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120 years

volume 120
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Africa's sparse bat fossil record

Climate finance across sub-Saharan Africa

A novel therapy for breast cancer patients

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A Mauritian tomb bat (*Taphozous mauritianus*). In an article on page 11, Mariette Pretorius asks why bat fossils in Africa are so rare, and how this rarity impacts our understanding of modern bats and their conservation.

Image: ©*skvorpahl on iNaturalist* (*CC-BY-NC*)

Working across disciplines: Robust debate in a context of trust

Search through the pages of the *South African Journal of Science*, and you will find hundreds of articles using the word 'interdisciplinary' and its variants, and the references to interdisciplinarity are almost invariably positive. Indeed, in the mission of the Journal (https://sajs.co.za/about) we describe the Journal as 'multidisciplinary' in its nature, and we have often in editorials and elsewhere referred to scientists from a range of disciplines working together.

Leaving aside the complex (and, paradoxically, often abstruse) arguments about the differences between interdisciplinarity, multidisciplinary, and transdisciplinarity, our Journal is part of a large consensus in which we need many ways of tackling difficult and complex problems, and none of us can provide the single 'right' answer to any of these. Especially in a fraught, divided and very unequal society, there is almost inevitably a social component to every technical problem, for example.

Our commitment to working and communicating across disciplines can be frustrating to potential authors and reviewers. We do not publish excellent work which is accessible only to a small disciplinary section of our readership. A number of emerging scholars have been, we fear, disheartened when their high-quality work is rejected, not because of concerns about the quality of the science, but because of the lack of accessibility to a non-specialist educated audience. Some authors have been trained to express their work using rather abstruse phraseology and syntax that is difficult to understand. Our Journal is certainly not the only one internationally committed to clear, plain, language usage (see https://sajs.co.za/inclusive-language-policy), but with an interdisciplinary journal, the bar is probably higher than with other journals, because words and usage conventions which are common currency in one discipline may not be familiar to readers in other disciplines.

Working across disciplines is also challenging for our editorial team. Each editor-in-chief comes from a particular disciplinary background, and it is not possible for this person, however competent, to assess fully the scientific quality of every submission. We are fortunate to have a team of very well-qualified associate editors and associate editor mentees, all of whom are subject specialists, and it is common at our Journal for the editor-in-chief to ask the appropriate associate editor for advice about whether to send a submission for review. Sometimes this process is even more complicated when we involve two or more associate editors in discussion before taking a decision about how best to handle a submission. This requires teamwork and coordination, and on reasonably rare occasions we have to ask for help from experts outside our small team if we do not have all the expertise. This takes effort – including anonymisation of submissions, confidentiality agreements, and so on, even before we decide on peer reviewers. It is simply not possible to have an editorial team which is expert in every possible sub-discipline which may be the home sub-discipline of a potential contributor.

At our Journal, we are fortunate to have good relationships within our team, so we are able to consult one another. This includes notionally less 'senior' colleagues, such as associate editors, informing notionally more 'senior' colleagues, such as the editor-in-chief, that they are wrong. In an ideal world, robust and open debate is at the heart of good science – we move forward as scientists and as a scientific community by changing our minds, adjusting to new evidence and techniques. But there is an interpersonal element to this, and this is the element of trust. In order to differ openly with a colleague, one has to have the confidence that this expression of difference will not be seen as vexatious, undermining, rude, or inappropriate.

This need for trust in interdisciplinary relationships and research is not just a question for a journal like ours – it is essential for all research partnerships across disciplines. It is easy to speak about interdisciplinary respect and trust, but there can be challenges in attaining it. Many researchers have been trained to lionise their own disciplines and to denigrate others. For example, there are quantitative researchers who have been trained to consider all qualitative data as 'mere anecdote', just as there are qualitative researchers who have been trained to see their own work as 'deep' and 'careful', with the implication being that the work of quantitative researchers is of necessity superficial and conducted without due care. It is unfortunately the case that there are indeed many qualitative researchers whose work could fairly be characterised as merely anecdotal, just as there are many quantitative researchers who conduct superficial and slapdash work. There are bad researchers in all disciplines. But stereotyping researchers from other disciplines as the 'other' is not helpful.

But there are other, perhaps less obvious, dangers. Just as it is not helpful *a priori* to decide that work from Discipline X is inferior or useless, it can be equally problematic for interdisciplinary research to take the opposite view – that work from Discipline X is inevitably good and helpful. Interdisciplinary respect is much more challenging than simply declaring that the work of colleagues in other disciplines is good, even when, and possibly especially when, one does not fully understand the methods used by those from other disciplines. There has to be space both for challenging interdisciplinary questions and for frank discussions about methods and conclusions. In the end, it may not be fully possible to understand what a colleague from another discipline has done, as it may take full academic training in that discipline to understand the colleague's assumptions and methods. But asking questions across disciplines is important, and being prepared to try to answer questions across disciplines is equally important. It is not respectful simply to take for granted that another researcher must be right just because their work is not immediately understandable across disciplines. Disciplinary defensiveness may be more common in disciplines of 'lower status' than others, although I am unaware of good data to support this supposition, but disciplinary defensiveness (as opposed to standing up for and explaining the strengths of an approach one is taking) may close down debate and may well be bad for interdisciplinarity.

In an academic world in which competition across disciplines and amongst scientists is commonly encouraged, in a world in which many of us compete for the same resources, the temptation either unfairly to denigrate the other or to praise the other without robustly interrogating their work, are two sides of an unhelpful coin. Academic conflict, furthermore, can both flourish and be inappropriately avoided in a divided and high-conflict society. We believe that it is the collective responsibility of all researchers to keep real, robust, debate going. This takes trust both in others and in the academic system which sustains us all.

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Hoosen (Jerry) M. Coovadia (1940–2023): Caring paediatrician, excellent scientist, courageous human rights activist and visionary leader

On 4 October 2023 the world mourned the loss of a caring paediatrician, an excellent scientist, a courageous human rights activist and a visionary leader. Professor Hoosen Mohamed Coovadia, fondly known as 'Jerry', was an exceptional and rare human being who blessed many lives – as a mentor, role model, colleague, and dear friend. He was an extraordinary human being who stood steadfast and unwavering for truth and justice, regardless of personal sacrifices and consequences. We have said goodbye to one of South Africa's greatest scientists and staunchest proponents of democracy and equality. He stood well above others in his integrity and unwavering commitment to a just world.

South African President Cyril Ramaphosa said in a statement:

> *Our nation's loss will be felt globally, but we can take pride at and comfort from the emergence of a giant of science and an icon of compassion and resilience from our country.*

Like many whose lives Professor Coovadia touched, one was left deeply impressed by his incisive and profound contributions to both scientific and political discussions. He was an unparalleled intellect and leader who never compromised on anything less than world-class excellence. As an academic, he always had so much to share, teach and instil in eager, young minds and the number of outstanding medical students, paediatricians and scientists he nurtured and graduated are a testament to his life-changing mentorship and leadership. His passion for science and the way he effortlessly transformed complex medical challenges into a series of achievable research questions was truly inspiring. His inimitable curiosity and systematic approach did not compromise on the robust rigour that he applied equally in the way he cared for his young patients. As a mentor, he set a high bar, repeatedly pushing the boundaries of knowledge and expecting no less from his mentees. He was consistently magnanimous with his guidance and generous with the time he committed to nurturing, advising and supporting each and every one of his students. I was truly blessed and privileged to have him as my mentor for almost 35 years and I owe much of my success to his wise guidance and to being an inspiring role model on how to serve humanity with humility and equanimity. The respect and warmth he gave to his students resulted in lifelong friendships that extended to their entire families and often included multiple generations. His textbook *Coovadia's Paediatrics and Child Health*, now in its 8th edition, is the go-to reference for thousands of medical students and paediatricians across Africa and in other low- and middle-income countries.

His passion for science was matched by his passion for freedom and justice for all. His prominent role in the struggle for a democratic South Africa and his principled stand against non-racialism were consistent with his character and with his always speaking to truth and doing what was morally the right thing to do.

Although he started his medical studies at the University of Natal in South Africa, he completed his medical degree in the 1960s at Grant Medical College in Bombay, where he met his lifelong partner and wife-to-be, Dr Zubie Hamed. Upon his return to South Africa following graduation, he worked at King Edward VIII Hospital and subsequently joined the Department of Paediatrics at the University of Natal Medical School, where he specialised in paediatrics and became a Fellow of the College of Paediatricians of the College of Medicine of South Africa in 1971. In 1974, he obtained his MSc in Immunology from the University of Birmingham in the UK.

It was his time at Grant College that was pivotal in terms of his political conscientisation. He was instrumental in forming a political body called the South African Students Association, which invited members of the African National Congress in exile, such as Dr Dadoo, to address them on freedom and the anti-apartheid movement. He was one of the key figures to rekindle the Natal Indian Congress in the 1970s and was subsequently elected its vice-president. In the 1980s, he was a key player in launching the United Democratic Front.

Politics and health were two sides of the same coin for him. He fought for equitable health care and was a founding member of the National Medical and Dental Association (NAMDA), which was set up by progressive doctors following the Medical Association of South Africa's complacency regarding the doctors who were complicit in Steve Biko's death.

He was formidable as an anti-apartheid activist – strategic and penetrating in his analysis of the tactics needed to advance the struggle for freedom. In the 1980s, he was part of a delegation to meet the African National Congress in Lusaka prior to the organisation being unbanned. He took part in the preliminary discussions and negotiations at the Congress for a Democratic South Africa (CODESA). As a result of his political activities, Professor Coovadia was targeted by the apartheid regime – his house was bombed during the political turbulence in the early 1990s, but he remained steadfast and undeterred from his commitment to a just and free South Africa.

Professor Coovadia's research contributions on the effects of poverty and malnutrition on child survival and development included the definitive work on nephrosis in black South African children, malnutrition and immunity, and measles. His research focus pivoted to paediatric HIV/AIDS in the early 1990s as he started to witness the unfolding tragedy in his paediatric wards at King Edward VIII Hospital in Durban. His particular focus was the transmission of the virus from mother to child, a field in which he challenged conventional wisdom about breastfeeding and became nationally and internationally recognised for his groundbreaking research on saving babies' lives by reducing HIV transmission from mother to child through exclusive breastfeeding.

Source: CAPRISA archives

Professor Jerry Coovadia fought for equitable health care and was a founding member of the National Medical and Dental Association (NAMDA).

He was appointed Chairperson of the inaugural Scientific Advisory Board to the Ministry of Health's National AIDS Programme established post-1994 and he served as the first international co-chair of the US National Institutes of Health Global Paediatric Network for AIDS research. His international stature in HIV/AIDS led to him being appointed as Chairperson of the XIIIth International AIDS Conference in Durban in July 2000. This conference is widely credited for expediting access to AIDS treatment in poor countries. It brought him national and international accolades but also resulted in clashes with some prominent government figures at the time, especially President Mbeki and Minister Tshabalala-Msimang. He undauntedly stood up to these AIDS denialists. Despite being vilified by some for his clashes with the President, Professor Coovadia persisted in speaking truth to power regardless, never faltering.

His leadership role in numerous national and global expert committees on health following his retirement as Chair of the Department of Paediatrics, including as President of the South African Medical Association, is a testament to his invaluable academic contributions. He was appointed the Victor Daitz Chair in HIV/AIDS Research, and Director of Biomedical Science at the Centre for HIV/AIDS Networking (HIVAN) at the Nelson R Mandela School of Medicine, University of Natal, and thereafter to the leadership of the Centre for the AIDS Programme of Research in South Africa (CAPRISA). In 2010, he was appointed to the government's National Planning Commission to guide the development plan of South Africa. He spoke extensively on South Africa's need for a National Health Service, with National Health Insurance as a stepping stone, being built on the foundations of primary health care. An unfinished dream he had was of restoring the abandoned Addington Children's Hospital on the Durban beachfront to the KwaZulu-Natal Children's Hospital of Excellence for the care of children with special health needs.

Professor Coovadia was the recipient of numerous distinguished and prestigious accolades and awards including the Star of South Africa and the Nelson Mandela Award for Health and Human Rights for his contributions to democracy and health. He received honorary doctorates from the Universities of Durban-Westville, Witwatersrand and Cape Town. He is one of a handful of South Africans to be elected as a Foreign Member of the US National Academy of Medicine. He received the Science-for-Society Gold Medal award of the Academy of Science of South Africa; the American Association for the Advancement of Science Scientific Freedom and Responsibility Award; a Lifetime Achievement Award during the HIV Congress in India; a Silver Medal for Excellence in Research (Medical Research Council); the SAMRC Presidential Award; the International Association of Physicians in AIDS and Care Award; and the Heroes in Medicine Award in Toronto, Canada.

Professor Coovadia was a patriot; he was deeply committed to a better and more just South Africa. He was a fierce critic of maladministration and corruption in government and was vocal about how he felt that the struggle for a free and just country was being jeopardised by greed and incompetence. A few years ago, he developed weakness in both limbs, which progressively deteriorated until he became wheelchair-bound. Notwithstanding his health challenges, he remained in good spirits and those who visited him benefitted from engaging in conversations on life, literature, global politics and new developments in science.

In an interview with the Academy of Science of South Africa in 2017, when asked what people don't know about him, Coovadia responded: "Despite some corroding bourgeois proclivities, I remain at heart and in mind, an adherent of equity and fairness in all things meaningful — justice for the poor and the elimination of poverty."

We pay tribute to his wife Dr Zubie Hamed, son Professor Imraan Coovadia and daughter Dr Anushka Coovadia, their children and his extended family for their support during his many years spent fighting for social justice and establishing a strong science base in South Africa.

We have lost a visionary who remained forever hopeful that South Africa would be a great country, one who cared for the poor and most vulnerable, notably its children. We have lost an icon in the world of medical science, unwavering in his commitment to saving lives through his research. We have lost a giant who towered above others in his steadfast and unwavering integrity and compassion. His demise has left us with a deep sense of loss, but his legacy lives on in all the lives he touched.

Hamba kahle Professor Jerry Coovadia.

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Statues and storms: Leading through change

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The storms facing higher education have not abated

Spare a thought for Max Price, who had a successful first term as Vice-Chancellor of the University of Cape Town (UCT) from 2008 to 2013. He knows his onions, visited departments regularly and was popular with academic staff: his contract was renewed for a second term. Until Chumani Maxwele threw poo on Rhodes' statue soon after the start of the second term in 2015, Price could not have foreseen that the time was out of joint.

Statues and Storms is the account of his torrid time over the next three years, during which Price was assaulted, had his laptop snatched and his office fire-bombed. The book is well written and well edited – editor Russell Martin excised a third of the original text, although Price "still thinks every word of it should have been retained."

There is little to fault Price's handling of events during the first year of the crisis in 2015. Although he had ignored Rhodes' gaze for nearly eight years, he was not the first vice-chancellor to do so. But since its removal in April 2015 the statue has not been missed, and perhaps one day it will be displayed elsewhere, appropriately contextualised. A second demand, the in-sourcing of workers, redressed (at least to some extent) the shameful manner by which they had been outsourced in the late 1990s.

The third – and least tractable – demand was a national one for free higher education. Here government, having faced off national demonstrations both outside parliament and at the Union buildings, had set up yet another commission, this time under retired Judge Heher, to investigate it.

Then, at the beginning of 2016, things spun out of control. Price found himself unable to set clear boundaries with a tiny group of students that threatened to disrupt campus life in a violent manner (it was unclear how much support this group commanded as it did not comprise elected representatives, but very clear that it espoused a particularly toxic form of racial identity politics). In not doing so, as Nicoli Nattrass perceptively remarks[1], Price "was legitimising a politics of racialised offence". Combined with his conspicuous lack of any successional planning, this has been his legacy to UCT.

Price's book is remarkable for its lack of humility. With the certainty of a colonial administrator, he justifies his every turn, claiming that his leadership blazed a trail for institutions both here and abroad. What is unclear is how his strategy is reconcilable with his articulated view (p. 280): "In a society where the laws are unjust, civil disobedience, i.e. unlawful behaviour, may be justified. Today, we live in a constitutional democracy in which the majority can exercise their voices without resorting to civil disobedience."

For a seasoned campaigner he also reveals a curious naïveté, for example in appearing disappointed when the Heher Commission did not report in time, and more so when government discarded its recommendations altogether.

Really? Wishing away pragmatic solutions had become a favourite pastime of Minister of Higher Education Blade Nzimande (the real villain of the piece), who had ignored a report on the feasibility of free higher education chaired by former Nelson Mandela University Vice-Chancellor Derrick Swartz.[2] And Nzimande had also shelved two related reports: on the future of university funding (chaired by none other than Cyril Ramaphosa); and a review of the National Student Financial Aid Scheme (NSFAS), chaired by Marcus Balintulo, former Vice-Chancellor of Walter Sisulu University.

Price does not provide much scholarly examination of the deeper issues underlying the protests – for this readers can turn to David Benatar's *The Fall of UCT*, although Ronelle Carolissen has noted that it lacks context on the corporatisation of universities this century.[3]

It seems unclear to Price why he appeared as the embodiment of this corporatisation, but it is in this context that his account is instructive. This century South Africa has experienced a large expansion in student numbers, together with below-inflation subsidy increases, leading inevitably to fee increases well above inflation.

David Attwell, also reviewing Benatar's book, makes another crucial point about context[4]: "For local students, the venality of state capture and corruption, the very real prospect of state failure, has opened up a profound moral abyss. We have a democratically elected government that is failing."

Both criticisms apply equally well to Price's book. In this context, a general decline in institutional loyalty is unsurprising. In particular, many black students attending historically advantaged institutions experience a feeling of alienation to the point that little respect for institutional culture or infrastructure exists. The challenge to our universities is to re-build that loyalty.

