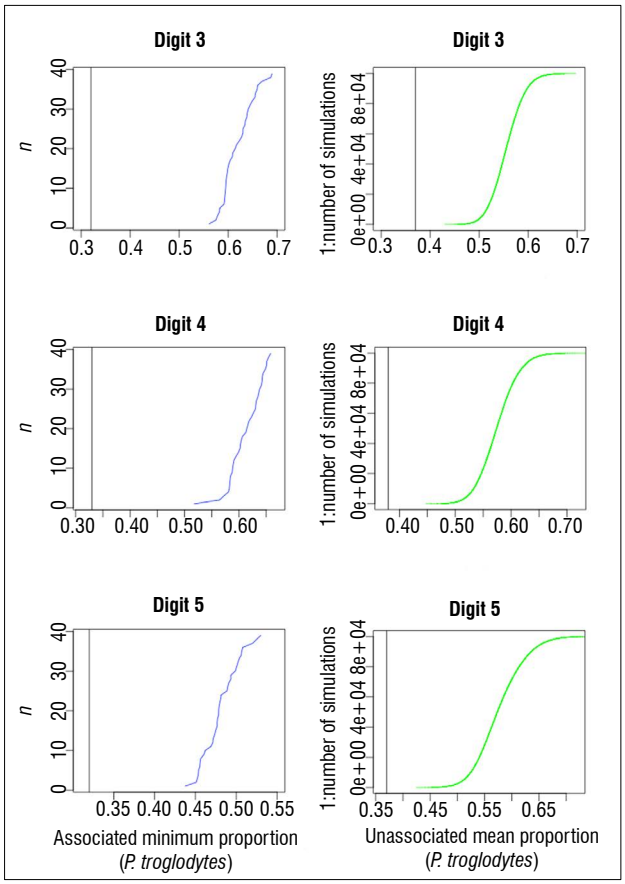

Figure 4: The associated (left) and unassociated (right) chimpanzee (*Pan troglodytes*) cumulative distribution functions (CDFs) for digits 3–5. Each corresponding *Homo naledi* value is represented by the vertical lines in each of the CDFs. The scales of the axes differ with digit and assumption.

Discussion

Homo naledi has a human-like hindfoot and midfoot, but it has curvature of the proximal pedal phalanges like some extant primate species and *Au. afarensis*.[39] It was unclear if its primitive phalangeal morphology was accompanied by primitive phalangeal proportions (i.e. longer phalanges relative to metatarsals), as direct proportions are not possible in this unassociated sample. In the present study, we analysed the length of the proximal phalanges relative to the metatarsals in *H. naledi* and compared these proportions to samples of modern humans, chimpanzees and *H. floresiensis*. Based on these comparisons, *H. naledi* could have medial column proportions similar to those of modern humans, but different lateral proportions from those of modern humans and chimpanzees. Additionally, *H. naledi* has proportions different from those of *H. floresiensis*.

Given the lack of associated proximal phalanges and metatarsals, the resampling method generates distributions of likely proportions in modern humans, considering the sample size and composition of *H. naledi* fossils, and permits us to study the pedal proportions in the largest pedal sample in the African hominin fossil record to date. Consequently, *H. naledi* provides insight into the evolution of this mosaic morphology in hominins, as this species demonstrates manual[27] and medial pedal phalangeal lengths similar to those of modern humans, but exhibits manual[27] and pedal curvature[40] dissimilar to modern humans.

Although palaeoanthropologists assess the length and curvature of the manual and pedal phalanges to identify certain locomotor behaviours in hominin fossils, the evolutionary mechanism through which length is modified is less clear. The human-like proportions of the manual and pedal phalanges of *H. naledi* could indicate serial homology[53,54], or the continued modularity[55] and shared developmental trajectories of these two structures[56,57]. However, developmental genetics[13] have demonstrated the existence of regulatory elements that are expressed in one limb but not the other, suggesting manual and pedal skeletal element covariation is not constant. Additionally, cortical neural mapping suggests that the hand in human and nonhuman primates developed more independently from the foot than previously assumed.[58]

If covariation of the hand and feet are inconsistent, the shorter phalanges of *H. naledi* may indicate a locomotor adaptation unique to *H. floresiensis.* Shorter toes have been demonstrated to minimally decrease mechanical work of the digital flexor muscles while walking[16], and drastically decrease the mechanical work while running[15]. In addition to shorter medial phalanges, *H. naledi* also exhibits an elongated tibia[59], which has been demonstrated to significantly positively correlate with optimal walking speeds[60]. At the same time, the curvature of the pedal phalanges, in addition to other primitive features of the upper limb, suggest that *H. naledi* was likely engaging in locomotor grasping with a human-proportioned medial pedal column. An implication of the results is that the lateral side of the foot might have been more effective for pedal grasping rather than the medial side. Lateral forefoot grasping could represent a hominin strategy for limited climbing given the loss of an opposable, grasping hallux. Future directions of this research include comparing these *H. naledi* pedal proportions to those of additional primate samples to better understand the lateral pedal morphology of *H. naledi*.

A foot with a combination of traits like that of *H. naledi* has not previously been observed in the fossil record. Because of the paucity of pedal material in early hominins, the ancestral foot of *Homo* is unknown. The foot of *H. floresiensis* has been hypothesised to represent the primitive condition of the genus *Homo* with curved and elongated proximal phalanges. Both *H. floresiensis* digit proportions are larger than inferred for *H. naledi* and are additionally outside the modern human distribution. *H. naledi* toe proportions are different from those of *H. floresiensis*, while both species suggest deep phylogenetic placement in the genus *Homo*. Without knowing the proportions in *H. erectus*, it is unclear as to which pedal form, if either, represents the ancestral form to *H. erectus* and later *Homo.*

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Authors' contributions

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Developmental stress in South African hominins: Comparison of recurrent enamel hypoplasias in *Australopithecus africanus* and *Homo naledi*

Discovery of a new hominin (*Homo naledi*) in the same geographical area as *Australopithecus africanus* creates the opportunity to compare developmental dental stress in higher latitude hominins with low that in latitude apes, among whom repetitive linear enamel hypoplasia (rLEH) recurs seasonally at about 6 or 12 months. In contrast to equatorial Africa, a single rainy/dry cycle occurs annually in non-coastal southern Africa. It is predicted that LEH will recur annually but not differ in duration between ancient and more recent hominins. Data were collected from epoxy casts of anterior teeth attributed to *H. naledi* (18 incisors, 13 canines) and *A. africanus* (29 incisors, 8 canines) using a digital microscope, surface scanner and scanning electron microscope. The location, number, width, depth and distance between defects (including perikymata counts and spatial measurements) of 136 LEH events were compared among crown moieties (deciles 4–6 and 7–9), tooth types and taxa. Enamel defects are concentrated in the cervical half of anterior crowns, and in similar numbers in each taxon. Contrary to expectations, *H. naledi* show bimodal LEH durations reconstructed at about 2 and 8 weeks compared to just 4 weeks in *A. africanus*. Both taxa show bimodally recurrent episodes of LEH centring on 2 and, more commonly and severely, 6 months. A combination of two independent annual stressor types, one disease and one seasonal, could explain the observations. These estimations of duration and recurrence of developmental stress require evaluation using actual perikymata periodicity for *H. naledi* and more refined understanding of palaeoenvironments for both taxa.

Significance:

- Seasonal stress is a central concern in the biological and health sciences. Because of the innate way that enamel is deposited, the timing of stress in the childhood of apes, modern humans and their fossil ancestors can be measured with a precision of about 1 week.
- Application of this method to South African Pliocene *Australopithecus africanus* and Mid-Pleistocene *Homo naledi* reveals that, unexpectedly, both forms show semi-annual stress – a finding that is tentatively attributed to two independent annual stressors, possibly disease and malnutrition.