Beyond Price's legacy to UCT, that of #FeesMustFall has been of profound national significance. In December 2017, campaigning to be re-elected as ANC President, Zuma announced that government had rejected the Heher recommendations (an income-contingent loan scheme, loans being recovered by the South African Revenue Service once the graduate's income reaches a certain threshold). Instead it would provide fees and maintenance grants (as opposed to loans) to university students with a household income below ZAR350 000 per annum – almost doubling the previous threshold of ZAR180 000.

Ramaphosa chose to implement this, and the consequences have not been trivial. The NSFAS budget has risen more than threefold (from ZAR15 billion to ZAR50 billion) between 2017 and 2023.[5] NSFAS now receives 53% of the higher education budget, with the country's 26 public universities receiving the

remainder in subsidies. The original problem – above-inflation fee increases – has not been resolved.

Free university education might be affordable if student numbers were capped – no bad thing if this were to be matched by a significant expansion in the vocational training component of our higher education system. The principle that the state should set the number of subsidised university places nationally in each discipline was adopted in the 1997 White Paper on Higher Education.[6] Twenty-six years on we are still awaiting the implementation of this policy. What remains of the NSFAS, once corruption has claimed its share, has instead become a social grant for young people, the majority of whom sadly never graduate.[2]

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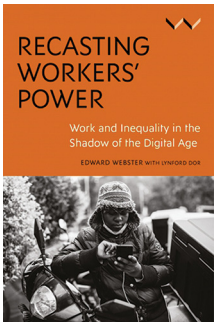
BOOK TITLE:
Recasting workers' power: Work and inequality in the shadow of the Digital Age



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From casting to recasting: Reviewing the *Recasting of Workers' Power*

In 1985, Eddie Webster's book entitled *Cast in a Racial Mould: Labour Process and Trade Unionism in the Foundries*[1] was published by Ravan Press. Among many other things, the book discusses how iron and steel moulds of the East Rand near Johannesburg cast or divided workers according to their skin colour, where white workers and their unions had to struggle over many years to defend and advance their privileges at the workplace. On the other hand, the book, which became one of the critical knowledge foundations of Labour Studies in South Africa and the world over, demonstrates how black workers in South Africa's metal sector were able to cast their net wide by building a trade union called the Metal and Allied Workers Union (MAWU), which became the shield and spear of black metal workers.

Webster and his team's most recent book, *Recasting Workers' Power: Work and Inequality in the Shadow of the Digital Age*, reveals how work and the labour processes have changed since the 1990s (p. ix–xiv). The recent book analyses and discusses an entirely different world of work from that in the 1980s. The resistance workers 'cast in a racial mould' were the black industrial proletariat, who were often regarded as blue-collar workers who were the core of the workforce that confronted what von Holdt[2] characterised as the "apartheid workplace regime". The militant layer's political and organisational leverage waned as the manufacturing sector declined in the 1990s.

In some ways, the "recasting of workers' power" is about the second phase of workers' power since the 1970s and the 1980s. A new social force is being born to replace the old one. The changing nature of work, the deepening oppression of workers, and the weaknesses of trade unions are recasting or reshaping an extremely precarious workforce working in the informal economy, digital spaces, and factories. Despite being weakened by capital, these workers are finding ways to recast their power to resist extreme forms of subjugation in labour.

Like in *Cast in a Racial Mould*, Webster and his team adopt dualism to unpack workers' oppression and resistance in South Africa, Uganda, Kenya, and other countries. The observations, in-depth interviews, and documentary analysis are deployed to reveal the duality of oppression and resistance in the labour processes. In other words, this ethnographic approach enabled Webster and his team to show new organisational forms emerging in the formal and informal economies of the Global South, disputing the perspective that neoliberal globalisation has ultimately defeated the workers of the Global South. Of course, Webster and his team understand that the workers of the Global South are engaged in what I describe as an asymmetrical warfare persecuted by the states, businesses, and the powerful forces of the Global North.

However, workers discussed in the recent book have various forms of power in this asymmetrical warfare. To this end, this new book examines organising strategies through the prisms of three other forms of power: coalitions (the power of society), associational power (the power of collective organisation), and institutional power (the laws that uphold labour rights).

The book also makes the case that labour is still relevant by deploying various sources and forms of worker power. Webster and his colleagues assert that precarious workers, including digital workers, are redefining their resistance to the growth of precarious forms of labour. The book acknowledges that workers and trade unions have been undermined by capitalists. Trade union density, or the rate at which employees join unions, has decreased both globally and in South Africa, which is one indication of this reality.

Webster rejects the "end of labor thesis" (p. ix) and demonstrates that even the most alienated platform workers possess the capacity for individual and collective resistance against complete subjugation by capitalist and platform systems. Webster and Dor's work (Chapter 4) transcends mere analysis of the issues of digital oppression and offers a sense of hope for labour, particularly within the context of the Global South. Despite all the challenges confronting platform workers in South Africa and the Global South, this is true. Masikane also shows that, notwithstanding the formidable algorithms in place, the collective strength of smartphone-based platforms thwarted the operations of Uber Eats in December 2020 (p. 101–124). This resistance compelled platform employees to impose a fixed fee of EUR0.50 for each delivered meal.

As a scholar and activist who witnessed the rise and decline of manufacturing workers and their trade unions, Webster has not given up hope on labour, despite its changes in shape and form. As he was with the workers who led the Durban strikes of 1973, he is now with the platform economy workers, informal workers, and precarious workers searching for an organisational response in this asymmetrical war against this new form of vampire capitalism.

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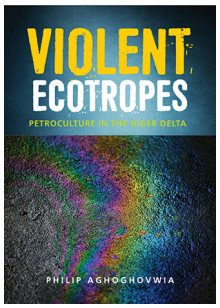

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And the band played on: Conflict-preneurship and the long history of violence in the Niger Delta

As I read Philip Aghoghovwia's *Violent Ecotropes: Petroculture in the Niger Delta*, I could not help but appreciate the echoes of Rob Nixon's[1] *Slow Violence and the Environmentalism of the Poor*. The slow violence in the Niger Delta is an ugly symptom of a runaway extractive economy. The adage, 'the more deadly virus is not HIV/Aids, it is greed', comes to mind. In this publication, the greed is not only confined to an enduring capitalist system but also local elites, something akin to what Umair Haque terms "a class of billionaires so amoral they'd make Caligula blush"[2]. It is because of this class of 'conflict-preneurs', to borrow a term from Akufo-Addo[3], that the violence has continued unabated in the Niger Delta.

Luis Fernández Carril, writing about the staying power of capitalism in his essay, *The Ontological Crisis of the Anthropocene*, could not have agreed more:

> *Life, capitalism, modern institutions, and political and economic systems seem inevitable, perennial, and immortal. As captured by the now famous adage: It is easier to imagine the end of time than to imagine the end of capitalism.*[4]

Violent Ecotropes: Petroculture in the Niger Delta offers a well-articulated and timely analysis of a major theme in contemporary development studies. The book engages local epistemologies and ontologies on the violence in the Niger Delta. Aghoghovwia's masterful use of literary works published between 1998 and 2015 points to the reality that the violent ecotropes are not a black swan event but a manifestation of local people's struggles from the colonial era. The author is to be commended for articulating perspectives from those who live on the margins of history. Violence is a recurring theme in the poetry collections of the Delta, an issue that is troubling to the author.

Chapter 1 uses plays to "depict a tragic reality that attends everyday human existence in the Delta environment." The chapter grapples with the flaws of modernity as encapsulated by the Delta. The author attributes this to power struggles and coins the term petromodernity. Petromordenity is about making huge profits at a huge cost to the communities and the environment.

In the second chapter, the author uses fire as a metaphor. The chapter focuses on Ogaga Ifowodo's *The Oil Lamp* (Africa World Press, 2006). *The Oil Lamp* shows how fire is destructive to the environment. Fire is used as a metaphor for the destructive nature of neoliberalism. Neoliberalism with its attendant apocalyptic horsemen (disease, poverty, violence) wreaks havoc on the communities. Ifowodo and a host of writers "put under the spotlight the overwhelming social and ecological deprivations suffered by the citizenry, the denial of basic rights, and the fate of the postcolonial nation under corrupt military regimes."

Chapter 3 discusses the latent violence in the Delta. Ibiwari Ikiriko's *Oily Tears of the Delta* (Kraftgriots, Ibadan, 2000) depicts how the infrastructure of oil extraction becomes an arena of contested power. *Oily Tears* is a call to arms. The literary works in this chapter are critical of what the author terms "oily" intrusions into the Delta. The "oily" intrusions have caused a lot of suffering as seen by the displacements in the Delta.

Chapter 4 analyses the Nollywood film *The Liquid Black Gold (*Executive Image African Movies, 2008). *The Liquid Black Gold* grapples with the violence associated with oil extraction in the Delta. According to Aghoghovwia, *The Liquid Black Gold* discusses the generational rivalry between the young and the old, a product of a gerontocracy culture. This has resulted in tensions in the communities. The chapter also draws on the works of Frantz Fanon (*The Wretched of the Earth*, Grove Press, 1961) and Rob Nixon (*Slow Violence and the Environmentalism of the Poor*). Fanon's work is premised on resisting imperialism. Nixon argues about the impact of what he terms "slow violence" on the locals and the environment.

The author shows the complexity of the Niger Delta conflict. On one hand, there is the brutality of international capital, and on the other, is the evil nature of the disaster of capitalism as encapsulated by local conflict entrepreneurship. The book reflects the Hobbesian nature of life which is nasty, brutish and short. The people in the Niger Delta have suffered for so long. There seems to be no light at the end of the tunnel. One is inclined to argue that solutions that have been and are being proffered to solve the conflict in the Delta amount to Orwellian dishonesty and Potemkin facades meant to hoodwink the local communities.

In line with the above observations, the title of Mary Trump's book *Too Much and Never Enough*[5] resonates with the insatiable greed of the Delta Region's conflict-preneurs, who have realised that the spoils of conflict far outweigh initiatives for peace. They have benefitted handsomely from the conflict, and so they have dug in. A term in the field of disaster management used about conflict-preneurship is disaster capitalism. Disaster capitalism is the use of catastrophe in conflict and post-conflict situations to promote and empower a range of private, neoliberal capitalist interests. What is being witnessed in the Niger Delta is disaster capitalism, therefore the use of the term could have enriched the book.

Addressing environmental turmoil is fundamentally about advancing social justice. Questions of justice are critical to *Violent Ecotropes*. The author could have engaged more with the different dimensions of justice. These dimensions range from who gets what (distributional justice) and whose knowledge (epistemic justice), to who gets to decide (procedural justice) and ultimately who gets left behind (recognition justice).[6]

Also, Yuval Noah Harari's overhasty jump theory[7] could be useful in understanding the Niger Delta's long history of violence. According to Harari, humans rose to the top of the food chain in a relatively short time. In a bid to solidify their position at the top, humans have become brutal. Humans will go out of their way to eliminate other

species (including their own) to remain at the top of the food chain. Thus, humanity's overhasty jump is one of the major reasons for violence, and, I strongly believe, what hinders successful outcomes in a multi-species approach to environmental management. As already alluded to, humans will protect their place at the top of the food chain at any cost. Perhaps it is time to address humanity's insecurity at the top of the food chain. Part of the solution is the realisation that a multi-species approach means a win–win for all species.

Violent Ecotropes is well articulated, intellectually stimulating and provides new knowledge about the conflict in the Niger Delta. The chapters are concise and make interesting reading. I therefore very highly recommend the book.

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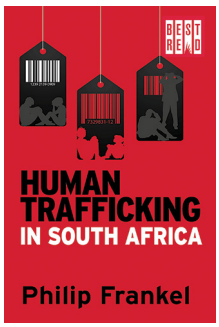

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Human trafficking: Misery and myopia in South Africa

Frankel's second comprehensive book surveying the landscape of human trafficking and counter-trafficking governance in South Africa, written during the COVID pandemic, offers a considered and nuanced account of this heinous and pervasive phenomenon. Frankel's description of the diverse manifestations of the crime remains dispassionate and analytical throughout. Drawing from local research, international reports, indices, and measured media reports from 2016 onwards, as well as interviews conducted with key stakeholders, academic experts, victims, perpetrators, and civil society, Frankel weaves together a cogent narrative that is accessible to the wider public.

What sets Frankel's work apart is twofold: (1) the inclusion of 'outlier' aspects of trafficking[1] ignored by the vast majority of South African trafficking research; and (2) an interdisciplinary approach to understanding the phenomenon.

The book is divided into seven chapters. Frankel provides a foundation for understanding trafficking in persons from an international perspective in Chapter 1, as well as key concepts such as the nature of social vulnerability, the complexities of the trafficking process, and victim and perpetrator profiles. The controversial nature of trafficking and questions of prevalence are also addressed here. In the next three chapters, Frankel paints with broad brushstrokes how sex trafficking, child trafficking and labour trafficking manifest in the South African context. Frankel successfully offers a critical gaze on the state of human trafficking research, and the disproportionate focus by some researchers and policymakers on sex trafficking (historically to the disadvantage of other forms of trafficking). He further highlights the stark realities of child trafficking – and the often multiple, and concurrent, forms of exploitation children are forced to endure. Children are particularly vulnerable to being exploited for sex, labour, forced marriage, illegal adoption, and their organs. Child labour, also discussed in the chapter on the regional framework, is a particularly significant issue in both South Africa and the surrounding region. Labour trafficking, which is preeminent in Africa, and disproportionately affects male victims, who are predominantly exploited in agriculture, mining, and commercial fishing, does not receive as much attention in the South African context.

He illustrates the need to challenge stereotypical understandings of victims and perpetrators. Various criminal syndicates in the more organised forms of trafficking are also unpacked throughout these three chapters. What becomes apparent is that although human trafficking is understood as a clandestine crime, it is more often than not a crime hidden in plain sight. This is reflected in some offender profiles that mirror Hannah Arendt's contention about the "banality of evil"[1] and is particularly true in cases of 'incidental trafficking'. A reoccurring theme throughout the book is the role that corruption and complicity of various state institutions play in the perpetuation of trafficking within South Africa – even more dangerous when apathy and self-interest are intermixed in a counter-trafficking environment plagued by incapacitation of key stakeholders.

Having provided a conceptual understanding of the often-intersecting broad categories of trafficking, and the operational challenges that exist in successfully addressing them, Frankel turns his focus to counter-trafficking in South Africa, and the regional framework in Chapters 5 and 6. These two chapters provide a unique analysis that has not been well addressed in previous research. Frankel offers a comprehensive and analytical critique of counter-trafficking, and the legislative and policy framework within which it occurs, and its coordination structures. Frankel claims that "deficiencies in the PACOTIP create dysfunctionality in its key implementation vehicle...the policy framework is at this point in its existence a very weak tool for catching traffickers" (p. 109).

One of the most damning findings in the book is the penetration of the South African political economy by transnational criminal networks coupled with a relative absence of political will and capacity. This in turn plays out in the apparent reluctance of the criminal justice system to punish perpetrators commensurate with their crimes, and poverty of resources allocated to rehabilitation and reintegration systems for victims (p. 116). Issues that are similarly mirrored across the region.[2] Chapter 6 then turns to the regional framework and the transnational nature of trafficking. As Frankel succinctly notes, "at a time of globalisation we cannot comprehensively understand trafficking within the Republic without reference to what takes place immediately outside its territory" (p. 124). The regional perspective is often lacking in South African trafficking research and/or strategic initiatives. Frankel discusses the regional threat matrix as witnessed in the six countries comprising the southern African region, and more generally in the Southern African Development Community (SADC). However, he does not survey the East African migration-trafficking nexus originating in Ethiopia and traversing through Kenya, Tanzania, Malawi and Mozambique. This is a minor critique – as the logic for his exploration of trafficking in the region is limited to southern Africa.

One of the book's strengths is its commitment to not only highlight the problems but also to propose tangible solutions. Frankel's ten-point counter-trafficking strategy is rooted in a deep understanding of the South African context, acknowledging the need for comprehensive and collaborative efforts. He advocates for capacity building and strengthening law enforcement, confronting corruption, improving victim support systems, mobilising civil society and a proactive approach to dismantling trafficking networks. Frankel delivers a clarion call to policymakers, civil society, and citizens alike to contribute meaningfully to the fight against human trafficking in South Africa.

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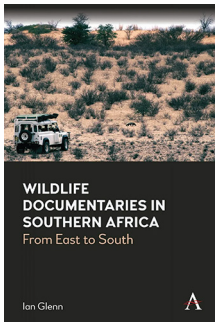

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Ian Glenn's 'Wildlife Documentaries in Southern Africa: From East to South'

When Theodore Roosevelt, the former US President, led a scientific expedition to Africa in March 1909, he chose east Africa as his destination. The safari, sponsored by the Smithsonian Institution, set out to collect big game, birds, mammals, reptiles and plants for the US National Museum in Washington DC. In the end, Roosevelt and his son Kermit, a first-year student at Harvard University who accompanied his father on the trip, killed and collected 512 animals. As Ian Glenn explains in his marvellous new book, it is not surprising that Roosevelt and his son chose east Africa for their expedition. Starting in the early 1800s, east Africa – to which the world owes the word safari (Swahili for journey) – was the world centre for so-called 'big game hunting'. Any big game hunter worth their salt plied their trade in the region. In fact, Frederick Courteney Selous and Edward North Buxton, the world's leading big game hunters of their day, helped arrange Roosevelt's 1909 trip. Between the mid-1800s and the mid-1900s, east Africa was the place to be for American and European hunters. It was also the destination of choice for monied tourists who wanted something other than old European cities for their vacations. It was not surprising, therefore, that when wildlife documentary emerged as a genre of filmmaking in the mid-20th century, east Africa occupied pride of place in that emergence. However, starting in the 1970s, east Africa began gradually to lose its place to southern Africa as both a premier tourist destination and the home of wildlife documentary filmmaking in Africa. Glenn's book offers a compelling explanation of this change.