Introduction

The great attraction of enamel hypoplasia studies in biological anthropology is that comparative studies of developmental well-being can include modern, ancient and even fossil assemblages.[1-4] Previous studies of enamel hypoplasia in single teeth from large apes (gorillas, chimpanzees and orangutans) found that, generally speaking, several enamel furrows are often observable, especially on the canine teeth, representing a time span of 'felt stress' of 5 or more years[5], and that the average interval between successive furrows is in the order of 6 months or multiples thereof; i.e. 12 or 18 months.[6-9] Both western African apes (chimpanzees and lowland gorillas from Cameroon) and orangutans from Indonesia live in low latitude contexts, where commonly there are alternating twice yearly rainy and dry seasons driven by semi-annual passage of the inter-tropical convergence zone in Africa and twice yearly moisture-carrying monsoonal winds passing over the islands of Borneo and Sumatra.[6,7] By contrast, chimpanzees from Senegal, who experience only one wet season alternating with one very long dry season, show a reconstructed average interval between repetitive episodes of enamel hypoplasia of just under a year.[9,10]

The assertion that repetitive linear enamel hypoplasia (rLEH) shows an average recurrence of 6 or 12 months, is not without challengers[11,12], but see Smith et al.[13] Furthermore, linking the recurrence with semi-annual moisture cycles, which are in turn linked to metabolic stressors such as seasonal food shortages, respiratory disease, malaria or intestinal worms[8], remains speculative. With the discovery of *Homo naledi*, who lived in the same geographical area as *Australopithecus africanus*, it becomes possible to compare temporal ontogenetic patterns of enamel hypoplasia between low- and higher-latitude hominoids. Given the simple alternation, in central southern Africa, of a relatively warm, wet austral summer and cold, dry austral winter (i.e. only a single moisture cycle annually)[14-16], it is predicted that South African hominins will show rLEH with an average recurrence of about 12 months (null hypothesis). Rejection of this hypothesis will weaken any direct connection between rLEH and seasonality.

The study of enamel hypoplasia among South African fossil hominins has a long history[17]; however, these previous studies have an emphasis only on prevalence and little attention has been given to ontogenetic patterning[18]. The concentration of transverse enamel defects in the cervical half of the *A. africanus* canine crown was interpreted as reflecting abrupt weaning stress.[19] Recent studies of South African hominin enamel defects (137 *P. robustus* vs 200 *A. africanus* teeth) show increasing methodological sophistication and a concern for how intrinsic enamel formation (perikymata packing and crown formation span) could affect LEH expression and numbers of defects[20,21] (perikymata are regularly deposited enamel increments). For the first time, a formal analysis of duration of stress from defect width was performed, finding that *A. africanus* showed a wide range of furrow widths confounding simple interpretation of duration of stress. There was no difference between assemblages in defect width or constituent perikymata counts. A geographically enlarged study found that east African *Australopithecus* (n=10) had a markedly larger number of 'within LEH' perikymata (mean=8.2, range 4–14) than *A. africanus* (mean=4.6, range 3–7).[21] This latter study is

noteworthy also for estimating defect duration in actual days from counts of perikymata in the occlusal wall of one *Australopithecus* from eastern Africa. Assuming a perikymata periodicity ranging from 8 to 10 days, stress lasted from 48 to 60 days. The author concluded, not unreasonably, that the number of perikymata within defects is a stronger predictor of defect width than is the spacing of perikymata adjacent to an LEH. In summary, studies of enamel hypoplasia in South African hominins show that, for comparative prevalence studies, the duration of crown formation span needs to be countenanced; and, secondly, that there are taxonomic and geographical differences in defect duration whose meaning needs further evaluation. There are no formal studies of defect depth or recurrence in South African hominins.

With the recent availability of surface-scanner microscopes and the discovery of a new hominin species (*Homo naledi*) that lived in the same higher-latitude geographical area as South African *Australopithecus*, we have the ability to conduct detailed studies of taxonomic and temporal variation in measures of enamel furrow defects and compare these to low-latitude apes with a view to furthering our understanding of aetiology. A major weakness in the reported research is that periodicity of perikymata in *H. naledi* remains unknown. Acknowledging this problem, reconstruction of temporal patterning of LEH is based on the range of Retzius periodicities reported for hominins in the literature.

Materials and methods

Linear enamel hypoplasia is described in two samples of South African fossil hominin teeth (Figure 1). They are drawn from greatly different time periods but lived in similar geographical areas and were likely subject to comparable annual cycles of insolation and moisture characteristic for the latitude.[22,23] The climate today in the area is decidedly seasonal and quite arid generally. The *A. africanus* sample is drawn from Member 4 Sterkfontein, aged >2 million years[24] and Makapansgat Member 3 (aged >2.6 my)[25]. Our picture of the climate for Pliocene Sterkfontein/Makapansgat can be glossed as probably wetter, more wooded and less seasonal, somewhat like Cameroon today[26-28] (but see Avery[29]). Palaeoenvironmental reconstruction of the climate for the Sterkfontein Valley, based on micro-mammals, concluded that at the time of deposition the site was drier and more seasonal than today.[29] However, there is evidence based on the presence of lianas in Member 4 that Sterkfontein exhibited dense, humid forest-type vegetation.[26] Makapansgat to the north is thought to have been much wetter and wooded at Member 3 with reduced seasonality of rainfall.[27,28] The drier austral winter months might have posed nutritional difficulties for the hominins.[30]

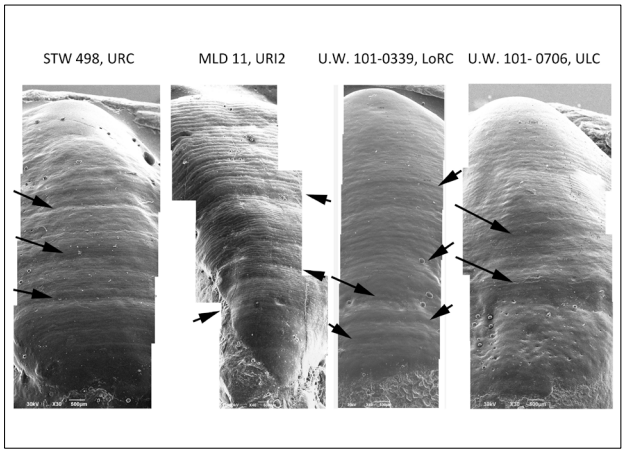

Figure 1: Examples of teeth with repetitive linear enamel hypoplasia (arrowed): STW=Sterkfontein (*Australopithecus africanus*), MLD = Makapansgat (*Australopithecus africanus*), U.W.101=*Homo naledi*; U=upper, Lo=lower, L=left, R=right. Thresholds for diagnosis of any particular defect are based on agreement among scanning electron micrographs (shown here), and scanning and digital microscopy images.

The *H. naledi* sample is derived from site U.W. 101, also known as the Dinaledi Chamber, within the Rising Star Cave system.[31] These fossils are dated at 236 ka to 335 ka.[32] The Middle Pleistocene of southern Africa has been described as semi-arid and, at intervals, more humid with an interval of greater cold.[33]

Cast preparation

Teeth from both sites were chosen specifically because they showed obvious enamel defect furrows and, often, countable perikymata in relevant crown parts. Here I report incisor and canine teeth only as they are thought to record most of any stress encountered during development (although not later childhood).[34] While original teeth were examined for dental selection, this study is based on casts from moulds (Table 1). Moulds were taken by Mark Skinner and Debbie Guatelli-Steinberg in President Regular Jet impression material, so as to span from the incisal/occlusal edge to the cervical margin and a small portion of root. As described by Guatelli-Steinberg et al.[35] casts were made by DGS and Mackie O'Hara in Struer's Epofix, a high-resolution epoxy. In addition, this study employs an earlier generation of casts for certain teeth whose labial surfaces were obscured in the later casts. Teeth were not assigned to individuals (the tooth being the unit of analysis) so there may be statistical redundancy; however, the advantage of this approach is that it avoids false associations of antimeres that can be so similar between individuals. The Dinaledi assemblage is commingled and there are numerous individuals of similar ontogenetic stage that are morphologically similar, making false associations a strong possibility. In order to have adequate sample sizes for tooth types (incisors/canines), no distinction is drawn between isomeres nor between central and lateral incisors.

Table 1: Distribution of counts of linear enamel hypoplasia events along incisor and canine crowns, from apex to cervix in deciles, compared between *Australopithecus africanus* and *Homo naledi*[a]

	Tooth type				
	Incisor[b]		Canine[b]		
Decile	*A. africanus*[c]	*H. naledi*[c]	*A. africanus*[d]	*H. naledi*[d]	Total
1					
2					
3					
4		2	1		3
5	4	3	1	3	11
6	2	11	3	5	21
7	6	10	6	6	28
8	4	7	4	7	22
9	6	9	4	7	26
10	_	3	1	2	6
Total	22	45	20	30	117

[a]*Includes specimens MLD11-30, 43, STW75, 111, 132, 151, 183a,b, 222, 369, 446, 498; Dinaledi Chamber specimens currently numbered as U.W. 101-0038, 0039, 0073, 0335, 0337, 0339, 0377, 0412, 0501, 0591, 0706, 0709, 0816, 0886, 0908, 0931, 0932, 0952, 0985, 0998, 1005b, 1005c, 1012, 1075, 1076, 1126, 1131, 1132, 1133, 1556, 1588*

[b]*Test of tooth type (taxa combined): Pearson chi-square=1.082,* p=*0.982*

[c]*Test of taxa (incisors): Pearson chi-square =6.684,* p=*0.351*

[d]*Test of taxa (canines): Pearson chi-square =2.573,* p=*0.860*

Visualisation and instruments for recording developmental enamel defects

The term stress is defined here as a physically discernible effect of a stressor on enamel, i.e. a 'defect'. 'Stressor' is an inclusive term embracing nutritional, disease and Selyean-type physiological departures from homeostasis.[36] LEH were imaged with three instruments: a Keyence digital microscope VHX-100, a 'μsurf Mobile Plus' optical scanner, and a JEOL JSM-6490LV scanning electron microscope. Besides employing these instruments for high magnifications of perikymata and enamel furrows, a comparison of image types from all three instruments at low power (ca 10–15X) increased confidence in identifying and numbering successive LEH. The task of matching LEH between low- and high-magnification pictures for perikymata counting was accomplished by noting small irregularities (e.g. scratches) or imperfections in the cast (e.g. bubbles) that could be located on images from all three instruments. LEH were measured with a 'μsurf Mobile Plus' optical scanner and analysed with μsoft Analysis Premium 6.2 software from NanoFocus® AG (Oberhausen, Germany). With this instrument, magnification was performed with a 10X lens that provides a square field of view 1600 μm on a side. Width and depth measurement outputs are averages, calculated by the instrument, from 516 measurements over this space. Scanner images were levelled, missing points filled in, and form removed. Form removal optimises measurement of defect depth by minimising the effect of object curvature. Because an object's surface is rarely level or completely flat, true depths are calculated trigonometrically from width and depth measures originally taken orthogonal to the instrument's plane.[37] 'Width' is defined as an orthogonal measure from the occlusal shoulder/high point, which visually demarcates the onset of an episode of LEH, to the deepest point of the defect, assessed with reference to the cervical high point of a defect. Typically, width defined this way is about half the overall width of an LEH.[38] I also refer to this measure as 'onset width' to distinguish it from 'recovery width'.

There are two options for estimating duration and recurrence of LEH: perikymata counting and spatial measurements. These measurements are not mutually exclusive and may be compared. Periodicities of perikymata are taken from the literature (see below). While periodicity of striae of Retzius, and their surface expression as perikymata, are thought to be invariant for the individual, it may be that some teeth, particularly deciduous teeth, show different periodicities than do permanent teeth from the same individual.[39] Periodicity is reported to range in humans from 6 to 12 days in permanent teeth but, of these, 95% had periodicities between 7 and 10 days[40] with a mode of 8 days[41]. As yet, Retzius periodicities for *H. naledi* are unknown. A northern African *Homo sapiens* (Djebel Ihroud, Morocco) of geological age somewhat less than that of the Dinaledi *H. naledi* remains has a stria periodicity of 10 days.[42] Retzius periodicities in *A. africanus* from South Africa are shown in Table 2.

In that perikymata generally decrease in width and increase in number progressively from occlusal margin to cervix, especially in *H. naledi*[35], it is necessary, for somewhat worn labial surfaces, to calculate the likely number of perikymata within an LEH in a particular crown location from the average width of perikymata within the relevant decile of crown height. Statistical analyses of perikymata number, LEH widths, depths and inter-defect distance use two-tailed parametric (Student's *t*-test) and non-parametric (Mann–Whitney) tests. Alpha is set at 0.05 for all statistical tests.

Results

Anatomical distribution and frequency of LEH defects

The objective of this study was to compare the duration, recurrence and severity of felt stress between *H. naledi* and *A. africanus*. Developmental stress, preserved as enamel hypoplasia in these ancient and more recent South African hominins, is concentrated in the cervical half of incisors and canines from both groups. There are no significant differences in the anatomical distribution of LEH along the tooth crown compared between tooth types or between taxa (Table 1). Similarly, the number of LEH furrows per tooth crown (medians range from two to three LEH) does not differ significantly between incisors and canines (*H. naledi* z=-1.305, p=0.192; *A. africanus* z=-0.942, p=0.346) nor between the ancient and more recent hominins for tooth types combined (z=-0.279, p=0.780). The lack of marked differences in the location and number of LEH between tooth crown types and taxa makes the following comparisons of LEH furrow measurements (size and perikymata number) more straightforward.

Table 2: Retzius periodicities in *Australopithecus africanus* from South Africa

Specimen	Retzius periodicity in days	Source
MLD2[a]	7	43
MLD11/30[b]	6	44
STS2	11	44
STS24	10	44
STW11	6	45
STW40	6 or 7	45
STW90	7	45
STW151[a,b]	8	43
STW188	6	45
STW284	6 or 7	45
STW285	7	45
Taung	8	45
Mean/median	7.3–7.5/7.0	

[a]*Authors reconstruct total canine crown formation time as close to 5 years*

[b]*In this study*

Furrows in enamel potentially vary not only as a result of ecological differences[46] but also by location on the teeth (occlusal to cervical) and tooth types (incisor and canine)[47]. Until these variables are understood and controlled in some fashion, it is not possible to evaluate whether any apparent differences between sources are meaningful. Consequently, the first task is to evaluate the effect of location and tooth type on measures of LEH (width, depth, perikymata number).

Here I have chosen, in order to generate sufficient sample sizes for statistical analysis, to simplify crown location from one of ten deciles to two groupings: deciles 4, 5 and 6 versus deciles 7, 8 and 9. Deciles 1 through 3 were eliminated because there are no LEH in these deciles; decile 10 was not included because perikymata within this decile peter out. For similar reasons, data were combined by tooth type (e.g. combining data from maxillary and mandibular and lateral and central incisors and maxillary and mandibular canines). Variables of perikymata number within LEH, defect width and depth, in terms of anatomical factors, are evaluated in Table 3.

Comparison of the contrasting number of perikymata within the occlusal wall of an LEH defect in *H. naledi* incisor versus canine teeth suggests that the more occlusal decile moiety of the incisors is sampling an earlier phase of infancy than is the canine (given normal patterns of crown formation in hominoids[48]). Of 12 comparisons, in only 2 does crown location of an LEH matter (i.e. show statistical significance) (incisors from *H. naledi,* in which LEH in the occlusal moiety (deciles 4 to 6) contain few perikymata and are shallower) (Table 3). By contrast, in 5 of 12 instances, tooth type matters (interestingly most of these relate to the *H. naledi* LEH assemblage). In both taxa, canine defects are significantly deeper than are incisor defects, but only in the cervical decile moiety. Consequently, in order not to generate a confusing number of analytical groups and to maximise sample size for statistical analysis of potential differences in LEH expression between taxa, I have chosen, for most of the following analyses, to combine decile moieties but to keep tooth types separate.

Table 3: Descriptive statistics for anatomical variables of decile moiety and tooth type as they affect linear enamel hypoplasia (LEH; in μm); only statistically significant differences are shown

			Tooth type							
			Incisor				Canine			
Source	**Measure**	**Decile moiety**	***n***	**Mean**	**s.d.**	**Median**	***n***	**Mean**	**s.d.**	**Median**
H. naledi	Perikymata in LEH	4–6	14	*2.7[a,e]	2.5	2.0[b,f]	3	6.7[e]	3.1	6.0[f]
		7–9	12	6.8[a]	3.6	6.0[b]	10	7.7	4.8	7.5
	Width	4–6	16	*254[g]	174.4	237[h]	6	509[g]	307.8	501[h]
		7–9	26	307[i]	115.2	266[j]	18	475[i]	229.9	438[j]
	Depth	4–6	16	10.8[c]	5.96	11.00[d]	6	24.74	22.92	16.34
		7–9	26	16.1[c,k]	8.41	15.1[d,l]	18	*40.1[k]	35.82	26.86[l]
A. africanus	Perikymata in LEH	4–6	5	4.2	2.3	4.0	1	3.0	–	4.0
		7–9	13	*3.7	2.8	3.0	5	2.4	1.1	2.0
	Width	4–6	6	427	192.6	390	5	309	99.3	321
		7–9	16	392	266.4	302	13	421	173.5	381
	Depth	4–6	6	17.28	9.70	14.77	5	25.54	20.35	17.75
		7–9	16	11.39[m]	5.91	10.24[n]	13	*33.8[m]	24.69	26.03[n]

**not normally distributed*

test of LEH location on crown: [a]t=*-3.423,* p=*0.002;* [b]z=*-3.275,* p=*0.001;* [c]t=*-2.182,* p=*0.035;* [d]z=*-1.943,* p=*0.052*

test of tooth type: [e]t =*-2.412,* p=*0.029;* [f]z=*-2.137,* p=*0.033;* [g]t =*-2.470,* p=*0.023;* [h]z=*-1.99,* p=*0.0.047;* [i]t =*-2.861,* p=*0.009;* [j]z=*-2.411,* p=*0.016;* [k]t =*-2.790,* p=*0.012;* [l]z=*-2.315,* p=*0.021;* [m]t =*-3.195,* p=*0.007;* [n]z=*-0.4034,* p=*0.00006*

Duration: Width of defects

Metrical

Dental crowns grow from cusp tip to cervix; consequently, there is a relationship between disturbances of enamel formation and time; that is, 'duration'. Acknowledging at the outset that enamel crowns may not form at a uniform rate, the first analysis is simply a comparison of defect width between tooth types and between taxa. In this work, width is technically 'onset width' and does not include recovery to normal enamel contour, i.e. 'recovery width'. Median widths of defects range from a high of 413 μm in *H. naledi* canines to a low of 263 μm in *H. naledi* incisors; with *A. africanus* widths falling within this range. The only difference of note relates to *H. naledi*, whose markedly narrow incisor defect widths occlusally (see above) lie behind the taxonomic differences (z=-1.959, p=0.05).