As Glenn explains, "The big idea of this book is that, starting in the early 1970s, wildlife films made in southern Africa, mostly but not exclusively by southern Africans, started winning major international awards and mark a crucial move away from east Africa as the centre of African wildlife film. More than that, they start influencing modern trends in the genre and provide some of its most important achievements" (p. 2). At the centre of Glenn's wonderful book are many of these pioneering filmmakers, including Beverly and Dereck Joubert, who have won eight Emmys, as well as Carol Hughes and her late husband David who won six Emmys and a Golden Panda, the premier British prize for the best wildlife film of the year. The Hugheses won the very first Golden Panda award in 1982 for their 1979 film *Etosha: Place of Dry Water* (p. 1). This makes the Jouberts and the Hugheses South Africa's most successful filmmakers, as measured by international accolades. Given the ubiquity of wildlife films, filmmakers such as the Jouberts and the Hugheses are also likely to be among the most watched in the world. Through a series of interviews with many of the leading wildlife filmmakers, Glenn takes the reader mercifully away from David Attenborough. In fact, Glenn cuts Attenborough down to size by showing how Attenborough himself drew direct and indirect inspiration from some of the filmmakers that Glenn writes about. Glenn does this through a masterful analysis of which filmmaker worked with whom, how one influenced another, and how they all created an extended network through which flowed ideas, influences and personalities. For example, while Attenborough was listed as the presenter of the 1987 BBC documentary *Meerkats United*, once voted by BBC viewers as the best wildlife documentary of all time, Attenborough's role was basically limited to that of a voice-over artist. The South African Richard Goss made that film (p. 7–8).

As Glenn points out, "There is a massive disparity between popular interest in wildlife documentary and academic attention to the genre, particularly in southern Africa." (p. 6) This means, among other things, that we have no reliable data on how many people actually watch these documentaries. We know they are popular the world over; we just can't quantify that popularity. But we know from the awards won and the outsize influence that wildlife filmmakers from southern Africa have on the genre, that the region dominates the business. Part of the explanation for this dominance, Glenn argues, is that filmmakers from southern Africa have made the greatest use of new technologies (p. 8). They were also among the first to draw ethical implications from their work on wildlife. For example, Michael Rosenberg, a South African who spent most of his working life in London and won more Golden Pandas than any other wildlife filmmaker, produced *Fragile Earth*, one of the first series of documentaries to educate the public about environmental degradation and the importance of conservation; the Jouberts produced work that compared the emotional capacities of humans with those of elephants.

In his explanation of the shift in wildlife documentary filmmaking from east to southern Africa, Glenn argues that changes in wildlife policies in east Africa drove the shift. When, for example, Kenya banned hunting in 1977, hunters and filmmakers moved down south. This did not mean that the change in location was seamless. The Kruger National Park, for all its status as Africa's most iconic reserve, had none of the vistas offered by the Serengeti. But, as Glenn reminds us, southern Africa had places such as the Kalahari and the Namib, which could more than compensate for what the Kruger lacked. The change in location ushered in new directions in wildlife documentary filmmaking, thanks to discoveries of phenomena not found elsewhere. Among these novel finds was the Jouberts' discovery of a bitter rivalry in Botswana between large lion prides and hyaena clans. This led to *Eternal Enemies*, the 1992 award-winning film narrated by Jeremy Irons. One of my favourite stories in a book brimming with rich tales concerns the advent of open vehicles for game viewing. According to Glenn's informants, Mala Mala and Londolozi, two private lodges in southern Africa, pioneered this. Then African trackers took it a step further by inventing and designing the tracker seat that is now standard in all safari vehicles. Robert Maluka, a technician in the Londolozi workshop, made the very first of these seats (p. 47).

In *Wildlife Documentaries in Southern Africa*, Glenn has given us a fun read and much-needed inspiration for future research. The public and scholars from across a range of disciplines are going to find in this book wonderful stories and excellent ideas.

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The elusive echo: The mystery of Africa's sparse bat fossil record

Significance:

The scarcity of bat fossils in Africa poses a significant challenge to both scientific understanding and current conservation efforts. While this article engages in informed speculation regarding the reasons behind this scarcity, it does not lessen the importance of the issue. Without a robust fossil record, tracing the evolutionary history, biological adaptations, and historical ecological roles of bats becomes difficult. Understanding their past is instrumental in mitigating current threats to bats like habitat loss and climate change. Thus, the intriguing lack of a comprehensive fossil record not only limits scientific inquiry but also hinders effective conservation measures.

Bats, the only mammals capable of sustained flight, are a fascinating group of creatures. With over 1400 species[1], they are the second most diverse group of mammals, surpassed only by rodents[2]. From the tiniest serotine bat, weighing only two grams, to the giant golden-crowned flying fox with a wingspan of over a metre, bats are found in nearly every habitat worldwide.[1] They play crucial roles in ecosystems, from pollinating flowers to controlling insect populations. In addition to keeping ecosystems healthy[3], their activities have direct economic benefits for agriculture and forestry. Without bats, crop yields would be lower, and the cost of pest control would rise dramatically.[4] Yet, despite their global presence and ecological importance, the story of bat evolution, particularly in Africa, remains elusive due to a surprisingly sparse fossil record. This scarcity renders bats a 'silent taxon' in the annals of palaeontology; they are vitally important yet leave few traces behind. Why are bat fossils in Africa so rare, and how does this impact our understanding of modern bats and their conservation?

To understand the gap in our library of bat fossil discoveries, it is important first to understand how fossils are formed.[5] Bones require the correct mixing pot of ingredients to become fossilised. If these criteria are unmet, the material simply decays, leaving no trace of existence. Following an organism's death, it must be quickly covered by sediments, such as sand, silt, or mud, to protect it from scavengers and decomposition. Over time, these layers of sediment accumulate, with the weight of the upper layers compacting the lower layers into rock. As groundwater saturates the remains, it carries minerals like silica or iron that replace the organic material in the bones or plant matter, a process known as permineralisation, leaving behind a permanent imprint of the material in the rock.

Rich in bat biodiversity, Africa presents a puzzling gap in our understanding of bat evolution. The fossil record of bats in Africa, especially during the Paleogene period (66 to 23 million years ago), is notably scarce compared to those of North America or Europe. Until recently, the evidence for early Tertiary African bats came from a handful of localities[6], primarily in North Africa, with only one site in sub-Saharan Africa, in Tanzania. The oldest known bat fossils from Africa date to the early Eocene, around 50 million years ago, and were discovered in Algeria.[6] None of these fossils represents complete specimens and consists only of a few fragments of bone and teeth. South Africa has an extremely sparse bat fossil record, with currently only 55 specimens recovered across the country, most of them relatively 'young' fossils from the Pleistocene (2.58 million to 11 700 years ago).[7] This scarcity becomes even more intriguing when we consider the fossilised evidence of bat guano found in African caves, like Arnhem in Namibia[8] and Gcwihaba in Botswana[9]. These remnants suggest that large bat colonies thrived in these locations many years ago, making the question even more pressing: where are the fossils of these bats? According to a 2019 article published in *Palaeontology*[10], there may be several reasons why the global bat fossil record is so sparse, which can be extrapolated to South Africa. Early bats likely resided in forested areas – environments not typically conducive to fossil formation. In these hot and humid settings, rapid decay of organic matter is common[11], largely due to high bacterial activity. If we extend this logic to caves, the same factors – heat, humidity, and heightened bacterial activity – can accelerate decomposition, thereby reducing the likelihood of fossilisation, even in places where large bat colonies may have existed.

Dispersal mechanisms of ancient bat species pose another layer of intrigue in our quest to understand their fossil scarcity. Modern bats exhibit remarkable dispersal capabilities[1], ranging from local migrations to extensive journeys. These behaviours influence where their remains might be found postmortem. However, when it comes to their prehistoric ancestors, our knowledge is limited to speculation and educated conjecture.

Another proposed reason could be the delicate nature of bat bones. Generally, most southern African bats alive today are relatively small and lightweight, ranging from about 2 g to 100 g.[12] One of the earliest fossil bats, *Icaronycteris index*, discovered in Wyoming, USA, had tiny bones, some reportedly as thin as human hair.[13] These bats lived during the Eocene, approximately 52 million years ago. We only know about them because they lived around lakes that facilitated extraordinary preservation; the combination of fine sediment and oxygen-depleted water at the lakebed enabled rapid burial of fossils, protecting the remains from scavengers and other decomposers.[10] However, the tiny fossil of a prehistoric bird chick called *Enantiornithes*[14] from 127 million years ago shows that size is probably not an issue when it comes to fossilisation, and the type of sediment where an organism dies plays a more important role.

Alternatively, the nature of fossil discovery and collection could contribute to bat fossil scarcity. Fossil discovery requires significant resources and specialised equipment. Specialised mesh sieves are used to sift soil for fossils and fragments, known as traditional or dry sieving.[15,16] The sieving process typically begins

with larger meshes, which filter out bigger fragments. Following this, progressively finer sieves are employed to capture smaller and more delicate specimens. However, it is during these initial stages of sieving with larger meshes that the brittle bones of bats are most at risk. The process can inadvertently damage these fragile specimens, thereby contributing to their scarcity in the fossil record.

Fossil hunting also requires a significant amount of time and expertise, and some regions may simply have been explored less than others. In 2008, after 25 years of fieldwork[17], scientists published the discovery of six new bat species from Egypt, dating to about 35 million years ago[18]. The study was based on 33 fossil specimens, translating to a little over one specimen discovery per year. This highlights the effort and patience required in palaeontology and the necessity of long-term commitment. Certainly, the niche nature of studying bats, particularly bat fossils, presents unique challenges. In academia and research, areas that garner more attention often receive more funding and resources. North America and Europe have historically seen more extensive palaeontological funding and efforts, naturally leading to a richer fossil record. In contrast, Africa, despite its potential for significant discoveries, has faced limitations in financial and human resources. As bats are not as popular to study as other animals or topics, finding experts specialising in bat palaeontology is rare. This scarcity of specialists compounds the existing issues caused by the lack of a comprehensive fossil record for bats. Addressing this imbalance would require not only increased investment in African palaeontological research but also a concerted effort to cultivate local expertise and infrastructure in this field.

Regardless of the reason, the absence of bat fossils significantly hinders our understanding of these fascinating mammals. Without a robust fossil record, tracing bats' evolutionary history and biological adaptations like flight and echolocation becomes a daunting challenge. Our gaps in knowledge extend to their historical roles in ecosystems as well. The scarcity of fossils limits our understanding of how bats have interacted with their environments over time, which in turn could offer valuable insights into their present-day ecological roles. Bats play crucial roles in the ecosystem[18] through insect control, pollination, and seed dispersal; however, without a comprehensive fossil record, we lack a baseline to understand how these roles might have evolved or how resilient they might be to current or future ecological changes.

This limited understanding carries immediate implications for bat conservation. Conservationists are navigating partially in the dark without knowing the historical ranges and ecological roles of different bat species. The absence of a comprehensive fossil record could result in an underestimation of the historical diversity and population density of bats, thus leading to insufficient or misguided conservation efforts. Furthermore, understanding a species' past genetic diversity could be instrumental in current conservation strategies, particularly in mitigating the threats posed by habitat loss and climate change. In essence, the scarcity of bat fossils not only hampers scientific understanding but also complicates the implementation of effective measures to protect these ecologically vital and interesting creatures.

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Palaeo-landscapes and hydrology in the South African interior: Implications for human history

Significance:

Recent research reveals that the arid western interior of South Africa has experienced substantially more humid conditions on several occasions during the last 70 000 years. These findings, likely regional in scope, speak to changes to the resource base available to prehistoric hunter-gatherers. Together with recent archaeological findings from this region, there has emerged a growing recognition that previously archaeologically overlooked areas of South Africa's arid interior need to be included in models of human history. This presents new challenges for archaeologists and palaeoclimatologists, particularly given the prevalence of surficial, rather than stratified, archaeological evidence throughout much of this region.

Introduction and context

South Africa hosts a remarkable archaeological record that stretches deep into the past.[1] It is a region at the centre of discussions surrounding human prehistory, and findings relating to southern African archaeology attract international media and public interest. This archaeological record has motivated a substantial ancillary body of research that seeks to reconstruct the long-term evolution of regional climates and landscapes. Such changes will have shaped the resources available for past hunter-gatherer societies, and represent local manifestations of the global glacial and interglacial climatic cycles that prevailed throughout the Pleistocene.[2,3] In South Africa, data for the late Pleistocene (the last 125 000 years) suggest glacial-interglacial changes in mean annual temperature of 5–6 °C[4] and time-varying fluctuations in the extent and intensities of (subtropical) summer rainfall and/or winter rainfall[5]. Such palaeoclimatic information feeds into questions concerning regional ecological responses and whether (and the extent to which) observed archaeological shifts are indicative of behavioural adaptations to environmental change.

The distribution of archaeological sites across South Africa, some of which have been subject to decades of investigation, is geographically uneven. Simply laying a map (Figure 1) of the major Middle to early Later Stone Age (MSA to early LSA; ~300 ka to ~20 ka) sites onto a map of modern aridity might tempt one to infer that the distribution is a logical outcome of humans mostly using the more humid, well-resourced landscapes of the coastal margins and the wetter (and upland) eastern half of the country. Indeed, one of the largest 'gaps on the map' covers the western interior of South Africa, which broadly maps to the Nama Karoo Biome, a region characterised by arid conditions (an aridity index of 0.16±0.07 and mean annual precipitation of 250±90 mm[6]) and shrubby vegetation with sparse grass cover. While less prominent in the literature, archaeological materials spanning the Acheulian to the Later Stone Age have been described throughout even the most arid parts of this region.[7,8] Indeed, in some cases, these descriptions formed some of the earliest palaeoenvironmental and archaeological investigations undertaken in the region.[9] A major difference in the arid interior is that researchers are often dealing with *surface archaeology*; that is, scattered artefacts either lying directly on the land surface, or only shallowly buried (Figure 1). This stands in contrast to the deeply stratified deposits preserved and available to study in rock shelters, which are much more common along the Cape south coast and in adjacent mountain systems. In the absence of such stratification, even the *relative* age of surface materials is difficult to establish, and direct numerical dating can be particularly challenging.

Notwithstanding, one might ask what the abundant presence of such archaeological materials, even across rather arid landscapes, represents. Could it indicate a 'background scatter', generated by an essentially sparse human presence over long periods? Could it suggest that people were regular visitors at certain times, perhaps using these environments when conditions were more favourable? Such questions speak to the adaptive flexibility of human populations in the past[10], and, indeed, over the decades, several workers have speculated whether particular biomes or environments were more or less favoured at certain times[11]. We might further speculate, as some workers have, as to whether the materials we do observe are focused on particular landscape settings that offer desirable resources, and what clues such evidence provides in terms of how people used the landscape.[12]

Our recent paper[13] sought to set a framework for addressing these questions, not through analysis of archaeological materials, but by first considering the more basic question of whether there were good reasons (or more specifically, optimum times) for humans to have occupied these (presently) arid regions. The paper joins a growing body of work[14-16] that challenges assumptions that the South African central interior was characterised by aridity during cooler global glacial phases[17,18].

Geological evidence

Carr et al.[13] present a palaeohydrological reconstruction for a region largely encompassing the Nama Karoo (including some areas marginal to the Grassland and Savanna Biomes), spanning the last 70 000 years – a period encompassing the later MSA and the transition, at some point in the last 40 000 years, to the LSA. They followed up work that several decades ago reported evidence for lake shorelines *and* archaeological materials along the margins of now dry or ephemerally inundated pans, primarily at sites near to Brandvlei[8,19] in the Northern Cape Province and in the very western margins of the Nama Karoo Biome at Alexandersfontein, south of Kimberley[20]. Previous workers identified these palaeo-lakes and inferred the existence of perennial surface waters based on the presence of wave-deposited shorelines, lake mud deposits stranded above the modern pan floors, and even reports of workers

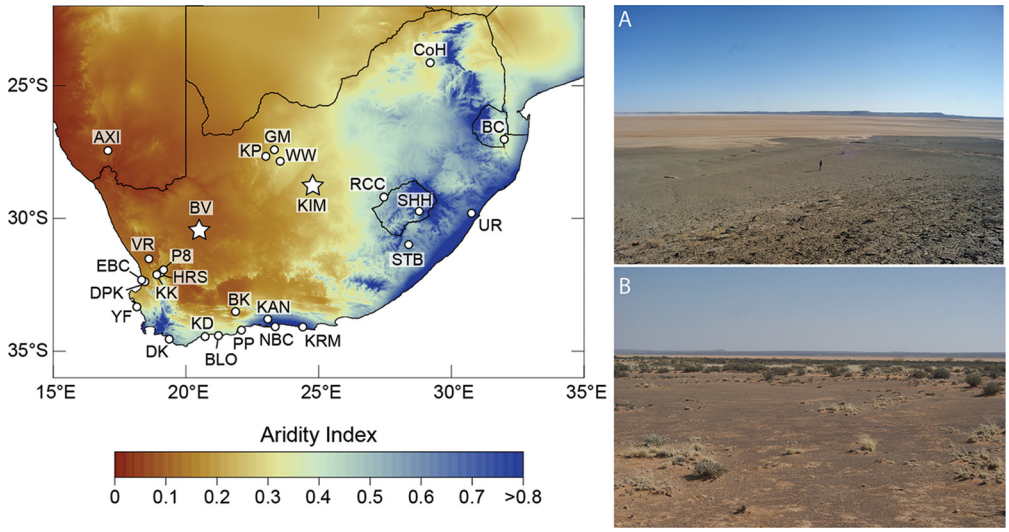

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Figure 1: The distribution of major Middle Stone Age sites (some sites also include Early and Later Stone Age materials) in South Africa with a map of aridity (aridity index calculated with data from Trabucco and Zomer[6]). AXI=Apollo 11; BLO=Blombos Cave; BC=Border Cave; BK=Buffelskloof; CoH=Cave of Hearths; DK=Die Kelders; DPK=Diepkloof; EBC=Elands Bay Cave; GM= Ga-Mohana Hill North; HRS=Hollow Rock; KRM=Klasies River; KK=Klein Kliphuis; KD=Klipdrift; NBC=Nelson Bay Cave; PP=Pinnacle Point; P8= Putslaagte 8; RCC=Rose Cottage Cave; SHH=Sehonghong; STB= Strathalan B; UR=Umhlatuzana; VR=Varsche Rivier; WW=Wonderwerk; YF=Ysterfontein; KP=Kathu pan. The key locales investigated by Carr et al.[13] are shown (stars) (KIM= Kimberley and BV=Brandvlei). The photos of sites considered in this work show: (A) the margins of Hoek van Spruit se Vloer pan, south of Brandvlei, which exhibits varying densities of Middle and Later Stone Age lithic scatters around its margins (where the figure is standing); (B) the margins of Verkeerdevlei pan, southeast of Vanwyksvlei. Here the dark stoney surface in the foreground and middle ground is composed of abundant patinated artifacts, including diagnostic Middle Stone Age elements.

finding fish and crab remains during early 20th century quarrying.[19] In all cases, the likely ages of these deposits and landforms were weakly constrained. The new work first sought to address their ages through the application of radiocarbon and optically stimulated luminescence (OSL) dating methods. However, it was also able to identify additional sites with evidence pertinent to these questions; notably the presence of freshwater mussel deposits at pans that are today very rarely inundated. The application of OSL dating was particularly significant as this method could provide numerical ages for deposits that were devoid of organic matter or biogenic calcite (e.g. shell).