Number of perikymata within defects

Perikymata are the surface expression of depositional increments (Retzius lines) whose formation (number of days to form one perikyma/Retzius) is thought to be invariant within the permanent teeth of an individual, although somewhat variable within and between taxa (see above). Hence, even not knowing Retzius periodicity, it is reasonable, as a first step towards estimating LEH duration, to compare the number of perikymata within LEH (occlusal wall) between taxa.

Observed

There is no significant difference in perikymata number observed within an LEH between species for incisors (median counts=5.0 and 3.0 in *H. naledi* (n=29) and *A. africanus* (n=19), respectively) (z=-0.958, p=0.338) but there is for canines (median counts =7.0 and 4.0 in *H. naledi* (n=13) and *A. africanus* (n=9), respectively) (z=-2.501, p=0.012). This difference arises from the relatively large number of perikymata (mean=7.5) within LEH in *H. naledi* canines. Interestingly, it could be concluded that *A. africanus* incisors and canines are expressing the same kind of stressor but that *H. naledi* incisors and canines are recording stressors that differ in duration.

Predicted and observed

The previous analysis is based on rather a limited number of *H. naledi* canine defects; it is desirable to increase this sample if possible. All else being equal, there should be a strong correlation between LEH widths measured metrically and in terms of perikymata in the occlusal wall. In this study the correlation is 0.35 (n=67, p=0.003) and differs somewhat among tooth types and taxa. Apart from measurement error, the other major factor reducing the correlation is that LEH defects often contain more closely spaced perikymata because of reduced secretion (compression) affecting Retzius increment width.[37,49,50]

Given the noted correlation, it is reasonable to calculate, for those LEH defects without observable perikymata, the likely number of constituent perikymata given their widths. As discussed elsewhere[35], the pattern of perikymata packing can differ between taxa and tooth types; specifically, in comparison to *Australopithecus*, *H. naledi* shows more widely spaced perikymata occlusally and narrower perikymata cervically, especially in the incisors. Consequently, in this study, all measured widths for defects without countable perikymata are divided by the mean perikymata width observed for a particular combination of decile, tooth type and species. As a check on the validity of this approach, one can examine the relationship between observed and predicted number of occlusal wall perikymata within an LEH (r=0.50, p<0.00003). The average number of observed versus predicted occlusal-wall perikymata (n=62) differs by only one perikyma (4 vs 3).

Assuming, then, that one can legitimately combine predicted with observed perikymata counts, we can now compare relative durations of LEH among taxa and tooth types in terms of perikymata count. The results are shown in Table 4a and Figure 2. Inclusion of LEH defects that did not include countable perikymata almost doubles the sample available for analysis of relative duration – from 70 to 120.

There is a striking difference between the two taxa in that both incisors and canines from *H. naledi* show a bimodal distribution of durations, which is not shown by *A. africanus* teeth (Figure 2).

Table 4: (a) Linear enamel hypoplasia (LEH) widths in terms of number of perikymata in occlusal wall: combining both those observed and those predicted from occlusal wall width. (b) Comparison of perikymata counts in occlusal wall of LEH defects (observed plus predicted) between tooth type and taxa (short and long modes shown).

(a)		Tooth type						
		Incisor			Canine			
		Observed	Predicted from width	Both	Observed	Predicted from width	Both	Total
Homo naledi	*n*	29	17	46	13	15	28	74
	Mean	5.0	5.5	5.2	7.5	7.3	7.4	
	s.d.	4.0	2.6	3.5	4.3	4.9	4.5	
	Median	4.0	6.0	5.0	7.0	9.0	8.0	
Australopithecus africanus	*n*	19	4	23	9	14	23	46
	Mean	3.7	58	4.0	3.3	4.1	3.8	
	s.d.	2.6	2.9	2.7	1.5	2.4	2.1	
	Median	3.0	4.9	4.0	4.0	4.0	4.0	
								120

(b)		Tooth type						
		Incisor/durations			Canine/durations			
		Both	Short	Long	Both	Short	Long	Total
Homo naledi	*n*	46	22	24	28	10	18	74
	Mean	5.2	2.3	7.8	7.4	2.3	10.2	
	s.d.	3.5	1.2	2.8	4.5	1.2	2.9	
	Median	5.0	2.0[a,e]	7.0[b,f]	8.0	2.0[a,g]	10.0[b,h]	
Australopithecus africanus	*n*	23	16	7	23	17	6	46
	Mean	4.0	2.7	7.1	3.8	2.9	6.3	
	s.d.	2.7	1.2	2.8	2.1	1.1	2.3	
	Median	4.0	2.5[c,e]	6.0[d,f]	4.0	3.0[c,g]	5.5[d,h]	
								120

[a]*Comparison of tooth type/short duration (*H. naledi*): z=-0.021,* p=*0.984* [b]*Comparison of tooth type/long duration (*H. naledi*): z=-2.862,* p=*0.004*

[c]*Comparison of tooth type/short duration (*A. africanus*): z=-0.630,* p=*0557* [d]*Comparison of tooth type/long duration (*A. africanus*): z=-0.529,* p=*0.628*

[e]*Comparison of taxa/short duration (incisor): z=-0.966,* p=*0.334* [f]*Comparison of taxa/long duration (incisor): z=-0.939,* p=*0.348*

[g]*Comparison of taxa/short duration (canine): z=-1.391,* p=*0.164* [h]*Comparison of taxa/long duration (canine): z=-2.524,* p=*0009*

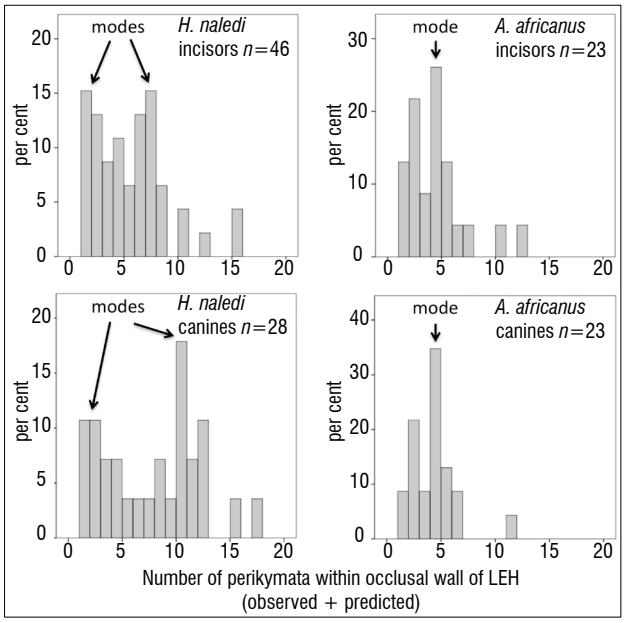

Figure 2: Distribution of occlusal wall perikymata counts compared among tooth types and taxa. *Homo naledi* shows bimodal distributions while *Australopithecus africanus* does not.

Consequently, I have elected to divide durations into two groups: short duration with four or fewer perikymata in the occlusal wall versus long duration with five or more perikymata. The proportion of stressful episodes that are deemed long in duration (i.e. five or more perikymata) make up 57% in *H. naledi* compared to only 28% in *A. africanus* (Pearson chi-square = 9.278, $p=0.003$). In other words, *H. naledi* appears to have experienced stressful episodes of short *and* markedly long duration.

A comparison of defect durations (perikymata count) between tooth types and taxa is provided in Table 4b. It can be seen that it is the large number of (observed plus predicted) perikymata within defects in *H. naledi* canines that is creating significant differences between tooth types ($z=-2.862$, $p=0.004$) and between taxa ($z=-2.524$, $p=0.009$). The relatively wide defects in *H. naledi* canines are mirrored both in observed perikymata counts and in those perikymata counts predicted from measured widths.