Quantifying hydrological and ecological change

The results suggested the presence of perennial waters in the western arid interior at 55–39 ka, 34–31 ka and around 21 ka.[13] In the east of the study region, at Kimberley, the age of a previously hypothesised[20] 44 km^2 palaeo-lake was constrained to 25–32 ka; burial of these lake deposits by unambiguously Holocene age (10–11 ka) terrestrial colluvium further supported the notion that the cooler phases of the last glacial cycle were associated with a substantially different hydrological balance (i.e. ratio of evaporation to precipitation) from the present. A key development of this work was to move beyond dating phases of 'higher' moisture availability to develop a model that could account more specifically (i.e. climatically) for the hydrological changes implied by the geological evidence. By anchoring the model to the new geological data, we also sought to extend the findings to consider the implications for *regional hydrology*. For this we used the Shetran hydrological model[21] to simulate surface water as well as soil water and groundwater flow (Figure 2). The modelling implied that significant hydrological invigoration across much of the Orange River catchment would have been required to sustain these lakes, with the most dramatic changes in water balance in the west. Temperature change (lower temperatures leading to lower evaporation rates) was likely to have been an important control, but increased rainfall was also needed to fully replicate the geological evidence. In the Brandvlei region, this amounted to potential evapotranspiration being reduced to 21% of present and rainfall increasing to 215% of present (to approximately 550 mm per year). A landscape of presently dry pans and ephemeral river channels was thus at times associated with perennial rivers and lakes and the regional water table would have intersected the modern landscape across stretches of this interior region (Figure 2). Modelling also facilitates the development of testable hypotheses; if water resources were an important control on human occupation of the interior, the outputs offer suggestions in terms of where to look for new archaeological evidence.

In water-limited ecosystems, once the regional hydrology changes, ecological changes will follow, and using the modelling results, it was possible to develop hypotheses as to the associated vegetation responses. Crucially, the likely response of herbivores to these new conditions could also be considered. Here the modelling predicts a wetter, grassier and more herbivore-rich environment; a much more resource-rich landscape that would have presented many opportunities for hunter-gatherer communities.[13] Indeed, there is independent faunal evidence to support these proposed changes[22], and the results also explain some intriguing (but rarely discussed) elements of the Pleistocene faunal record; notably the presence of aquatic mammals like hippos (*Hippopotamus amphibius*), and lechwe (*Kobus leche*) which feed on aquatic plants, in several late Pleistocene faunal records in the arid interior.[22]

Implications and future perspectives

Considering this evidence, a parsimonious explanation for the archaeological 'gap on the map' (Figure 1) in the arid interior is not one of unfavourable (palaeo)climates, but more likely a reflection of geology and geomorphology. That is, the landscape is (was) unsuited to the preservation of the sorts of stratified archaeological records that have attracted intensive research efforts elsewhere. It is worth noting that where such sites are located in the interior, such as Wonderwerk Cave, Ga-Mohana Hill and Kathu Pan to the north of the aforementioned lake study sites, Early Stone Age, MSA and LSA archaeology, including some early MSA materials dating to the penultimate glacial period (Marine Isotope Stage 6), are indeed preserved.[14,15,23]

While unstratified, there is abundant surface archaeological evidence for hunter-gatherers in the interior region. The question of whether, at a regional scale, this is consistently concentrated around (palaeo) hydrological systems[24] requires more work, but Carr et al.[13] describe both MSA and LSA materials at all of their sampled/observed sites (Figure 1).

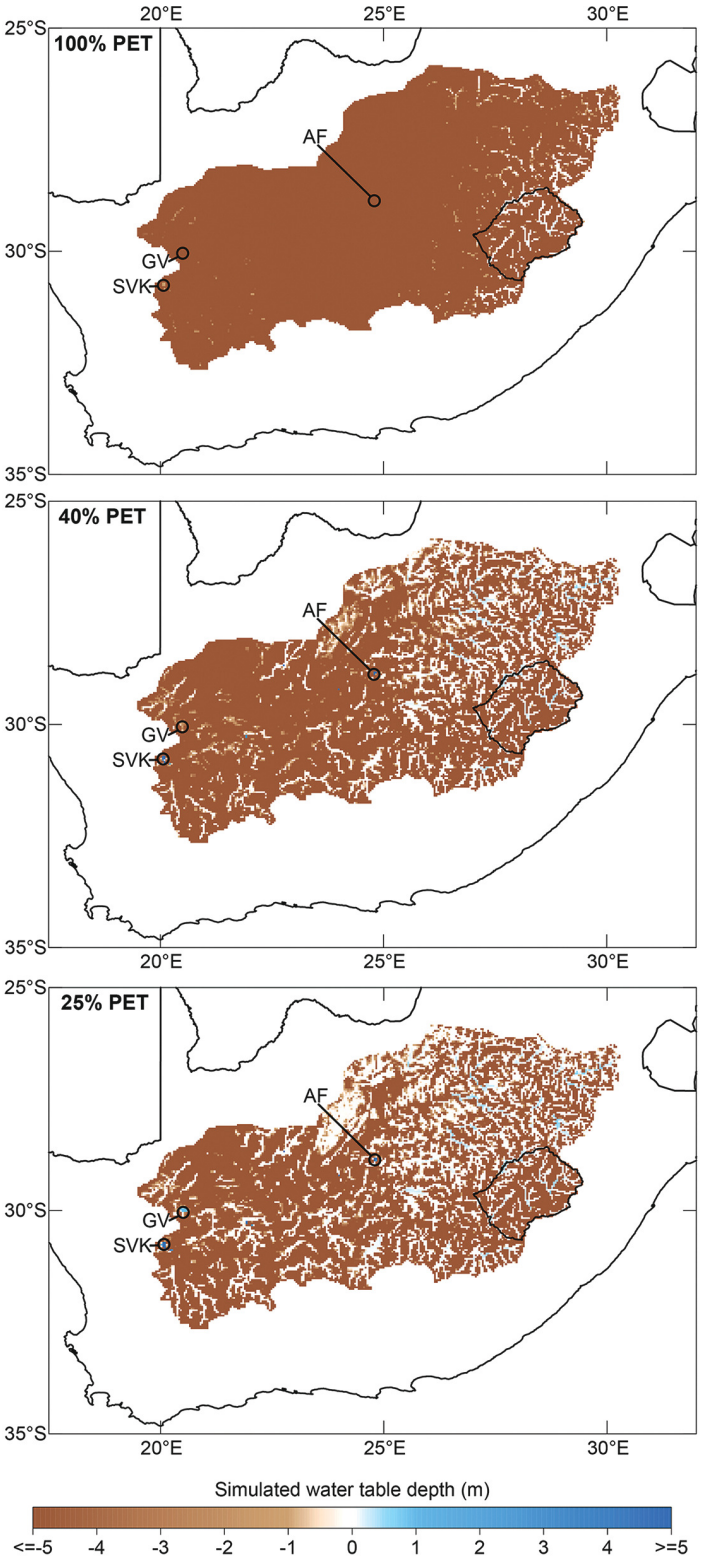

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Figure 2: The results of the Shetran modelling, showing the modelled depth of the water table across the Orange River catchment for several potential evapotranspiration (PET) scenarios; white and blue shading indicates the water table intersection with the modern ground surface.[13] It is important to consider that the size and climatic heterogeneity of the region depicted means that it is unlikely that all of it ever experienced precisely the same water balance or level of potential evapotranspiration. The situation is thus idealised rather than actual, but sites for which direct field evidence for palaeolakes and perennial surface water flow has been identified are also shown (GV = Grootvloer; SKV = Swartvolkvloer; AF = Alexandersfontein).

At Alexandersfontein the density reaches greater than 50 artefacts/m^2 at one locale on the edge of the proposed palaeo-lake.[13,20] Here MSA artefacts were also found in stratified deposits, although age constraints for these materials are required. Looking further afield, it is clear that several pan sites, while lacking obvious shoreline deposits, were also associated with abundant MSA lithic scatters, and this includes some sites for which the hydrological modelling predicts palaeo-inundation (Figure 2). The role of springs in shaping landscape usage should also be considered.[12]

Thus, one might wonder to what extent our collective views on South African deep history are skewed by the stark nature of the modern conditions in the arid zone, and by a research focus on deeply stratified archaeological sites on the coastal margins. A growing body of work is developing around this issue, including the description and dating of new sites such as Ga-Mohana[15] and work further afield in the Makgadikgadi Basin of Botswana[25]. More broadly, these works prompt us to consider the significance and potential of the interior surface archaeological record. The importance (and acknowledged challenges) of integrating surface archaeology into our wider understanding of human history is recognised globally, but the results discussed here suggest there is value in considering how the interior's open-air record of human existence can be integrated into a broader understanding of South Africa's past.[26] Given its very *emplacement* within the landscape, if its chronological hurdles can be overcome, this surface archaeological record has the potential to deliver new behavioural information. That it spans a wider temporal and spatial range than rock shelter sites, moreover, and captures a broader range of activities and behaviours[27], makes it all the more enticing. Crucially, though, to interpret the interior's archaeology properly, and to fully grasp its strengths and limitations, we must also start to understand the geomorphic processes that shape surface archaeology.[28] Doing so may be nothing short of the key to understanding when, why and how humans inhabited these perennial – but not permanent – thirstlands.

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Preprints, press releases and fossils in space: What is happening in South African human evolution research?

Significance:

Uploading unreviewed manuscripts to a preprint server promotes accessibility and facilitates rapid breakthroughs. We, however, question the motivation of Berger and colleagues who used the new eLife publishing model to launch what appeared to be a carefully curated media campaign around an unreviewed narrative, thereby manipulating accepted norms in scientific publishing. This team has engaged in ostentatious public displays under the guise of promoting science, including launching precious fossil remains into space. Given these ethical concerns, we call on the public, heritage and scientific practitioners to reflect on the current state, and future, of human evolution research.

2023 was a big, busy year for the field of human evolution research, or palaeoanthropology, in South Africa – it attracted headlines, debate and controversy. The focus is the Rising Star Cave system, within the UNESCO Cradle of Humankind World Heritage Site, known as the Cradle, which is home to the fossil remains of our distant relative, *Homo naledi*. The Cradle has produced much of what we know about early human evolution and its cave sites are the single richest collection of early human, or hominin, fossils anywhere on earth. The caves and fossils of this region have been the subject of research, debate and media interest for almost a century. But 2023 marked a departure from what is considered normal in even this oft acrimonious, competitive research field.

On 5 June 2023, three multi-authored manuscripts were posted as pre-prints on the bioRxiv server, by a team led by Lee Berger.[1-3] These manuscripts had been submitted previously to the online only journal *eLife* and were sent for peer review on 4 May 2023. The posting on the preprint server a month later was done in accordance with the new eLife open publishing model, launched in March 2023.[4]

There followed a huge, coordinated, and thorough media coverage of not the actual manuscripts but the central, as yet unreviewed, narrative that *Homo naledi* had buried their dead, and made art and stone tools. The news reverberated around the world, with headlines on CNN, *The New York Times*, *National Geographic* and beyond. This was accompanied by a blitz of media interviews and television appearances by Berger. This gave the impression of a carefully planned and curated media exercise, with field photos, figures from the manuscripts and dramatic artistic reconstructions featured in online and print media.

Then on 12 July 2023, peer reviews of the three manuscripts were posted on the respective webpages of each preprint on the eLife system[5]; four reviews appeared each for Berger et al.[1] and Berger et al.[2], and three reviews appeared for Fuentes et al.[3] Ten of these eleven independent peer reviews rejected the claims put forward in the three manuscripts. A subset of senior authors responded[5], but are yet to revise the manuscripts. Five days later, on 17 July 2023, a Netflix documentary titled *Unknown: Cave of Bones* was released in 24 countries around the world, featuring the same narrative as the unreviewed manuscripts and initial media releases, that is, that *Homo naledi* had buried their dead, and made art and stone tools. This was followed in October 2023 by a book with a similar title.[6]

How did all of this happen? How could an unreviewed narrative enter the public realm in such a comprehensive way and then be almost unanimously rejected by peer review? The answer is eLife's new publishing approach, and what we view as the deliberate exploitation of this model by the Berger et al. research team. eLife launched their new publishing model in March 2023.[4] This model is a marked departure from the traditional model in which authors submit a manuscript and a journal editor either desk rejects or sends the manuscript for peer review. The editor then accesses the reviews and passes these back to the authors with the editorial decision to either reject or publish a revised version of the manuscript, with minor or major revisions. This has been the standard practice since the mid-1970s, as a measure of quality control and a means to improve the standard of scientific outputs. Only in rare cases is a manuscript accepted more or less as is; we emphasise this point: almost all manuscripts are subject to some level of revision prior to publication.

eLife states, in their own words, that while "authors still receive a high-quality peer-reviewed eLife publication", their new model is different in two key ways.[4] For clarity, we quote them directly: "Firstly, all papers that are invited for review are published on the eLife website as a Reviewed Preprint, giving readers an earlier view of the reviews and editor's assessment. Secondly, the authors control the next steps. This can include submitting a revised preprint or publishing their Reviewed Preprint as a Version of Record which will be sent to indexers like PubMed and can be listed in funding, job applications and more."

Our view is that these two key differences have been exploited by Berger et al. The requirement that the manuscripts be placed on a preprint server was satisfied, but the team then used this version of the manuscripts to launch their massive media announcement. In their later response to the eLife commissioned reviews[5], the team disclose that they had "benefited from a previous round of review of the manuscript describing the proposed burial features, which underwent two rounds of revisions in a high-impact journal over a period of approximately 8 months during 2022 and early 2023". The manuscript including the deliberate burial data set and accompanying narrative had been peer reviewed, and presumably rejected by a 'high impact journal' editor, meaning that the authors had an idea of how their interpretation was going to land with the scientific community. Then, rather than wait for a new set of

peer reviews, they chose to go ahead with the media campaign without having met peer review approval.

Immediately after the preprints were released, critical commentary emerged.[7] The manuscripts were criticised by the reviewers, who wrote long, detailed, meticulous reviews of all aspects of the data, claims and interpretations. These reviews are all publicly available on the eLife site.[5] The team responded to the reviews by thanking the reviewers but argued that they maintained their original interpretations, although they are yet to present a detailed scientific rebuttal of the criticisms, nor revise the manuscripts. This means that the original, unreviewed versions are taking the place of reviewed manuscripts and the authors, not the editors, are deciding what quality of research is considered acceptable.

There was very little media coverage of the peer-review reports and responses from the scientific community, compared with the huge media blitz around the preprints. Discussion on X (formerly Twitter) exploded with commentary and opinions; *Nature* covered the response to the reviews[8], but the mainstream media that had disseminated the deliberate burial/art/tool narrative looked the other way when this interpretation was condemned by the scientific community.

The 'Cave of Bones' Netflix documentary soared to the top of the 'most watched' in South Africa in the weeks after it first aired. This team appeared to have moved beyond interpretation of their data, to create an entire narrative arc to explain their observations, without having been subject to the usual rigours of scientific publication. Indeed, they took deliberate steps to curate and promote their version before it was approved by the peer-review process. Filming an entire documentary is not a trivial exercise, and this piece was made, edited, scored and readied for release before the actual science had been reviewed, criticised, revised and taken its place within what the scientific community accepts as new knowledge. This is not just a muddle of dates, or a slip of the tongue at a stressful press interview by a media-shy academic. This appears to be a deliberate and well-planned exploitation of a new publishing model to shortcut the usual scientific process of academic publishing.

How did we get here? What are preprints, what is their normal role, and how is their use going to impact future research? These are important questions. As we are not experts on this topic, we offer up an explanation from the preprint server bioRxiv[9]: "Because this [sic traditional] process can be lengthy, authors use the bioRxiv service to make their manuscripts available as 'preprints' before certification by peer review, allowing other scientists to see, discuss, and comment on the findings immediately." For other scientists to see, discuss and comment; not to orchestrate a press release and Netflix documentary.

The bioRxiv explanation continues: "Readers should therefore be aware that articles on bioRxiv have not been finalized by authors, might contain errors, and report information that has not yet been accepted or endorsed in any way by the scientific or medical community." This is a very clear and precise warning that places the preprints into the context in which they should be used and makes clear how they are intended to be viewed. There is also no ambiguity about how these preprints should be used by the media; bioRxiv cautions, "We also urge journalists and other individuals who report on medical research to the general public to consider this when discussing work that appears on bioRxiv preprints and emphasize it has yet to be evaluated by the medical community and the information presented may be erroneous." None of this caution was mentioned in the media coverage nor the Netflix film.

What we saw unfold in 2023 is the intersection of an established publishing norm in some fields (preprints) and a research team that has sought to disseminate a singular, interpretative narrative prior to peer review. Preprints per se are not the issue here – posting unreviewed research on a preprint server is not new or controversial; we saw during the pandemic that this was useful and productive, and how research on treatments for COVID-19 and vaccine development could proceed very quickly when aided by the sharing of results and open reviews.

But palaeoanthropology is not a field that needs urgent research and rapid breakthroughs. Given the huge and wide public interest in human evolution and our origins, this research field benefits from much slower, measured, and careful research. The Cradle has produced an invaluable fossil record, and the Rising Star Cave is no different. The puzzle of how so many fossil bones of a small-brained hominin ended up in a now inaccessible chamber of a deep underground cave system is an intriguing question. A slow, rigorous, traditional approach to researching this cave and its associated fossils will yield exciting new results; there is no demonstrable need to peddle an unreviewed narrative to the public.

June and July 2023 were eventful and controversial months for palaeoanthropology research and publishing in South Africa. Surely no one could have anticipated what followed just two months later. Berger, with the permission of the South African Heritage Resource Agency (SAHRA)[10] and the curating institute responsible for the Cradle fossils, the Evolutionary Studies Institute at the University of the Witwatersrand[11], sent a thumb bone of *Homo naledi* and a fragment of the collar bone of *Australopithecus sediba*, into space. These two fossils were placed in a custom-made carbon-fibre tube and carried by billionaire Tim Nash, who was a passenger on the Virgin Galactic space flight on 8 September 2023, and is also a landowner in the Cradle.[10,11]

The reason given in the request for temporary export of the fossils out of South Africa by Berger was "to promote South African science"[10]. However, the media coverage of the fossil spaceflight was even more focused on an American audience than the June preprint splash. Coverage by the South African media, a week later, focused on the outrage of both local and international scientists[12-14] who argued that this endeavour had little scientific merit and was a publicity stunt. As if palaeoanthropology in South Africa had not suffered enough reputational damage, this took place during the month of September, Heritage Month in South Africa, during which we reflect on, celebrate and honour our heritage.

This space flight takes us into murky waters, raising questions of ethics such as 'whose heritage is this anyway?' and questioning why privileged people can take fossils to space for no valid reason, while the poor communities from where the fossils originate are excluded from even talking about how they could benefit from accessing the material.[14] We are referring to the case of the local community at Taung in the Northern Cape and their repeated requests for not only access but for a return of the 'Taung child' fossil to the town.[15]

While it feels like this surely must be the end of this story, it is not. On 10 November 2023, a peer-reviewed article was published in the *Journal of Human Evolution* titled 'No scientific evidence that *Homo naledi* buried their dead and produced rock art' in which Martinón-Torres et al.[16] systematically dismantle every aspect of the three preprints and argue convincingly that the evidence provided by Berger and his team in no way supports their interpretations. There was some media coverage of this article and the reaction to it, but, again, not on the same scale as that of the June coverage.

So, looking back at an eventful 2023, we are left with more questions than answers. Is the media narrative and a fascinating story more important than peer review? Are we looking at sensational documentary films setting the pace, tone and quality of South African research into human origins? Are some claiming to promote South African science actually doing more harm than good? Are our precious, rare fossils being used to promote individual agendas with disregard for the risks? Is it not our academic responsibility to entrench our work, and especially public engagement initiatives, in scientific integrity?

In our view, the answer to all these questions is yes. We end with a final question for the South African palaeoscience, and broader research, community: Is this what we want? We call on this community, as well as on the funders, heritage practitioners, permit granting agencies, and government research bodies, to take a long hard look at human evolution research and its associated disciplines in 2023 and consider where we want to be in 2024 and beyond.

Competing interests

We have no competing interests to declare.

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Radio communications through rock strata – South African mining experience over 50 years

Significance:

The pioneering work done in South Africa in developing radio communications technology for use underground in mines is summarised. Propagation took place, in the main, directly through the rock strata with incidental coupling into power cables, pipes, rails and other conductors. The research established the optimum frequencies for communications as well as the most appropriate antennas. Specialised radio equipment was developed for this task as constrained by the technology of the time. Size and weight were major constraints; ultimately, handheld equipment, using single-sideband modulation, was produced that functioned exceptionally well in numerous situations underground.

Introduction

It was early in 1938 that the medical superintendent of Rand Mines, Dr A.J. Orenstein, asked Professor Basil Schonland, the Director of the Bernard Price Institute of Geophysical Research (the BPI) at the University of the Witwatersrand, about the feasibility of radio communications underground in mines. Orenstein had long been concerned that firefighting and rescue teams were severely hampered by a lack of communication between those personnel and anyone else when they ventured into the most hazardous of situations. Schonland was sceptical that radio signals would propagate over useful distances through rock strata, but agreed to investigate.[1,2]

The war, radar and the Special Signals Services

International events soon intervened as war with Nazi Germany loomed. South Africa declared war on 6 September 1939, just three days after Britain. From then, the research focus of the BPI shifted inexorably. Henceforth, all its resources, as limited as they were, would be given over to the investigation of RDF, or radar as it was known in those earliest days (see Figure 1). What followed, was the formation of the Special Signals Services (SSS), as part of the South African Army's Corps of Signals with Lt Col Schonland as its commanding officer.[2,3] And immediately, the SSS co-opted the services of engineers and physicists from South Africa's major universities – one of whom was a young engineering graduate from Durban by the name of Trevor Wadley.

The development of South Africa's own radar equipment and its deployment, along with subsequent British radars, around the country's coastline as well as in East Africa, the Middle East and in Italy, has been reported extensively elsewhere.[2-4] It was that massive wartime effort at the BPI that was the spur to the formation of the Council for Scientific and Industrial Research (CSIR), which was formally established in October 1945 with Schonland as its President. And the CSIR's first specialist laboratory to come into existence was the Telecommunications Research Laboratory, with Wadley among its first members of staff.[5]

Wadley and radio underground

Wadley's genius was soon evident. He designed a revolutionary type of radio receiver that became the mainstay of British naval communication when the equipment was produced by a British company. Subsequently, he developed

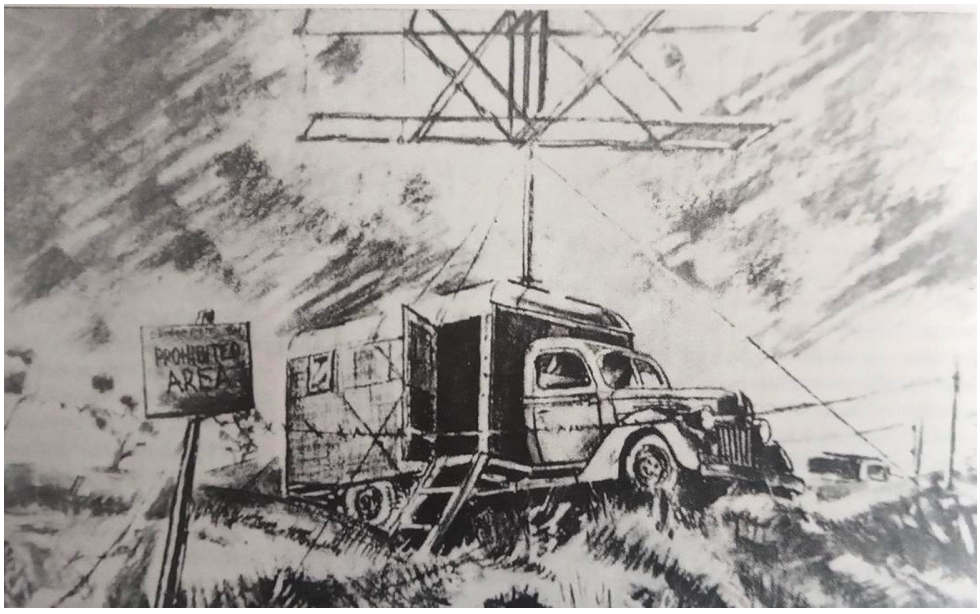

Figure 1: The mobile radar system designed and constructed by the Special Signals Services at the Bernard Price Institute of Geophysical Research, University of the Witwatersrand, in 1942.

a distance-measuring device of quite unparalleled accuracy called the Tellurometer which revolutionised the field of surveying.[5,6] Remarkably, he also turned his attention to the problem of radio communications in mines that had first been raised almost a decade before.

In 1949, Wadley wrote a report for the Transvaal and Orange Free State Chamber of Mines describing the outcome of his research and his recommendations for suitable equipment.[7] The important question he answered was what the optimum frequency was in order to achieve maximum communication range directly through the rock. Reliance could not be placed on signals propagating via the underground tunnels because of their irregular shapes, their curvature and roughness, which ruled out line-of-sight communications.

Electrical properties of rocks

In order to determine how electromagnetic energy might propagate through the lossy dielectric medium of rock, one requires a knowledge of its propagation constant γ where:

$$\gamma = \alpha + j\beta = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)}\,.$$

Here α is the attenuation constant, β is the phase constant and $\omega = 2\pi f$ is the angular frequency. The other terms are the fundamental electrical parameters of rock: its conductivity (σ), dielectric constant (ε) and magnetic permeability (μ). Of these, only the permeability remains constant with changes in frequency, while most geological materials are also non-magnetic.[8] By contrast, both rock conductivity and dielectric constant are frequency dependent.[8,9]

Wadley measured both the resistivity (the reciprocal of conductivity) and the dielectric constant of quartzite and some shales typical of the gold mining region of the Witwatersrand. He used borehole samples with apparatus specially designed for the task. In his report he showed how the resistivity of quartzite varied from about 9×10^4 to 5×10^3 ohm-metres over a frequency range from 100 kHz to 3 MHz. By contrast, the dielectric constant hardly changed and had a value of about 6. Using these data, he calculated the attenuation of a radio signal propagating through 300 m of quartzite and showed how it increased rapidly with frequency, implying that the lower the radio frequency, the better for communicating through rock.

Antennas in lossy media

The fact that the antennas would be surrounded by rock complicated the situation considerably. Wadley considered that a long centre-fed dipole antenna laid along the tunnel floor, or footwall, would be an appropriate antenna for a fixed station underground. For the portable equipment he chose a frame aerial which is essentially a loop of wire (perhaps of many turns) that would be wound around a miner's helmet or 'hardhat'. He measured the impedance of the dipole at a particular frequency and attributed the results to the electrical characteristics of the surrounding rock. From those measurements he deduced the antenna's loss from 10 kHz to 10 MHz. As expected, there was a trade-off, between the rock-induced loss and the improved performance of the antenna as its apparent length, relative to the wavelength, increased with frequency.[7]

By contrast, the small loop antenna was difficult to treat theoretically because the interchange of energy between the air-space and rock was not well understood. This was undoubtedly true and it was to be many years before the underlying electromagnetics principles affecting such electrically small antennas, when immersed in lossy dielectric media, were fully explained.[10,11]

The optimum frequency

Wadley produced a graph of the total loss in decibels (dB) suffered by a radiating signal over a distance of 900 m for frequencies between 30 kHz and 3000 kHz. The graph went through a distinct minimum at about 300 kHz, which, therefore, is the optimum transmitting frequency for that particular distance. The graph also showed that for communications over greater distances a lower frequency would be required, while a higher frequency could be used over shorter distances.[7]

As in all radio communication systems, it is not just the strength of the signal that determines optimum performance but rather the signal-to-noise ratio. A deep-level mine presents an almost unique environment from a noise point of view. The great thickness of the overburden removes, almost completely, any electrical noise generated above ground (including by lightning) and therefore the only noise will be that caused by nearby electrical equipment and within the radio receiver itself. In the case of mining emergencies, all electrical power is usually switched off in the affected area, leaving just the receiver-generated noise which can be reduced substantially by careful design.[7]

The radio equipment

Wadley recommended that two types of transmitters be developed: a static set, producing about 4W of power to be used at a fixed point underground where it could make use of a fairly long antenna; and a portable set, generating only a tenth of the power and using a considerably smaller antenna. Naturally, each transmitter had its companion receiver, with each being of a modern superheterodyne configuration for optimum performance. Based on those specifications, he predicted that the normal operating radius would be about 600 m. A workable signal should still be received at a distance of around 750 m, while the absolute limit would be about 900 m. An appropriate transmitting frequency should be about 350 kHz.[7]

Because the radio technology of those days was all based on thermionic valves, the equipment would naturally be rather bulky. Wadley estimated that the larger unit would weigh no more than 14 kg, while its portable counterpart might be about a third of that.

Wadley never published his results in the open literature. This was an unfortunate omission because there was a real dearth of such quantitative data at that time.[10]

An industrial hiatus and a mining catastrophe

It was not until the late 1950s, on the formation of what was to become the research laboratories of the Chamber of Mines, that Wadley's recommendations received serious attention from the South African mining industry. The problems foreseen by Dr Orenstein all those years before had by no means gone away: if anything, the expansion of the post-war gold and coal mining industries, and the stepped-up production then taking place, had exacerbated the problem of underground fires, accidents and, of course, the ever-present risk of rock falls at the increasing depths at which gold was being mined. On 21 January 1960, a disaster occurred at Coalbrook Colliery in the northern Free State when the mine workings collapsed, entombing 435 men, all of whom perished. Immediate attempts to rescue them were set in train with the Mines' Rescue Brigade of 250 men leading the effort. These highly trained personnel were all experienced miners who had volunteered for the dangerous task of firefighting and rescue work underground. They were trained at the Chamber's Rescue Training Station in Johannesburg.[12] However, once they went underground, those rescue teams were without any form of communication.

Designing the equipment

The underground radio project had been resurrected by the Electronics Division of the Chamber's laboratories during the late 1950s. Wadley's findings and recommendations underpinned their work. Their own calculations had confirmed that a system loss of 150 dB between transmitter and receiver was tolerable and the family of curves in Figure 2 indicated the optimum frequencies for particular distances between them.[13]

Despite the decade or so that had elapsed since the invention of the transistor, and its rapid embrace by many sectors of the electronics engineering industry, the germanium transistors of that era were still limited to low-frequency and relatively low-power applications. They were also thermally sensitive devices, which was an important consideration to be born in mind given the very high temperatures experienced in deep mines.

The radio equipment would be used by members of the Mines Rescue Brigade, known as 'Proto teams' because of the Proto breathing apparatus they used. It required its user to clench a snorkel-type

breathing tube between their teeth and to wear a nose clip. Both made speech impossible. This restriction had a great bearing on the design of the radio equipment.

Standard practice during mine emergencies was to establish a so-called fresh-air base, as close as possible to the disaster area, where breathing apparatus was not required. The Proto team, carrying the portable radio equipment, would then go forward from there to carry out its task.

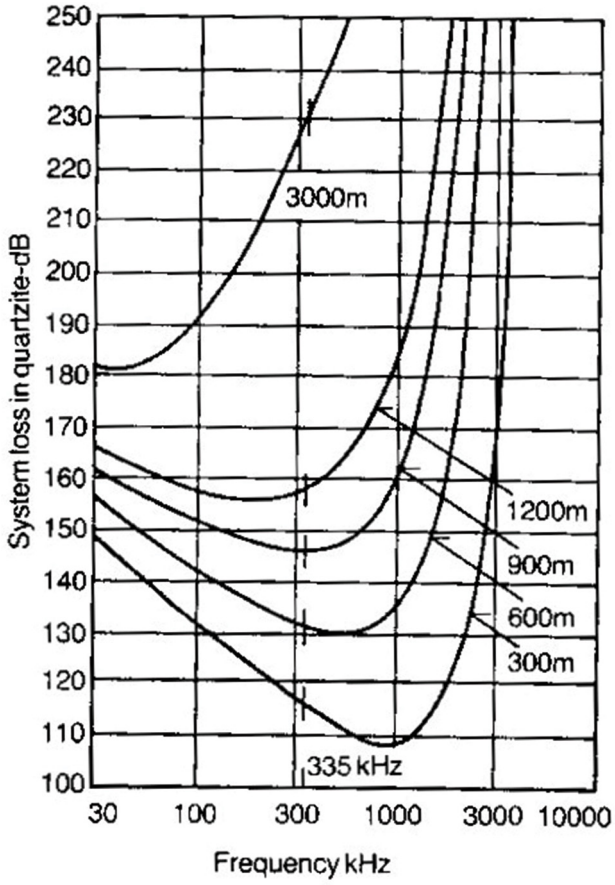

Figure 2: Calculated system loss with frequency for various distances through quartzite rock.