Severity

Depth of defects

An assumption in this study is that, with caveats noted later, defect depth is a measure of 'felt stress'. Sustained stress, with no change in intensity, will produce deeper defects.[20] A comparison of defect depth between those of short versus longer duration confirms this phenomenon ('short duration' median depth = 10.9 μm, 'long duration' median depth = 21.5 μm; $z=-5.019$, $p<0.0001$). Consequently, in an analysis of defect depth one has to separate the sample by defect duration. As shown in Table 5, after controlling for defect duration, LEH are significantly deeper in canines,

compared to incisors, in *H. naledi*/long duration defects and in *A. africanus*/short and long duration defects. It may be concluded that defects in canine teeth are usually deeper than those in incisors; this difference is attributable to innate anatomical features of striae angle in canine teeth.[20] In a comparison of sources, LEH are significantly deeper only in short duration defects in *A. africanus* canines. It may be concluded that there is not much difference between the sources in defect depth. Defects are significantly deeper in long duration defects for *H. naledi* incisors and both tooth types in *A. africanus*. In sum, the most important difference in a study of defect depth is that defects of long duration are more severe than are those of short duration.

Table 5: Linear enamel hypoplasia defect depths (μm) compared between tooth types and between taxa

			Source	
Tooth type	**Duration interval**		***Homo naledi***	***Australopithecus africanus***
Incisor	Short (<5 PK)	*n*	22	16
		Mean	9.3	11.0
		s.d.	5.0	6.3
		Median	9.8[a,e,i]	10.2[c,e,k]
	Long (5+ PK)	*n*	24	7
		Mean	17.7	16.6
		s.d.	7.7	8.5
		Median	16.2[b,f,i]	12.9[d,f,k]
Canine	Short (<5 PK)	*n*	9	16
		Mean	11.9	23.7
		s.d.	5.8	12.4
		Median	9.9[a,g,j]	23.3[c,g,l]
	Long (5+ PK)	*n*	17	6
		Mean	47.1	46.7
		s.d.	34.0	31.9
		Median	33.1[b,h,j]	34.9[d,h,l]

[a]*Comparison of tooth type/short duration* (H. naledi): z=*-0.740,* p=*0.459*
[b]*Comparison of tooth type/long duration* (H. naledi): z=*-3.546,* p≤*0.001*
[c]*Comparison of tooth type/short duration* (A. africanus): z=*-3.317,* p=*0.001*
[d]*Comparison of tooth type/long duration* (A. africanus): z=*-2.429,* p=*0.014*
[e]*Comparison of source/short duration (incisor*): z=*-0.769,* p=*0.455*
[f]*Comparison of source/long duration (incisor*): z=*-0.520,* p=*0.627*
[g]*Comparison of source/short duration (canine*): z=*-2.774,* p=*0.004*
[h]*Comparison of source/long duration (canine*): z=*-0.140,* p=*0.889*
[i]*Comparison of durations/incisor* (H. naledi): z=*-4.068,* p<*0.00001*
[j]*Comparison of durations/canine* (H. naledi): z=*-0.3584,* p=*0.0003*
[k]*Comparison of durations/incisor* (A. africanus): z=*-1.403,* p=*0.161*
[l]*Comparison of durations/canine* (A. africanus): z=*-2.064,* p=*0.040*

Angle of onset

For this analysis, it is assumed that the steeper the angle of descent into an LEH furrow, the more intense is the felt stress.[37] The angle is calculated from the relationship between width and depth of defect (Table 6). In the overall sample, the distribution of angle of onset is uni-modal and left skewed. Defects are significantly more steeply inclined (i.e. considered more intense) in defects of longer duration (as defined) and in canine teeth. There are no differences in defect angle between taxa. In a comparison of taxa, if one examines only the cervical moiety, there is a statistically significant difference for the incisor teeth (not the canines) apparently as a result of the more steeply inclined defects in *H. naledi* incisors (n=26 *H. naledi*, n=16 *A. africanus*; z=-3.212, p=0.001).

Table 6: Onset angle (tan theta) of linear enamel hypoplasia LEH furrow defects compared between durations, tooth types and taxa

			Angle	
Tooth type	**Duration**		***Homo naledi***	***Australopithecus africanus***
Incisor	Short	*n*	22	16
		Mean	0.044	0.032
		s.d.	0.019	0.014
		Median	0.039	0.027
	Long	*n*	24	7
		Mean	0.057	0.037
		s.d.	0.035	0.017
		Median	0.054	0.038
Canine	Short	*n*	9	16
		Mean	0.052	0.073
		s.d.	0.032	0.048
		Median	0.040	0.062
	Long	*n*	17	6
		Mean	0.085	0.08
		s.d.	0.062	0.024
		Median	0.067	0.076

[a]*Comparison of durations (tooth type and taxa combined):* z=*-2.510,* p<*0.012*
[b]*Comparison of tooth types (durations and taxa combined):* z=*- 4.178,* p=*0.00003*
[c]*Comparison of taxa (durations and tooth types combined):* z=*-1.027,* p=*0.304*

Recurrence: Number of perikymata between defects

Several of the teeth, belonging to both *H. naledi* and *A. africanus*, show fairly regularly spaced furrows that may be signalling a repetitive stressor (Figure 1). However, given the differences in perikymata packing among tooth types and taxa, this impression may well be illusory. The measures of central tendency (and tests of differences of means and medians) for spacing between adjacent LEH expressed as perikymata counts (Table 7) are misleading in that there is bimodality in the data. As may be seen in Figure 3, in the combined sample of tooth types and taxa (n=33) there are two spacing modes: one centred on about 8 perikymata and one on about 23 perikymata. Moreover, it is evident that while canine teeth from both taxa record only the wider spacing, the incisors from both taxa record the narrower *and* the wider spacing modes (Figure 3). I have elected to separate the two modes below and above 12 perikymata (see Figure 3) to recalculate the average number of perikymata (spacing) for each mode separately (Table 7). The sample sizes for each separate tooth type and taxon analytical unit are too small for statistical comparison. After lumping, with modes separated, there are no statistically significant differences in perikymata counts between LEH compared between tooth types and between taxa (Table 7). These results suggest that two spacings, centred on 8 and 23 perikymata, are common to both taxa (not forgetting that there are no canine teeth with narrowly spaced (as defined) LEH in the sample). It is important to note that the great majority (79%) of recurrences are of longer interval, not shorter.

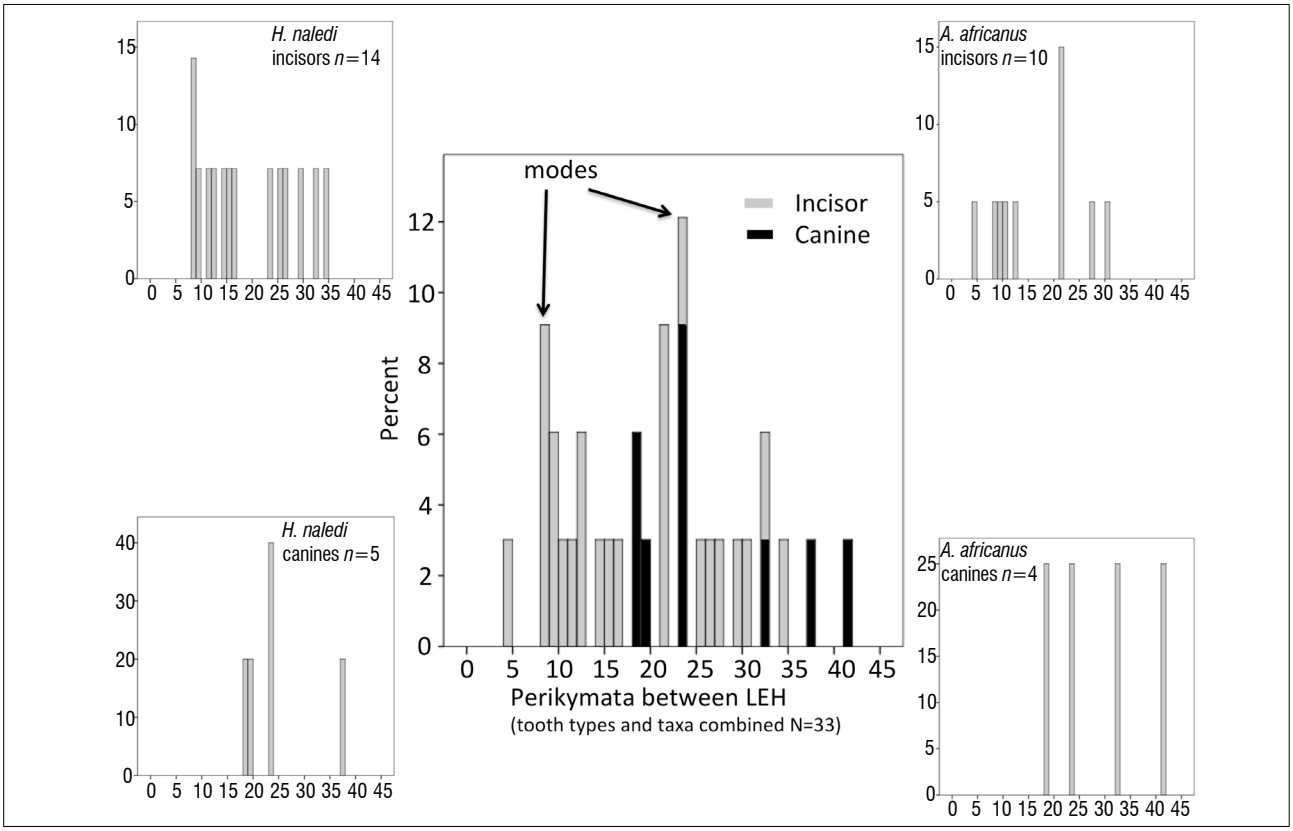

Figure 3: Distribution of perikymata counts between linear enamel hypoplasia (LEH) recurrences compared among tooth types and taxa. In combination, bimodality of recurrence becomes evident. Incisors show short- and long-interval modes of recurrence while canines show only the latter. This difference is attributed tentatively to the relatively later crown formation of canine teeth when the infant is becoming more independent.

Table 7: Number of perikymata (PK) between adjacent linear enamel hypoplasia defects for narrowly and widely spaced modes, compared between tooth types and between taxa; modes are defined on distribution of collective sample

		Homo naledi		*Australopithecus africanus*	
		Mode 1 (≤12 PK)	**Mode 2 (13+ PK)**	**Mode 1 (≤12 PK)**	**Mode 2 (13+ PK)**
Incisor	*n*	3	11	4	6
	Mean	8.3[c]	21.6[a, e]	7.8[c]	22.0[a, e]
	s.d.	0.58	8.29	2.63	6.20
	Median	8.0[d]	23.0[b,f]	8.5[d]	21.0[b,f]
Canine	*n*	–	5	–	4
	Mean	–	24.0[a,, e]	–	28.5[a, e]
	s.d.	–	7.62	–	10.15
	Median	–	23.0[b,f]	–	27.5[b,f]

Comparison of tooth types (Mode 2, combined taxa, n=*17,9):* [a]t=*-1.333,* p=*0.195;* [b]z=*-1.054,* p=*0.292*

Comparison of taxa (Mode 1, combined tooth types, n=*3,4):* [c]t=*0.369,* p=*0.727;* [d]z=*-0.185,* p=*0.857*

Comparison of taxa (Mode 2, combined tooth types, n=*16,10):* [e]t=*-0.708,* p=*0.486;* [f]z=*-0.581,* p=*0.586*

Predicted timings of stress

Duration

The range of Retzius periodicities (RP) reported in the literature can be used to reconstruct probable durations and recurrences of LEH (Table 8). Median values are used in this exercise. *A. africanus* has reconstructed durations of LEH ranging from 24 to 40 days. The actual Retzius periodicity is known (see above) for two *A. africanus* individuals (STW151 RP=8 and MLD11/30 RP=6).[43,44] For these two (ignoring possible redundancy from isomeres from single individuals), average duration =3.8 X 8=30.4 days (*n*=13 LEH in four teeth from STW151) and 3.3 X 6=19.8 days (*n*=6 LEH in two teeth from MLD11/30), respectively.

Earlier it was noted that *H. naledi* (but not *A. africanus*) shows two modal durations. Depending on the appropriate periodicity of Retzius formation, these range from 12 to 20 days and 42 to 100 days. Clearly, the Rising Star assemblage has a large proportion of stressful episodes (about 57%) that lasted a comparatively long time (ca 2+ months) compared to the *A. africanus* sample (ca 1 month) (see above).

Recurrence

Both taxa show bimodal recurrences of LEH: at 1.6–2.8 months *and* 4.3–7.6 months (range reflects optional periodicities (Table 8)). For *A. africanus*, where actual RP is known for two individuals (see above) recurrences occurred at an average of 6.1 months (MLD11/30, *n*=4 LEH) and 1.6 months (STW151, *n*=4 LEH) *and* 6.3 months (STW151, *n*=2 LEH). Recurrent values close to 6 months are reminiscent of LEH recurrences reported for low-latitude ape samples.[6-8]

This unexpected finding can be refined a bit if one allows the simplifying assumptions: (1) that reported modal stria periodicities (see above) prevail in the samples under study here and (2) that incisor teeth, which form relatively early in infancy, will record more shared stress in the

mother/infant dyad than will the canine whose later crown formation is likely to record events impacting only on the older, more self-foraging, infant. For canines alone, using genus-specific modal stria periodicities, the predicted interval between onsets of LEH from perikymata counts in hominins from South Africa is 0.50 years in *H. naledi* and 0.53 years in *A. africanus* (0.51 years for both taxa (n=9 canines)). These tentative impressions, based on small samples, can be tested more fully when actual Retzius periodicities for *H. naledi* become known.

Table 8: Reconstructed timing of defect durations (days) and recurrences (months) based on median perikymata (PK) counts (observed plus predicted in the case of durations); values in bold face font are based on modal periodicities for genus (see text for details). Bimodal intervals are observed in both taxa and countenanced here.

Source	Tooth type	Interval	*n*	PK count within linear enamel hypoplasia (LEH)	Optional periodicities				
					6	7	8	9	10
					Timing in days				
H. naledi	Incisor	Short	22	2.0	12	14	**16**	18	20
		Long	24	7.0	42	49	**56**	63	70
	Canine	Short	10	2.0	12	14	**16**	18	20
		Long	18	10.0	60	70	**80**	90	100
A. africanus	Incisor	–	23	4.0	24	**28**	32	36	40
	Canine	–	23	4.0	24	**28**	32	36	40
				PK count between LEH	Timing in months				
H. naledi		Short	3	8.0	1.6	1.8	**2.1**	2.4	2.6
		Long	16	23.0	4.5	5.3	**6.0**	6.8	7.6
A. africanus		Short	4	8.5	1.7	**2.0**	2.2	2.5	2.8
		Long	10	22.0	4.3	**5.1**	5.8	6.5	7.2

Summary of results

Anatomical features

- There are some significant differences between tooth types and decile moiety in the expression of LEH that have to be controlled when considering apparent differences between taxa.
- Defects of shorter duration (ca 2 perikymata) are naturally shallower.

General findings

- Defects of longer duration (ca 7 perikymata) are more intense (steeply angled).
- There is a bimodal distribution of defect recurrence intervals.
- Longer intervals between recurrences (ca 23 perikymata) are much more common than are short intervals (ca 8 perikymata) *and* are more intense than short intervals.

Comparison of taxa

- The concentrations of LEH in the cervical half of anterior teeth *and* the number of LEH per tooth crown are common to both taxa (*H. naledi* and *A. africanus*).
- *H. naledi* incisors have narrower LEH defects in occlusal moiety (deciles 4–6) and more severe defects in cervical moiety (deciles 7–9).
- *H. naledi* canines have defects that are twice as wide.
- In terms of defect duration, *A. africanus* show a unimodal tendency averaging around 1 month while *H. naledi* show a bimodal distribution averaging about 2 and 8 weeks.
- In terms of recurrence of LEH, both taxa show bimodal recurrences centring on 2 and, more commonly, 6 months.

Discussion

Incisors and the earlier forming parts of anterior tooth crowns, generally, tell a different story than does the later part of canine crown formation. Conceivably, the incisor ameloblasts are more sensitive to stress than are those which form the canine but I am unaware of observations to support such an inference. Rather, because incisors capture earlier commencing incidents in development, incisors will tend to record stress experienced through the mother as well as with its own development; also the younger infant has less developed immunity to disease.

The results for both taxa in this study are unexpected. Controlling for differences between crown moiety and tooth types, the two assemblages show both striking similarities *and* differences in the intensity, duration and recurrence of linear enamel hypoplasia. Firstly, bimodality of stress durations (at ca 2 and 8 weeks, evident in *H. naledi*) and bimodality of recurrence of stressful events (2 and 6 months, evident in both taxa) have not been reported previously. Secondly, the expectation that a single rainy/dry cycle, characterising the annual climate cycle in central South Africa, would produce annually recurrent episodes of LEH in hominins is not supported in this study. These findings will be discussed in turn.