An amplitude-modulated (AM) transmitter was designed for use at the fresh-air base. The frequency allocated by the Postmaster General for mining applications was 335 kHz. The transmitter's output power was approximately 5 W. To exploit the very low noise conditions expected during a disaster, the receiver was designed to have the lowest possible noise figure. The base station weighed 13 kg. However, the motor car battery needed to power it weighed rather more at 15 kg.[13]

The portable equipment to be carried by a Proto team brigadesman was as small and light as possible within the constraints imposed by the valve technology of the time. It was intended to transmit a simple on-off code by means of a push-button because of the radio operator's inability to speak. It was believed, quite rightly, that teaching everyone the Morse code was neither feasible nor necessary as long as a simple question and answer protocol was developed between the fresh-air base radio operator and his counterpart using the portable equipment. The portable transmitter, which resulted, produced about 2 W and its receiver also had the lowest possible noise figure. The portable set weighed just over 6 kg, including batteries.[13]

Loop antennas were used at both the fresh-air base and with the portable equipment. The base station antenna, shown in Figure 3, was a 1-m diameter multi-turn loop encapsulated in fibreglass and intended to be positioned horizontally on the ground. This orientation would ensure that it had all-round coverage, unlike the long length of wire intended by Wadley, which was markedly directional. The portable set, with its multi-turn loop antenna contained within the rigid carrying harness, is shown in Figure 4. The receiver's loudspeaker was mounted within the harness and positioned close to the operator's ear.

Underground trials

Numerous underground trials were conducted by the Chamber's engineers. It soon became apparent that the communication ranges achieved were often considerably greater than those predicted by Wadley. The reason was that the signals were being conducted (and then re-radiated) by any cables, pipes and even the rails used by the electric and diesel-powered locomotives that transported men, materials and, of course, the gold-bearing rock throughout the mine.[13]

By contrast, in areas completely devoid of all conductors, communication range varied considerably, not only from mine to mine but also within a single mine. The reason, of course, was the complexity of the geology.

Figure 3: The fresh-air base radio equipment, its battery and multi-turn loop antenna.

Figure 4: A brigadesman, using Proto breathing apparatus, with the portable radio equipment slung across his chest.

Extensive investigations carried out in subsequent years provided considerable insight into the propagation mechanisms involved through what was an inhomogeneous lossy dielectric medium, usually stratified and intersected by intrusions such as dykes. A most important theoretical analysis, carried out by J.R. Wait in the USA, provided the first detailed explanation of the phenomena.[14] He showed that rock stratification can actually guide radio signals to greater distances than would be possible through a homogeneous medium. This would later be confirmed both in US coal mines and in South African gold mines.[15]

But, despite the progress made, it was clear that the equipment was too bulky and heavy.

A solid-state solution

In the late 1960s, the Chamber contracted a company in Cape Town to produce a compact, fully transistorised transceiver modelled on the packsets then coming into service with the armies around the world.

Instead of a separate base station and a portable unit, a single piece of equipment could function in both roles, with the option to use a much bigger loop antenna when the equipment was set up at the fresh-air base. Single-sideband modulation instead of the AM would be used. For the same amount of transmitted power, single-sideband yields a 9 dB signal-to-noise ratio advantage at the receiver. The equipment, as produced, operated at 335 kHz and is shown in Figure 5 along with its elliptical loop antenna. Being completely solid-state, it was considerably smaller and lighter than the previous valve-based hardware and contained its own rechargeable battery supply. The transmitter power output was increased to 10 W and the receiver, again, was as sensitive as possible. Once again, small multi-turn loops were used with the portable equipment with a larger, single-turn, flexible loop at the base station. Attention was also paid to ensuring that the equipment was 'intrinsically safe' so that it could be used in the flammable atmospheres typical of some mines.[16]

Figure 5: The single-sideband 335 kHz solid-state transceiver with its elliptical loop antenna.

Once the prototypes had been evaluated and accepted by the Chamber's Electronics Division, a company in Braamfontein, Johannesburg, was commissioned, in 1972, to manufacture a small quantity for further testing by the Rescue Training Station personnel. Word had by now reached the United States Bureau of Mines (USBM) about these South African developments and they purchased six transceivers for evaluation in US coal mines.[15] Soon applications other than mining emergencies suggested themselves and the Chamber laboratories demonstrated the equipment's usefulness for complex underground activities such as raise-boring and tramming as well as within the stopes adjacent to the reef being mined. One of those special projects was the Chamber's Mining Technology Laboratory's mechanised mining programme at Doornfontein Goldmine near Carletonville. There, more than 3000 m below the surface, multiple rock-cutting machines were undergoing evaluation and assessment. It was believed that good communication between the machine operators and the maintenance personnel would improve the efficiency of the process significantly. But the extremely cramped confines of a gold mine stope made even that packset-size equipment too unwieldy and so the need arose for something even smaller.

Handheld communications

Examination of Figure 2 shows that a frequency close to 1 MHz could be used very effectively to communicate over a distance of 300 m through quartzite, with a considerable saving in transmitter power compared with 335 kHz. In addition, those experimental mechanised stopes were well served by armoured power cables and hydraulic lines. Tests had shown that this higher frequency propagated very effectively in and around the stopes, so an immediate design effort was mounted to produce a handheld transceiver.

The outcome was a single-sideband transceiver which weighed much less than a kilogram.[16] It was called the TXR-1 and operated at 903 kHz for reasons of the novel technology used (Figure 6). The transmitter output power was 1 W. The antenna was a flexible multi-turn loop that fitted, bandolier style, around the miner's body. The TXR-1 provided excellent two-way voice communications with a base station (using the same transceiver technology but with the addition of a 10-W power amplifier), plus a large loop antenna, erected in the storeroom close to the stope from where the whole operation was coordinated. More than a hundred TXR-1s in their canvas carrying pouches were produced over the following years to serve the rock-cutter stope.

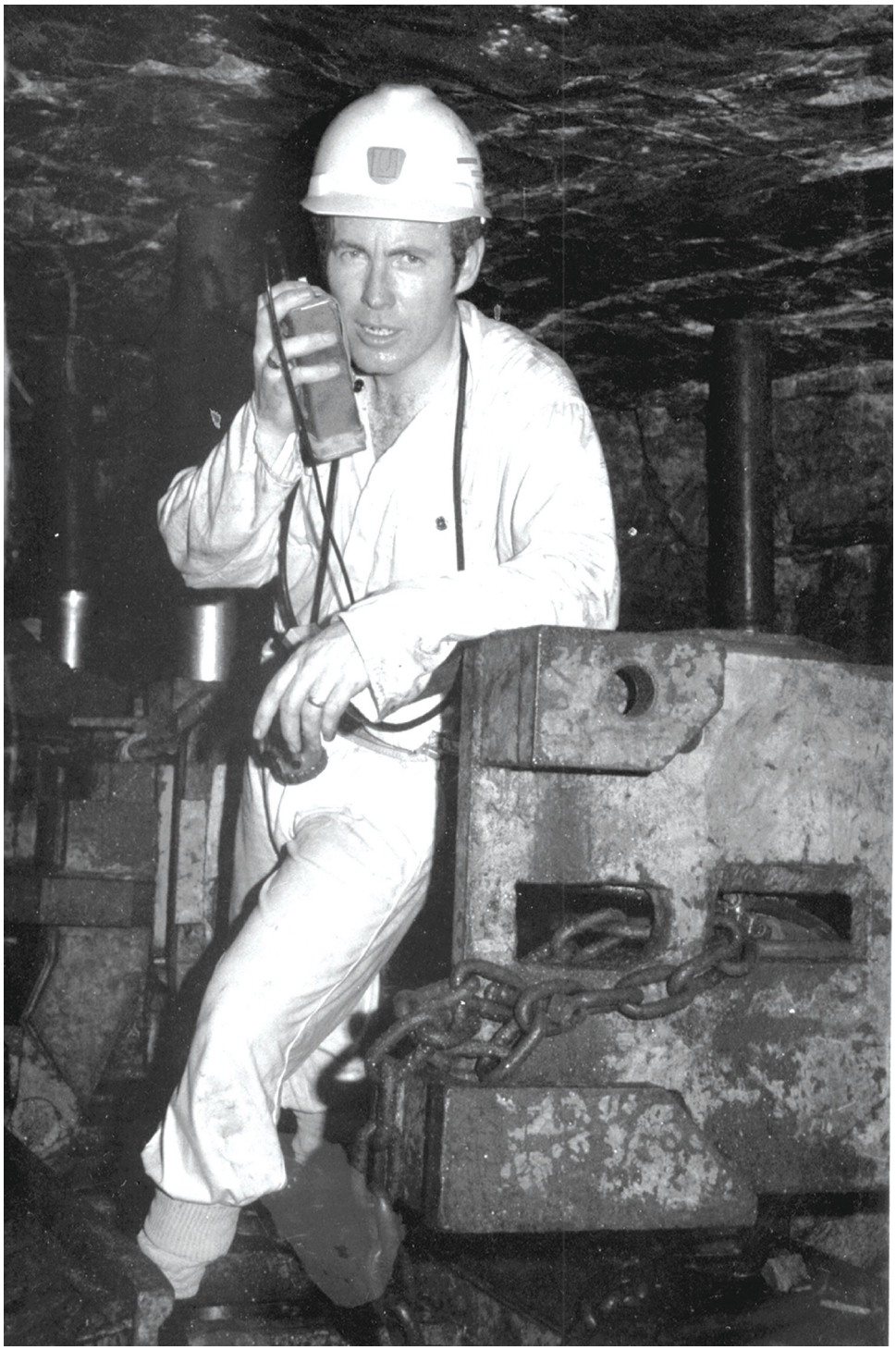

Figure 6: TXR-1 903 kHz handheld transceiver in a mechanised gold-mine stope.

Commercial opportunities

The undoubted success of the TXR-1 had indicated that a more sophisticated small radio transceiver might well find applications throughout the mining industry. With this in mind, the Electronics Division set about developing a prototype which would embody state-of-the art electronic techniques. The intention was that it should operate from 100 kHz to 1 MHz in 10-kHz steps.[17] Multiple mining activities all within the same relatively small area, if required, could then be accommodated on adjacent frequencies. Trials underground showed the hardware to be very acceptable, and so an approach was made to a commercial manufacturer of military-grade electronics equipment in Pretoria to customise it. The outcome was that, by 1978, the SCR-100 portable and SC-200 packset transceivers were available for sale to the mining industry. They immediately went into service with the Rescue Training Station (Figure 7) and in the rock-cutter stope. An energetic marketing exercise was then mounted by the manufacturer which resulted in many mines in South Africa, elsewhere in Africa and abroad, purchasing the equipment.[17]

An underground laboratory

The part played by power cables, water pipes and even rails in enhancing signal propagation was an undoubted fact, but the mechanisms involved were poorly understood. However, research in the USA and Europe had identified two possible modes of propagation known as the

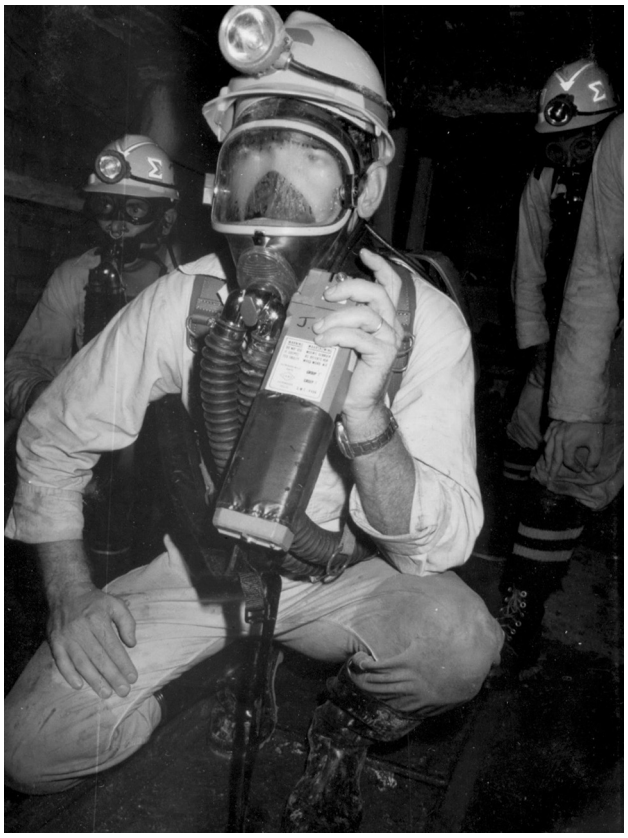

Figure 7: SC-100 portable transceiver used by a Rescue Training Station brigadesman wearing a full facemask.

monofilar and bifilar modes.[18] The details are beyond the scope of this Commentary, but suffice it to say that one or other of those modes can be used very effectively if the radio antennas are in fairly close proximity to those conductors. It was found that positioning a base station within an electrical sub-station, either underground or even on the surface, could yield really long-distance (>3000 m) radio communications by one or other of those modes.[19]

To investigate all the modes of propagation, an underground laboratory was required and a convenient site was found in a completely worked-out area of a mine devoid of electrical conductors. The rock was predominantly quartzite but there was also considerable stratification both above and below the test area. It became apparent that the direction of the electric field polarisation affected the rate of signal attenuation. Maximum signal strength occurred when the antennas were tilted some 40 degrees to the horizontal. This implied that the strata of the surrounding rock were affecting propagation. Examination of a map (see Figure 8) showing the geology of the area confirmed that dip angle of the strata.[17,20]

To investigate conductor-assisted propagation, a single 1400-m length of copper wire was suspended from the hanging wall of the tunnel. As no other conductors were present, it was assumed that the monofilar mode might propagate with the current return path being through the surrounding rock.[18] However, measurements showed rates of attenuation that were significantly lower than were expected between 100 kHz and 1 MHz. There had to be another conducting path for the signal. It turned out that a water trough filled with mine run-off water some 500 times more conductive than tap water, and considerably more conductive than quartzite, provided the return path. An extensive set of experiments confirmed this to be the case[21], and again there was theoretical support in the literature.[22]

In summary, Figure 9 shows a composite set of curves representing all the various propagation modes discussed above. It is clear that there is general agreement between experimental and theoretical results, while

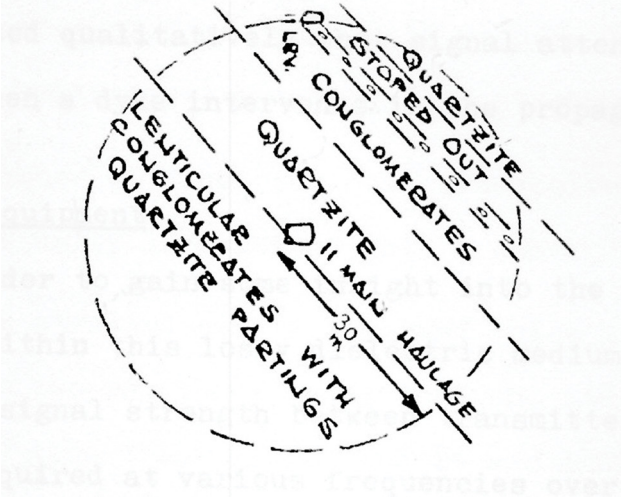

Figure 8: The geology of the rock surrounding the test area underground devoid of all conductors.

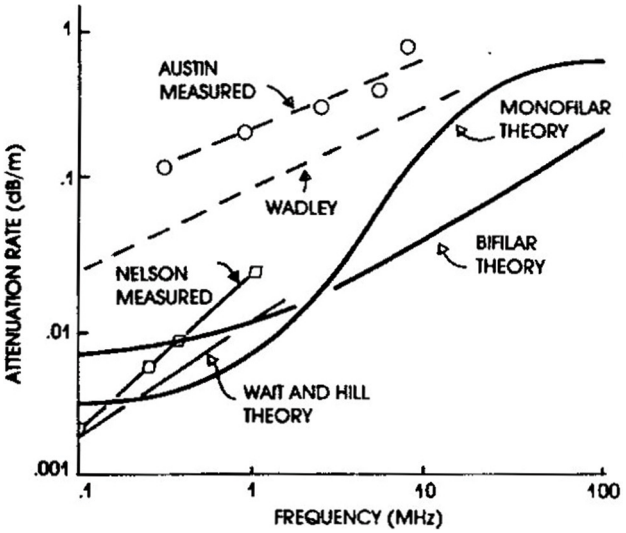

Figure 9: Comparison between theoretical and measured attenuation rates with frequency for various modes of propagation underground.

the frequency dependence and complexity of all the various modes of radio propagation underground are evident.[23]

Conclusions

The work undertaken on radio communication underground in South African mines in the 50 years after the issue was first raised in 1938, has been reviewed. Significant progress was made, particularly in the design of radio equipment suited to this demanding task. Modes of propagation, both directly through the rock and indirectly via any suitable conducting paths that spanned the area between transmitter and receiver, were identified and numerical data obtained to substantiate their characteristics.

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Competing interests

I have no competing interests to declare.

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Navigating the JIBAR transition: Progress, impacts, readiness, and analytical insights

Significance:

The move away from LIBOR to new risk-free rates is crucial in finance. In this Commentary, I examine South Africa's readiness for transitioning from JIBAR to these new rates, especially regarding interest rate derivatives. I delve into how this shift impacts pricing, unique to South Africa's market. Using a mathematical model based on a 2×2 Wishart process, I analyse caplet pricing considering backward- and forward-looking rates. Comparing these caplet types reveals the complexities of pricing in this changing financial landscape. The insights shed light on challenges and opportunities for South Africa and the finance sector as JIBAR nears its end, emphasising the need for robust mathematical strategies in navigating this transition.

Introduction

The world of Quantitative Finance and Risk Management has changed significantly since the 2007–2008 Global Financial Crisis (GFC). Problems that used to have simple answers in finance have become more complicated. Quantitative analysts, often called quants, used to be very confident in their understanding of the basics of financial modelling. These basics included clear benchmarks like LIBOR and JIBAR, reliable interbank credit, and stable single currency values (as mentioned by others[1,2]).