Duration

An explanation for bimodality of durations, demonstrable in *H. naledi* but not in *A. africanus*, has to be sought. Just as a reminder, defects of shorter duration are less severe (low onset angle) while those of longer duration tend to be steeper. A single type of stressor would not be likely to produce such a pattern whereas two different types of stress might do so. For example, invocation of disease stress lasting about 2 weeks versus, for example, seasonal stress lasting about 8 weeks would seem reasonable but raises the question of why *H. naledi* would show this pattern while *A. africanus* does not. However, the reconstructed difference of about 12 days in duration (see Table 8) compared between *A. africanus* and the 'short duration' mode in *H. naledi* is probably trivial which, then, changes the question to simply why only *H. naledi* experienced sustained seasonal stress.

Recurrence

The median number of perikymata between 'longer interval' recurrences of LEH, combining tooth types to generate large enough samples for analysis, is 22 for *H. naledi* and 23 for *A. africanus*, a statistically insignificant difference. Employing modal periodicities for stria formation, the average time between defects among both South African hominins is very close to 6 months which does not fit well with the annual temperature and rainfall cycle of central South Africa. There are four possible explanations for the inference of semi-annual recurrence of stress among hominins from this latitude:

1. The finding is only a statistical artefact. However, I simply cannot think of how this result, reported to occur commonly in Indonesia[7] and in central Africa[5] and, now in this study, southern Africa, would be generated by chance.
2. Annual cycles of temperature and moisture, which increase and then decrease, may create two optimum thresholds for eclosion and oviposition/biting of disease-causing insects. For example, both dengue and malaria show twice-yearly occurrence in Vietnam with only a single annual rainy peak.[51,52] Similarly, malaria recurs twice a year in southern China with only a single annual moisture cycle.[53,54] Such an explanation fails to explain the difference in duration of stress between the two assemblages reported here.
3. There prevailed in this location in South Africa, phenological or meteorological phenomena that created physiological stress semi-annually of which we are unaware. Some Cape Peninsula baboons

spend more time feeding and less time resting in the summer but are more reliant on energetically costly subterranean resources in the winter, suggesting that both summer and winter seasons are times of relative food scarcity.[55] However, such an explanation for the pattern observed in this study seems unlikely given the similarity of the observed inter-LEH interval to that observed in most, but not all, low-latitude apes.

4. The value is real but is a result of the existence of two unrelated stressors, each of which has an annual cycle. For example the interaction of three environmental variables (rainfall, temperature and vegetation) in Burundi, each with an annual cycle, creates semi-annual incidence peaks in malaria.[56] In such a scenario, one might assume that the stressors would be of different types and, as it would seem unlikely that two different stressors would occur for the same duration and with the same intensity, one would expect defect measurements to show bimodality. Indeed, as has been observed in this study, durations are bimodally distributed and 'longer durations' are more steeply angled (inferably, more intense). Support for the inference of independence can be found in the observation that exactly 50% of long interval recurrences (13/26) link with each of short and long duration LEH events.

Of these alternatives to explain semi-annual recurrence of stress, the last seems most likely; that is, invocation of two independent stressor types, each with an annual cycle. For example, a combination of independent annual cycles of short-term disease stress and longer-term seasonal stress could explain the pattern of LEH in *H. naledi* and *A. africanus.* In terms of climate, this could translate into winter and summer stressor types. It is not difficult to suggest candidates for seasonal stress. Winter stress would seem quite likely, e.g. at Sterkfontein, minimum cold temperature averages 3 °C in the austral winter months (June and July) and can go below freezing (www.meteoblue.com). At 3 °C, a wind of only 6 km/h creates a wind chill below freezing.[57] Chacma baboons on the southern coast of South Africa, exposed to average minimum temperatures of 3 °C in the austral winter, show elevated cortisol levels, indicating physiological stress.[58]

Temperature regulation in the infant of a small-bodied hominin like *H. naledi*[31] exposed to such conditions would indeed be a challenge and would predispose to respiratory disease. Respiratory disease is acknowledged to be the second-most common cause of mortality and morbidity in mountain gorillas[59] and common in Tai Forest chimpanzees[60,61]. Human influenza season in South Africa is well defined and peaks in the austral winter months[62] while most hospital admissions for paediatric diarrhoea occur in austral summer at the height of the rainy season[63].

Conclusions

The discovery of *H. naledi* in the same geographical area as *A. africanus* has created an opportunity to evaluate the temporal patterning of developmental dental stress in higher latitude hominins with low latitude apes among whom LEH tends to recur on average at intervals of 6 months, or multiples thereof, linked it is thought to moisture cycles influencing the likelihood of disease and/or malnutrition. It was predicted, as a null hypothesis, that stress would tend to recur annually in the South African hominins and would be of similar duration in both taxa. Neither expectation is borne out. In terms of duration, *H. naledi* shows bimodal durations of stress centred on 2 and 8 weeks while *A. africanus* shows unimodal duration of stress centred on 4 weeks. Canine stress lasted significantly longer in *H. naledi* than in *A. africanus*. In terms of recurrence, stress tended to recur bimodally every 2 months (less common) and 6 months (more common) in both fossil assemblages. These results, while tantalising, await confirmation from studies of Retzius periodicity in the *H. naledi* specimens and refined understanding of comparative palaeoenvironments and climate for *H. naledi* and *A. africanus*.

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A comparison of hominin teeth from Lincoln Cave, Sterkfontein L/63, and the Dinaledi Chamber, South Africa

Prior to the recovery of *Homo naledi* from the Dinaledi Chamber of the Rising Star Cave system, the Middle Pleistocene fossil record in Africa was particularly sparse. With the large sample size now available from Dinaledi, the opportunity exists to reassess taxonomically ambiguous teeth unearthed at the nearby site of Sterkfontein. Teeth recovered from Lincoln Cave South and area L/63 at Sterkfontein have been considered 'most probably *Homo ergaster*' and 'perhaps Archaic *Homo sapiens*', respectively. Given the similarities shared between Lincoln Cave, area L/63, and the Dinaledi Chamber with regard to climatic/geologic depositional context and age, two teeth from the former sites, StW 592 and StW 585 respectively, were compared with corresponding tooth types of *H. naledi* from the Dinaledi Chamber. The results of our study indicate that the Lincoln Cave and area L/63 teeth are morphologically inconsistent with the variation recognised in the *H. naledi* teeth.

Significance:

- The similar age and climatic/geologic depositional and post-depositional circumstances at Lincoln Cave South, area L/63 at Sterkfontein and the Dinaledi Chamber, Rising Star raise the possibility that these fossils might represent the same species.
- The teeth StW 592 and StW 585 are not consistent with the variation evident in the known *H. naledi* sample.
- The results of the study do not add to the question of the existence of at least two species of the genus *Homo* living in close proximity to each other in South Africa at approximately the same time.

Introduction

Lincoln Cave is located in the Lincoln-Fault Cave system adjacent to the Sterkfontein Cave system.[1] The deposit is divided in two by an old ramp made by limestone miners.[2] One section, dubbed Lincoln Cave North, consists of calcified deposits while Lincoln Cave South is uncalcified. The cave dates to between 252 600±35 600 and 115 300±7700 years ago based on uranium series dating of flowstones.[3] This range of dates has taken on new significance because of the discovery of *Homo naledi* within the nearby Rising Star Cave system, only 2 km from Sterkfontein, dated to between 335 000 and 236 000 years ago.[4,5] If these teeth could be attributed to *H. naledi*, they would show this species in a second cave context.

Excavations at Lincoln Cave began in 1997 and yielded fauna, artefacts and hominin remains.[2] Three hominin teeth have been recovered from Lincoln Cave South: StW 591 is an unerupted permanent left upper first incisor, StW 592 consists of an unerupted left maxillary first molar, and StW 593 is a lower right first incisor.[1] Reynolds et al.[3] suggested that these specimens represent *H. ergaster*. These researchers argued that the fauna and hominin dental material in Lincoln Cave may have resulted in part from the erosion of older Member 5 sediments and redeposition of some of this older fossil material 'into younger infills together with younger artifacts and fauna'[3]. If true, the teeth may be more than 1.5 million years old.

L/63 is an area of the Sterkfontein Cave system that consists of intrusive sediments that separate Member 5 East and West.[2] While Reynolds et al.[3] state that it lacks datable materials, the deposit differs from the surrounding Acheulean breccias and includes fauna suggesting that it includes younger material. That paper noted similarities in stratigraphy, fauna, and artefacts in L/63 and Lincoln Cave South, and proposed that the two deposits 'derived from the same catchment area'[1-3]. StW 585, a right maxillary canine, was recovered from L/63. This tooth is attributed to 'Archaic *Homo sapiens*' based on the short length of the root.[3(p.267)]

The Dinaledi Chamber in the Rising Star Cave system lies approximately 2 km from Sterkfontein and, at 335–236 Ka,[4,5] partially overlaps in time with the Lincoln Cave and L/63 deposits. *Homo naledi* was recovered in uncalcified deposits. The presence of uncalcified deposits in Lincoln Cave South and L/63 may indicate that younger material in these infills may share some aspects of geological history with the Rising Star deposits. Given the possibility that these deposits could potentially be contemporaneous, we carefully assessed whether the dental remains from Lincoln Cave and L/63 represent *H. naledi*. The present research details the similarities and differences between StW 585, StW 592, and specimens attributed to *H. naledi.*

Materials and methods

StW 585 was directly compared with the *H. naledi* maxillary permanent canines from the Dinaledi Chamber at the University of the Witwatersrand. StW 592 was compared with *H. naledi* maxillary first molars based on the description, image and measurements presented in Reynolds et al.[3] StW 591 and StW 593 were not available for study.

Results

StW 585 and the *H. naledi* maxillary permanent canines from the Dinaledi Chamber differ in significant ways. Lingually, StW 585 has a large tuberculum dentale (ASU grade 3) while *H. naledi* does not (Figure 1). The median lingual ridge of StW 585 divides the crown into small mesial and large distal fossae; the pattern is reversed in the *H. naledi* canines. While the distal crest of StW 585 is convex, it is less convex than that of *H. naledi*. StW 585 is

more mesiodistally curved, i.e. the mesial and distal crown edge curve inward toward the midline of the tooth, more than *H. naledi* specimens such as U.W. 101-337 (Figure 2). The crown of StW 585 is short and robust relative to its overall size while *H. naledi* canines appear tall (Figure 2, Figure 3).

Figure 1: Lingual view of StW 585 from L/63 area of Lincoln Cave (centre) and *Homo naledi* maxillary permanent canines from the Dinaledi Chamber. Left to right: U.W. 101-337 RC, U.W. 101-908 RC, StW 585 RC, U.W. 101-501 LC, U.W. 101-412 LC. Arrow shows large tuberculum dentale of StW 585.

Figure 2: Labial view of StW 585 from L/63 area of Lincoln Cave (centre) and *Homo naledi* maxillary permanent canines from the Dinaledi Chamber. Left to right: U.W. 101-337 RC, U.W. 101-908 RC, StW 585 RC, U.W. 101-501 LC, U.W. 101-412 LC.

Figure 3: Mesial view of StW 585 from L/63 area of Lincoln Cave (centre) and *Homo naledi* maxillary permanent canines from the Dinaledi Chamber. Left to right: U.W. 101-337 RC, U.W. 101-908 RC, StW 585 RC, U.W. 101-501 LC, U.W. 101-412 LC.

The StW 585 and *H. naledi* canines do share several traits, including, lingually, a mesial crest that is shorter than the distal crest, and a mesial shoulder that is more apically placed than the distal shoulder (Figure 1). The labial face is minimally curved incisocervically in both StW 585 and *H. naledi* (Figure 3). All have a mesial crest that is more concave than the distal counterpart. Also, the mesial and distal labial grooves are weakly expressed in all canines. A deep groove runs along the mesial length of the root, with a shallow groove along the distal length. StW 585 falls within the absolute size range of variation for *H. naledi* (Table 1). While root length is not a conclusive feature for determining species, StW 585 overlaps in size with the *H. naledi* sample.

Table 1: Measurements (in mm) of maxillary canines used in this study

C^1 Specimens	Mesiodistal	Labiolingual
StW 585	8.5	9.5
U.W. 101-337	7.8	8.3
U.W. 101-347	8.0	9.6
U.W. 101-412	8.7	8.4
U.W. 101-501	7.8	8.4
U.W.101-504B	7.3	
U.W. 101-706	8.5	8.2
U.W. 101-816	8.7	8.0
U.W. 101-908	8.9	8.7
U.W. 101-1277	7.9	8.2
U.W. 101-1548	7.3	
U.W. 101-1566		9.8

Homo naledi maxillary first molars (i.e. U.W. 101-1305 and U.W. 101-1688) were compared with StW 592 from Lincoln Cave South using data from Reynolds et al.[3] StW 592 has a prominent C5, while *H. naledi* maxillary first molars lack a C5 or other accessory cusps (Figure 4). The crista obliqua is continuous between the protocone and metacone in *H. naledi*, unlike StW 592. The StW 592 crown is larger than all *H. naledi* upper first molars (Table 2). Finally, StW 592 exhibits a more 'bulbous' morphology relative to *H. naledi* U.W. 101-1305 or U.W. 101-1688. These differences suggest that StW 592 is not *H. naledi*.

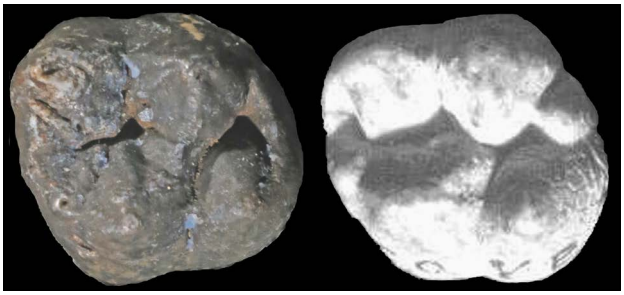

Figure 4: Occlusal view of *Homo naledi* U.W. 101-1305 (left) and StW 592 from Reynolds et al.[3]

Despite these differences, StW 592 and *H. naledi* first molars share a similar size gradient of the principal cusps: protocone > hypocone > metacone = paracone. In addition, occlusal outlines of the StW 592 and *H. naledi* molars are rhomboidal with a distolingual projection of the hypocone.

Table 2: Measurements (in mm) of maxillary first molars used in this study

M^1 Specimens	Mesiodistal	Buccolingual
StW 592	12.3	12.9
U.W. 101-020	11.4	11.6
U.W. 101-445	12.1	11.5
U.W. 101-525	11.5	11.6
U.W. 101-583	11.7	11.8
U.W. 101-708	11.6	11.6
U.W. 101-999	12.1	11.8
U.W. 101-1277	10.5	11.2
U.W. 101-1305	12.3	11.8
U.W. 101-1396		12.4
U.W. 101-1463	11	11.6
U.W. 101-1676	11.7	12.2
U.W. 101-1688	12.4	12

Discussion

Prior to the discovery of *H. naledi*, hominin material from the Middle Pleistocene of southern Africa was universally assumed to represent archaic humans.[6] However, the fragmentary state and poor geological context of the record between 780 Ka and 130 Ka in southern Africa means we must re-evaluate this assumption for all material. In our assessment, the teeth from Lincoln Cave South and L/63 do not fit the morphological pattern of known samples of *H. naledi.* The range of dates from the Dinaledi Chamber, between 335 Ka and 236 Ka, overlaps with the range of dates of flowstone from Lincoln Cave, between roughly 253 Ka and 115 Ka. However, the flowstones may not date the fossil-bearing deposits. We note the conclusion of Reynolds et al.[3] that the Lincoln Cave South and L/63 teeth may have been redeposited from much older Member 5 deposits, which prevents us from concluding that these teeth demonstrate a second, contemporaneous lineage in close proximity to *H. naledi*. With such redeposition and uncertainty of context, it is possible that the teeth do in fact represent a much earlier population of *Homo*. With that said, it is important to keep in mind that this research only examined one tooth from Lincoln Cave and one from area L/63. The recovery and availability of more fossils from Sterkfontein or other sites from this time frame with strong geological context may aid in understanding the normal variation of each tooth type and help resolve the nature of the evolutionary relationship between them and *H. naledi*.

Conclusions

The large sample of *H. naledi* teeth from the Dinaledi Chamber allows us to take a closer look at taxonomically ambiguous fossils from Sterkfontein to determine their similarities or differences. The Lincoln Cave and L/63 teeth, despite some parallels in depositional and post-depositional contexts, are inconsistent with known samples of *H. naledi*. If there is overlap in time, the results would suggest that more than one species of *Homo* was present in the Late Middle Pleistocene of South Africa. If not, the Lincoln Cave and L/63 teeth may represent an earlier species of *Homo*. Unfortunately, given the uncertainty of the dates, at present the Lincoln Cave and L/63 teeth offer little support for either scenario.

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Authors' contributions

J.K.B.: Conceptualisation, methodology, data collection, writing – the initial draft. J.I.: Conceptualisation, methodology, data collection, writing – the initial draft. S.E.C.: Conceptualisation, writing – the initial draft. D.J.d.R.: Methodology, validation, writing – revisions. J.H.: Conceptualisation, validation. L.R.B.: Conceptualisation, validation, project leadership, funding acquisition.

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