The financial mathematics community found itself confronted with the task of pricing progressively intricate structured financial products. However, the landscape was irrevocably altered by the GFC, introducing uncertainties stemming from unreliable market interbank credit and the volatility in frequency basis. Consequently, the industry responded by introducing the multi-curve pricing framework – a paradigm that entails the construction of multiple yield curves, each tailored to a specific tenor.[3]

In the context of South Africa, the transition away from the Johannesburg Interbank Agreed Rate (JIBAR) has emerged as a significant financial endeavour. This Commentary undertakes an exploration of the progress achieved thus far, the ramifications for a relatively modest market, the readiness of South Africa to navigate the complexities of the JIBAR transition, and the indispensable analytical groundwork required to ensure a seamless and prosperous shift away from JIBAR.

LIBOR and JIBAR background

LIBOR

In the early 1980s, financial institutions initiated a quest for a standardised benchmark to facilitate the pricing of a diverse array of financial instruments. The London Interbank Offered Rate (LIBOR), which made its inaugural appearance in 1986, emerged as the predominant benchmark within this context. LIBOR is defined as the rate at which an individual Contributor Panel bank could borrow funds.

It is essential to underscore that the rate submitted by each bank must be derived from the institution's assessment of its funding costs within the interbank market. In this context, "funds" encompasses unsecured interbank cash and funds procured through the primary issuance of interbank Certificates of Deposit.

However, in September 2012, Barclays Bank incurred a substantial fine of GBP290 million due to its illicit efforts to manipulate LIBOR. Such instances of benchmark rate manipulation, driven by individual and institutional interests, engendered diminished reliance on the benchmark and cast doubts upon its future viability. Consequently, the volume of transactions referencing LIBOR witnessed a noteworthy decline. In response, diverse working groups were convened to orchestrate international endeavours aimed at reviewing and reforming interest rate benchmarks. The overarching objective is to supplant existing benchmarks with risk-free or nearly risk-free rates.

The International Organization of Securities Commissions (IOSCO) has promulgated a set of guiding principles that pertain to benchmark rates. These principles encompass considerations of appropriateness, design, integrity, and efficacy. A pivotal aspect of these principles involves an assessment of the sufficiency of transaction volumes to serve as the foundation for a benchmark reference rate.

Within markets confronting the impending obsolescence of Interbank Offered Rates (IBORs), most notably those heavily reliant on LIBOR, a complex and protracted transition process becomes imperative.

JIBAR

JIBAR constitutes a prominent benchmark interest rate within the financial landscape of South Africa. Its functionality bears a resemblance to that of other IBORs, such as LIBOR, playing a pivotal role as a reference rate in diverse financial transactions, encompassing loans, derivatives, and various other financial instruments. JIBAR's calculation process involves the collaboration of five contributing banks, namely Standard Bank, Nedbank, FirstRand Bank, Absa, and Investec. On a daily basis, these banks disseminate a series of money market rates, signifying their willingness to engage in the purchase and sale of Negotiable Certificates of Deposit (NCD) to entities including the Johannesburg Stock Exchange (JSE) and the South African Reserve Bank (SARB). Subsequently, the

benchmark administrator, SARB, calculates the average midpoints based on these NCD rates for varying tenors, specifically, one month, three months, six months, and twelve months. It is worth noting that the three-month JIBAR rate holds particular significance within the South African financial landscape, serving as a critical reference rate for numerous loans, derivatives, and financial products.

Much akin to LIBOR, JIBAR carries inherent risks related to bank liquidity and interbank dynamics, potentially rendering it susceptible to substantial instability, especially during periods characterised by heightened volatility. Furthermore, its foundation rests upon an expert judgement model, thereby rendering it susceptible to potential attempts at manipulation. In light of these considerations, a strong impetus exists within the South African financial sector to mitigate the risks associated with rate manipulation, augment market integrity, and ensure that benchmark rates derive from genuine market transactions rather than expert judgements.

Practitioners active in South Africa's interest rate markets have raised legitimate questions regarding the necessity of transitioning from JIBAR to an alternative risk-free rate. Notably, JIBAR fails to conform to the sufficiency guidelines delineated by the IOSCO, prompting the SARB to embark on a reformative trajectory akin to the transformations undertaken by other central banks in relation to IBORs. During this transitional phase, an interim enhancement framework has been introduced, designed to fortify JIBAR over a finite period, pending the adoption of an alternative reference rate. A central facet of this enhancement revolves around elevating the obligation size imposed upon each contributing bank – a notable shift from the previous obligation of ZA100 million per point on the NCD curve to the current threshold of ZAR500 million per point. This augmentation serves to enhance JIBAR's adherence to the sufficiency principle delineated by IOSCO, thereby bolstering its robustness.

Anticipations regarding the alternative reference rate posit its character as a risk-free or near-risk-free benchmark, potentially devoid of term structure. In this context, ZARONIA (South African Overnight Index Average), derived from the repo market, has been embraced as the alternative reference rate of choice, symbolising a steadfast commitment to heightened transparency and accuracy within the South African financial landscape.[4] ZARONIA, renowned for its origins and reliability, emerges as a compelling candidate to supplant JIBAR, serving as a more representative indicator of short-term borrowing costs. Its robust attributes further accentuate its suitability for the role of JIBAR's successor.

Table 1 provides a statistical snapshot of the JIBAR and ZARONIA rates over the specified period. The relatively low standard deviations, detrended values, and nonlinear detrended values suggest that the rates remained stable, with limited variations and trends. The positive spot spread indicates that JIBAR rates tended to be higher than ZARONIA rates during this period. The values for detrended standard deviation are relatively low for both JIBAR and ZARONIA, indicating that, even after removing trends, the rates remained relatively stable. Negative values for kurtosis and skewness for both JIBAR and ZARONIA suggest that the rate distributions are leptokurtic and negatively skewed. This means that the rate distributions have thinner tails and are skewed to the left (negatively). Figure 1 provides a time-series representation of the relationship between JIBAR and ZARONIA over the course of approximately 14 months (data were collected from the South African Reserve Bank website from 28 July 2022 to 19 September 2023). It suggests a positive correlation between JIBAR and ZARONIA.

Table 1: Descriptive statistics of South African benchmark rates (3-month JIBAR and ZARONIA), 28 July 2022 to 19 September 2023

	JIBAR (%)	ZARONIA (%)	Spot spread (%)
Mean	7.3980	7.0158	0.3821
Standard deviation (s.d.)	0.9214	0.9338	0.0760
Detrended s.d.	0.2414	0.2204	0.0738
Nonlinear detrended s.d.	0.1596	0.1723	0.0594
Kurtosis	-1.0076	-1.0667	0.4772
Skewness	-0.4552	-0.3858	0.2495

Data source: South African Reserve Bank[5]

South Africa's readiness

A crucial question arises about how prepared South Africa is for the upcoming change. In my view, rushing this transition might not be necessary. South Africa's financial world is quite small, mainly involving five important banks that play a big role in determining the JIBAR. Unlike bigger and more developed financial markets, the risk of manipulating JIBAR in South Africa is much lower.

Therefore, there is no need to hurry with this transition to risk-free rates. We should remember that JIBAR will eventually not be used, but we do not know when exactly that will be. JIBAR is based on banks lending to each other without any guarantees, while the new benchmark rates are based on safer transactions without credit factors. Switching to these safer transactions raises important questions about how it will affect financial markets.

The SARB has taken proactive steps by creating a special group to find a new, suitable risk-free rate, similar to what was done in the USA and UK when they moved away from IBOR. Globally, there is a preference for using a very safe rate. However, it is crucial to recognise that many financial markets do not meet the requirements to develop such rates. Therefore, many markets, like the European Union and Japan, have chosen to quickly adopt nearly risk-free overnight and secured rates.

The SARB has made it clear that they want to approach this transition carefully to avoid causing instability and market swings. They are committed to following the best international practices.

Additionally, the uncertainty about JIBAR's future has raised questions about its current impact on swaps and agreements. The shift to new reference rates may affect derivative hedging. One major concern is not knowing if there will be a way to hedge existing loans and debt linked to the 3-month JIBAR after the transition. This situation could lead to a risk of differences between privately agreed loans and their related derivatives. Moreover, introducing new benchmark rates could significantly change the way existing hedging strategies work.

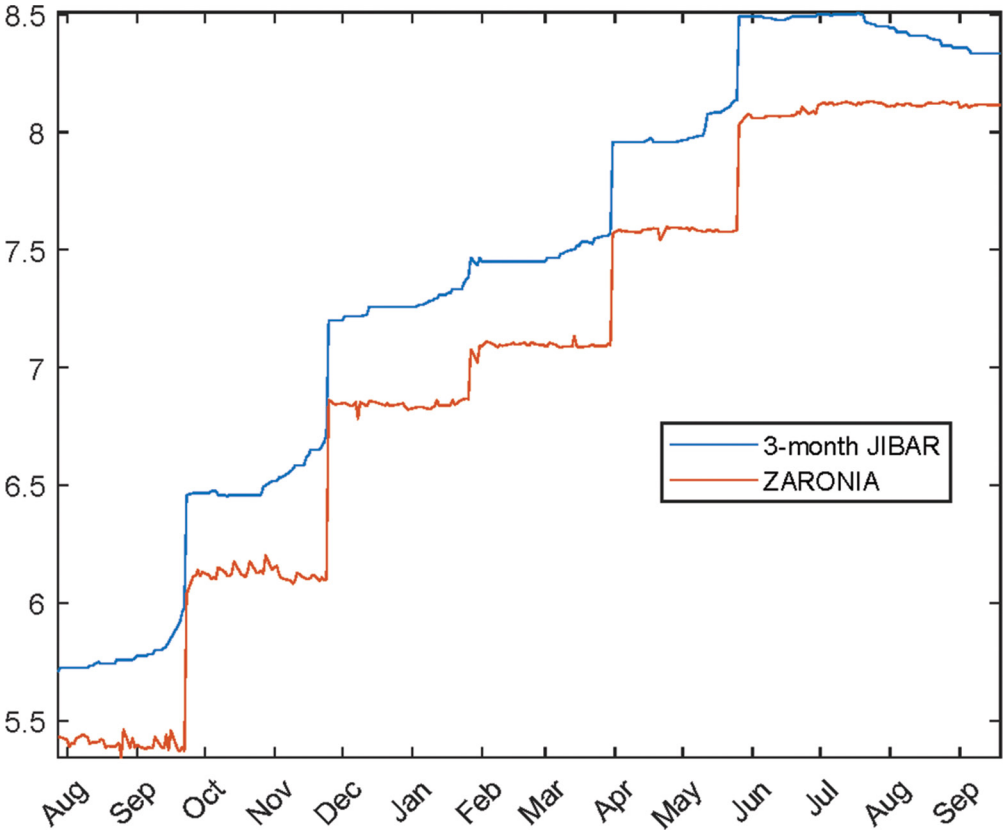
Derivative pricing

I initiate the discussion by exploring derivative pricing, specifically in the context of employing an alternative risk-free rate. In this regard, I examine the effective daily compounding rate applied retrospectively over the time interval T_{j-1}, T_j:

$$ARR\left(T_{j-1}, T_j\right) := \frac{1}{\tau_j}\left(\prod_{i=1}^{N}\left(1 + \delta_i RFR_i(t_i)\right) - 1\right), \forall i, t_i \in \left[T_{j-1}, T_j\right], \quad \text{Equation 1}$$

where $RFR_i(t_i)$ for $i \in 1, \cdots, N$ denotes the alternative overnight rates in the given reference period. In Equation 1, the variable τ_j signifies the cash day count fraction relevant to the accrued period, while δ_i pertains to the cash day count fraction corresponding to the overnight accrued period. Importantly, this rate encapsulates the actual rate operative over the specified period, distinguishing itself by its reduced volatility when contrasted with an average rate. It derives its foundation from the well-established Overnight Index Swap market, leveraging the extant cross-hedging capabilities inherent within this market.

Overnight risk-free rates distinguish themselves by their inherent risk-free or nearly risk-free nature, in stark contrast to the IBORs which encompass an amalgamation of factors, including a bank credit risk premium, liquidity considerations, and supply–demand dynamics. In the event of the permanent discontinuation of the pertinent IBORs,



Data source: South African Reserve Bank[5]

Figure 1: Analysing the dynamic interplay: JIBAR and ZARONIA rates, 28 July 2022 to 19 September 2023.

it becomes impractical to entirely replicate these multifaceted determinants. However, a judicious approach entails the application of a spread adjustment to the corresponding adjusted risk-free rates. The methodologies underlying this approach are devised with three primary objectives in mind:

- To effectuate the elimination or minimisation of value transfer ramifications at the juncture when the fallback is instituted.
- To eradicate or mitigate any potential for manipulation, thereby safeguarding the integrity of the transition process.
- To eliminate or mitigate against the disruptive impact on financial markets that may ensue at the moment that the fallback mechanism is activated.

Spread adjustment

As outlined in the current ISDA protocol[6], the primary alternative for derivatives linked to LIBOR rates involves using the combined overnight risk-free rate along with an extra credit adjustment spread.

The spread adjustment could be calculated based on observed market prices for the forward spread between the relevant IBOR and the adjusted risk-free rates in the relevant tenor at the time when the fallback is triggered. The spread is given by:

$$S(t) = FL(t) - FR(t), \qquad \text{Equation 2}$$

where *FL* is the *t* forward LIBOR rate and *FR* is the *t* forward risk-free rate. This spread gives a current representation of the prevailing market conditions and forward expectations. The fallback rate is then given by:

$$F(t) = FR(t) + S(t). \qquad \text{Equation 3}$$

Wishart processes

The application of Wishart processes in finance is central as it incorporates risks characterised by volatility-covolatility matrices. To acquaint oneself with the foundational concepts related to Wishart processes, it is recommended to refer to seminal works[7-9] and the contributions of Gnoatto and collaborators[10,11]. Additionally, the PhD thesis by Gnoatto[12] provides comprehensive insights into this subject.

Let us begin with a formal definition:

Definition 1. Consider a d × d-dimensional Brownian motion W ($W \sim \mathscr{B}\mathscr{M}_d$), along with arbitrary matrices Q and M belonging to $\mathscr{M}_d(\mathbb{R})$, an initial value x_0 within the closure of positive semidefinite real d × d matrices ($x_0 \in \bar{\mathscr{S}}_d^+$), and a non-negative parameter α. The Wishart stochastic differential equation is represented as:

$$dX_t = (X_t M + M' X_t + \alpha Q' Q)dt + \sqrt{X_t}\, dW_t Q + Q' dW_t' \sqrt{X_t}, ; X_0 = x_0. \qquad \text{Equation 4}$$

Here, X is a strong solution within $\bar{\mathscr{S}}_d^+$, characterising a Wishart process with parameters Q, M, α, and x_0. This process is conventionally denoted as $X \sim \mathscr{W}\mathscr{P}_d(Q, M, \alpha, x_0)$.

In the modelling context, define the filtered probability space $\left(\Omega, \mathscr{F}, (\mathscr{F}_t)_{t\geq 0}, \mathbb{Q}\right)$ and assume that the short rate is driven by a Wishart process *X*, specifically:

$$RFR(t) = \lambda_0 + tr[\Lambda X_t] \quad \text{for all } t \geq 0. \qquad \text{Equation 5}$$

Here, Λ belongs to $\bar{\mathscr{S}}_d^+$, and λ_0 is a scalar. It is essential to note that $tr[\cdot]$ signifies the trace operator applicable to any square matrix.

Monte Carlo pricing

In the domain of quantitative finance, the pricing of intricate financial derivatives frequently demands the application of advanced mathematical models and computational methodologies. One such derivative is the caplet, a financial contract that grants the holder the privilege to receive payments if a reference interest rate surpasses a predetermined strike rate. In this illustrative instance, I embark on the evaluation of caplet pricing, employing a Monte Carlo simulation approach (for a comprehensive discussion of this method, please refer to Glasserman[13]). What adds a noteworthy dimension to this scenario is the contemplation of both backward-looking and forward-looking caplets (each follows a 2×2 Wishart process). These processes are characterised by specific parameters, including volatility and drift matrices, providing valuable insights into the complexities of modelling interest rate dynamics, and valuing these derivative instruments.

The payoff of the caplet over the period $[T_{j-1}, T_j]$ is given by:

$$\tau_j \left(\frac{1}{\tau_j} \left(\prod_{i=1}^{N} (1 + \delta_i RFR_i(t_i)) - 1 \right) + S(t) - K \right)^+ \quad \text{Equation 6}$$

where K is the strike price of the caplet. This is equivalent to a geometric Asian option. The price at time $t \leq T_{j-1}$ of this option is computed as:

$$c_t = \mathbb{E}_t^Q \left[e^{-\int_t^{T_j} RFR(s)ds} \tau_j \left(\frac{1}{\tau_j} \left(\prod_{i=1}^{N} (1 + \delta_i RFR_i(t_i)) - 1 \right) + S(t) - K \right)^+ \right] \quad \text{Equation 7}$$

Equation 7 can be straightforwardly evaluated through numerical methods, such as Monte Carlo simulation. In this approach, we assume that the underlying alternative risk-free rate adheres to the Wishart process outlined in Equation 4. In the subsequent experiment, we specifically examine the following instance of the Wishart process:

$$M = \begin{pmatrix} 0.03 & 0.02 \\ 0.02 & 0.035 \end{pmatrix}, \; Q = \begin{pmatrix} 0.02 & 0.015 \\ 0.015 & 0.025 \end{pmatrix}, \; X_0 = \begin{pmatrix} 0.04 & 0.045 \\ 0.045 & 0.05 \end{pmatrix},$$

$$A = \begin{pmatrix} 1.00 & 0.00 \\ 0.00 & 1.00 \end{pmatrix}, \; \alpha = 0.1.$$

Table 2 and Figure 2 depict the pricing distinctions between forward- and backward-looking caplets in the context of a Wishart process. As observed, as documented in previous research[14], forward-looking caplets consistently exhibit lower valuations in comparison to their backward-looking counterparts. This disparity underscores the significance of comprehending the distinctive characteristics of these

Table 2: Monte Carlo prices and standard errors (s.e.) for backward and forward caplets, with backward caplets showing slightly higher values than forward caplets. Additionally, the Monte Carlo standard errors for these prices are exceptionally small, indicating a high level of precision in the simulation results. The spread adjustment S = 0.003821.

	Strike	0.025	0.03	0.035	0.04	0.045	0.05	0.055	0.06	0.065
Backward caplet	Price	0.0430	0.0406	0.0382	0.0359	0.0335	0.0312	0.0288	0.0265	0.0241
	s.e.	2.840e-05	2.8314e-05	2.8234e-05	2.8404e-05	2.8953e-05	2.870e-05	2.8820e-05	2.9052e-05	2.9058e-05
Forward caplet	Price	0.0423	0.0400	0.0376	0.0353	0.0329	0.0305	0.0283	0.0257	0.0235
	s.e.	4.723e-05	4.7860e-05	4.8295e-05	4.8157e-05	4.8140e-05	4.8502e-05	4.8525e-05	4.8265e-05	4.8746e-05

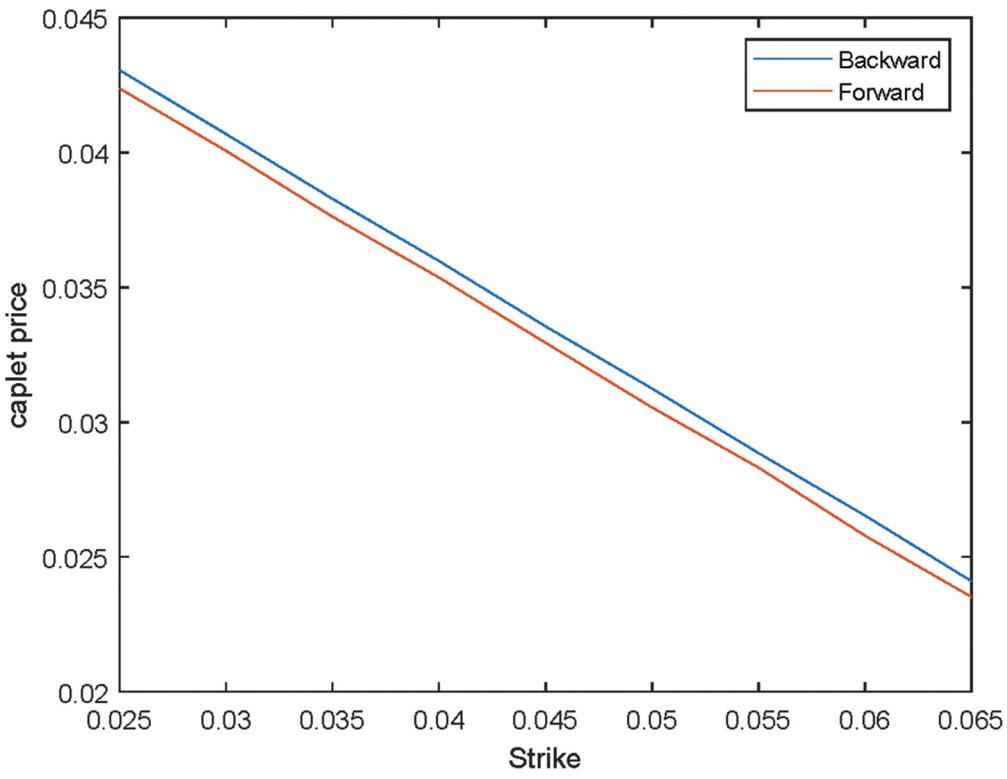


Figure 2: Comparison of caplet prices: forward vs backward looking rates in a Wishart process.

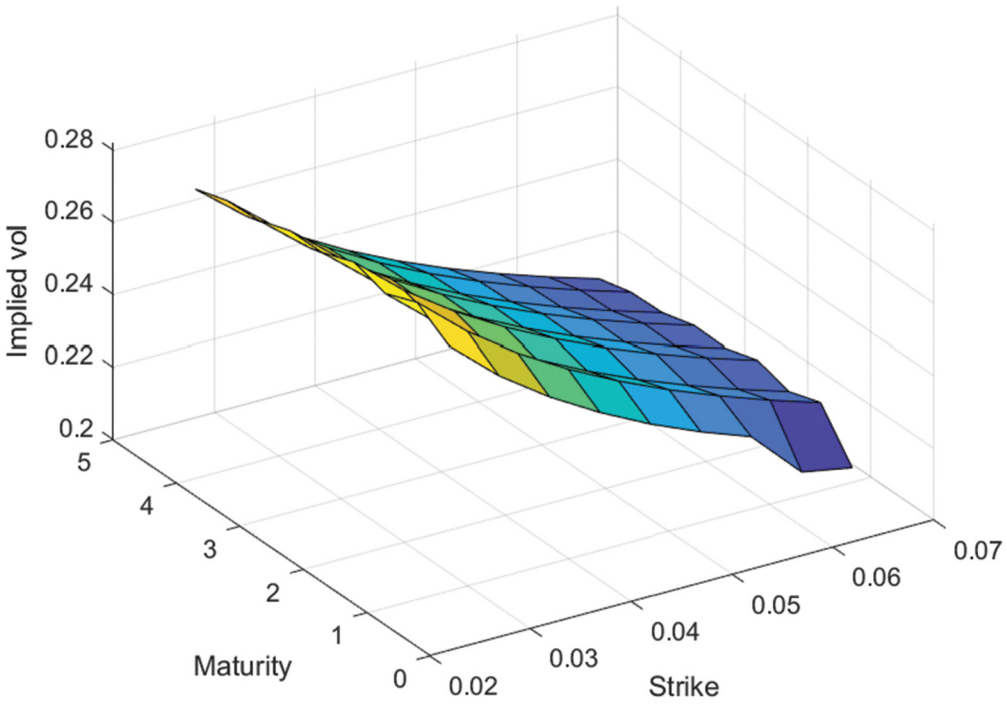


Figure 3: Volatility surface of backward-looking caplets computed using the Fourier-based method in a Wishart process.

caplets in the realm of risk management and financial decision-making, especially in the context of emerging benchmark risk-free rates.

Figure 3 presents the volatility surface of backward-looking caplets, computed using a Fourier-based method as discussed by Fantana[14], within the framework of a Wishart process. This visualisation offers valuable insights into the complex dynamics of interest rate derivatives.

Conclusion

As highlighted by SARB[4], the process of transitioning from JIBAR to alternative reference rates in South Africa represents a substantial and pivotal endeavour, bearing significant implications for the nation's financial markets. Notable advancements have been achieved in this endeavour, encompassing the establishment of an alternative reference rate, ZARONIA, and the extensive dissemination of knowledge within the market. Nonetheless, the transition is accompanied by persistent challenges, particularly in the context of adapting to the distinctive characteristics inherent to South Africa's financial landscape.

The consequences of this transition, particularly within a relatively compact market, underscore the importance of meticulous analysis and effective risk management. The indication of South Africa's readiness, propelled by regulatory backing and proactive involvement of market participants, is a positive signal. However, it is imperative to maintain a vigilant stance, ensure clear communication, and undertake comprehensive analyses as the transition unfolds. By actively addressing the identified challenges and conducting the requisite analyses, South Africa can navigate the JIBAR transition with success, ultimately contributing to the cultivation of a more resilient and transparent financial system for the foreseeable future (see for example Backwell et al.[15]).

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Competing interests

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Without access to social media platform data, we risk being left in the dark

Significance:

Social media data are essential for studying human behaviour and understanding potential systemic risks. Social media platforms have, however, begun to remove access to these data. In response, other countries and regions have implemented legislation that compels platforms to provide researchers with data access. In South Africa, we have lagged behind the Global North when it comes to using platform data in our research and, given the recent access restrictions, we risk being left behind. In this Commentary, I call attention to this critical issue and initiate a conversation about access to social media data in South Africa.

> *Subatomic particle physics has CERN. Astronomy has the Hubble telescope. Social science has the Internet, smartphones, email, social media, satellites, and a myriad of other ways to follow human behavior. The gods of the information age have produced a whole panoply of technologies for social research along the journey to other destinations.*
> *– David Lazer*[1]

For scientists interested in understanding the character and effects of individual and collective behaviour, the digital age has brought about new opportunities to observe and measure human interaction at scale.[2] The Internet, and social media platforms in particular, provides us with unprecedented (albeit socially and algorithmically biased)[2,3] access to robust data on these interactions[4]. Facebook, Instagram, Twitter/X, TikTok and other social media platforms have not only fundamentally altered the ways in which we communicate with others but, by scaffolding how we interact with and engage with individuals, ideas, and organisations, they have reconfigured the public sphere itself.

Throughout our everyday use of these platforms, we leave behind digital traces of our behaviour as by-products of our interactions with other users and entities.[5] These digital traces hold tremendous value for studying the nature and consequences of (mediated) human behaviour at individual, group, and population levels. For example, through social media platform data we can investigate, among other things, misinformation campaigns, election interference, the spread of infectious diseases, polarisation, and the effects of particular interaction patterns on user's mental health and well-being.[6-8] Collectively, such data provide an important lens that enables both fundamental research on human behaviour as well as research on the potential systemic societal and economic risks posed by social media platforms. This importance is reflected in the growing prominence of computational social science across academic disciplines.[9]

Despite the considerable opportunities that these data hold, and the widespread use of computational social science in the Global North, research in South Africa, and the Global South more generally, has thus far made only limited use of digital trace data compared to the engagement observed in the Global North.[10,11] While there are likely many factors underlying this general disparity, and numerous counter examples of interesting studies in the Global South leveraging digital trace data, unpacking these factors falls outside the scope of this comment. For now, it is sufficient to acknowledge the existence of this general disparity. Despite only limited use of digital trace data collected from social media platforms in South Africa, it is no less important here than it is in the Global North that we understand how these platforms impact, for better or worse, ordinary South Africans, our society at large, and potentially our hard-fought democracy.

"The way is shut" – restrictions on access to social media data

Unfortunately, while social media platforms continue to collect and analyse user data, in the wake of various scandals, the fears surrounding unfettered data use for the training of large-language models, and a general reluctance to face external scrutiny, most social media platforms have restricted and/or entirely removed access to the application programming interfaces (APIs) that researchers used to access platform data.[12-14] The shuttering of these APIs has brought large swathes of social media research to a halt and, in doing so, severely jeopardised the extent to which we can learn about behaviour online and the very real consequences that this behaviour can have for individuals and societies.[12,15]

While alternative approaches to collecting social media data exist (e.g. self-reports, web scraping, browser extensions, data donations)[5], and some researchers have partnered directly with social media platforms to access data, for various reasons these techniques fall short of the high-quality individual-level data available directly from platforms[4,5,14], or in the case of direct partnerships, are only available to a select privileged few (who are almost exclusively based at institutions in the Global North). For this reason, we require direct, equitable access to social media data, without which we will be left in the dark when it comes to important individual and societal questions.

"A light from the shadows shall spring" – regulations to compel data access

In response to these restrictions and the broader recognition of the power that online platforms hold, the European Commission has implemented several key regulations as part of a broader set of legislation designed to govern the digital sphere in the European Union (EU). With the aim of fostering a safer online environment, the *Digital Services Act* (DSA) will, among other things, compel online platforms operating within the EU to prevent and remove posts containing illegal content, to ban certain types of targeted advertising (e.g. sexual orientation, religion), and to provide greater transparency into how their content algorithms work. For "very large online platforms" (i.e. those

with at least 45 million monthly users in the EU, which covers most popular social media platforms and many other more general services like Booking.com and Google Maps), the act also requires that platforms (1) enable users to be able to opt out of recommendation systems, (2) be subject to external and independent audits, and (3) share data with researchers and other vetted independent 'watchdog' organisations.

This latter requirement, described in Article 40 of the DSA (see https://www.eu-digital-services-act.com/Digital_Services_Act_Article_40.html for the full text), is particularly important given the stranglehold that platforms have over access to data. Article 40 of the DSA compels very large online platforms to provide vetted researchers with access to data "for the sole purpose of conducting research that contributes to the detection, identification and understanding of systemic risks in the Union" and sets out the rules governing this access. While the DSA has been in effect since 25 August 2023, the code of conduct for practical compliance with the regulations remains a work in progress, and the full implementation will occur only in 2024 (see Klinger and Ohme[16] for a set of recommendations for what this should look like). Indeed, managing vetted researcher access to platform data poses substantial challenges for the protection of personal user data and privacy, but also for the design, implementation, and running of the necessary infrastructure to securely manage, store, and process researcher data access. Despite these challenges, the DSA, and Article 40 in particular, provides an important example for other countries seeking to break the stranglehold that social media platforms have over their data, and enable robust and equitable access to critical data for research purposes.

Although research using digital trace data collected from social media platforms in South Africa has lagged behind research conducted in the Global North, given the rapidly growing adoption of mobile Internet-connected communications technologies (i.e. smartphones), the increasing roll-out of 5G bandwidth, and the general digitalisation of our economy, it is likely that there exists a similar potential for systemic societal risks posed by social media platforms here as there is in other countries. Unfortunately, given the ongoing restrictions and closing of platform APIs, South African researchers are left without any reliable, legal means of accessing data from social media platforms. Without access to social media data, not only do we risk getting left behind when it comes to research on important topics (e.g. misinformation, online political interference, digital well-being) but, perhaps more importantly, we are left without any means of developing insight at scale into online behaviour and the potential risks that it imposes for South Africans and South African society.

"All we have to decide is what to do with the time that is given to us" – an example of how to move forward

To ensure free and objective research on behaviour on social media platforms and the potential systemic risks that actions on these platforms can pose for individuals and society, we require reliable access to platform data. The EU has set an example for how this access can be achieved. While it would be naïve to assume that South Africa holds the same degree of economic clout to impose similar regulations on platforms with any chance of them being effective, we should not be afraid to explore other creative possibilities to enable research with digital trace data to flourish and contribute to our collective understanding of the character and risks of online behaviour. These possibilities could include the development of infrastructure for data donation at scale or the establishment of large-scale consortia to leverage current best practices to collect and integrate available data (see, for example, the European Digital Media Observatory project). Alongside these possibilities, I propose that we embrace the 'Brussels effect' (i.e. the de facto though not necessarily de jure externalising of EU regulations outside of the region's borders due to various market mechanisms) and seek to leverage the DSA by (1) lobbying the South African government to implement similar regulations 'piggybacking' on the DSA, (2) coordinating with relevant stakeholders in the EU to ensure that the code of conduct makes provision for broader access (see Klinger and Ohme[16]), and (3) in lieu of formal policy, collaborating with researchers in the EU who will have access to social media platform data.

My second and third propositions extend from the fact that the DSA is implemented on the basis of the 'market location principle' (*lex loci solutionis*), which holds that, irrespective of the location at which the platform was established, because the platform offers services in the EU/to EU citizens, non-European data also fall within the scope of the regulations. This implies that data from South African social media users will be available to researchers within the EU (but not presently researchers in South Africa). Notably, Article 40 does not necessarily preclude access to individuals based outside of the EU. Article 40(8)(a) of the DSA read together with Article 2, point 1 of the Digital Single Market Directive suggests that to be eligible to access platform data one should be affiliated with a non-profit entity located in any country devoted to scientific research. The regulation does, however, restrict the geographic scope of the research foci for which access to platform data will be provided. Both Article 40(4) and Article 40(12) suggest that the research must study "systemic risks in the Union." In a broad interpretation of this restriction, Husovec[17] argues that "research focusing on risks in the Union needs to study non-EU countries to be scientifically sound." This interpretation suggests that, notwithstanding the data privacy concerns associated with cross-border data sharing and the practicalities of data access outside the EU, with careful justification, we can leverage this legislation to access data on South African social media users. Regardless, our 'first prize' would be the production of similar legislation in South Africa (proposition 1) so that we can avoid being reliant on partnerships with researchers in the EU. In doing so, we would not be alone; recognising the growing prominence of the digital/online environment, many other countries are developing legislation in this regard. The UK Online Safety Bill, for example, contains similar provisions to the DSA.

With this Commentary I have aimed to call attention to this critical issue, highlight the need for increased use of digital trace data in South African research, raise concerns about our rapidly disappearing access to platform data, and initiate a conversation about the need for policy enabling research with social media data in South Africa. While the EU has provided an example for how we can achieve increased transparency and access to social media data, developing and implementing the relevant legislation fit for our economy will not be an easy task. We will require input from experts in many disciplines (e.g. law, economics, computer science, and the social sciences at large) and the establishment of resource-intensive data intermediaries who can steward (collect, maintain, share) access to platform data as well as the development of infrastructure to enable and manage these procedures (data clean rooms, virtual laboratory environments, etc.), all while being mindful of the substantial ethical and privacy risks posed by increased data access (see de Vreese and Tromble[14] for a discussion of how research data access can co-exist with data privacy regulations, and point five in Klinger and Ohme[16] for recommendations on how data sensitivity can be managed). Despite these challenges, I believe that, without proactive effort, we risk being left behind without any robust means of studying the potential systemic risks at play.

Competing interests

I have no competing interests to declare.

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Why so few Ps become As: The character, choices and challenges of South Africa's most talented young researchers

In this research article, we examine why so few of the most promising young scientists in South Africa, those who obtain a P or 'prestigious' rating from the South African National Research Foundation, go on to obtain an A rating, i.e. become leading international scholars in their fields. Drawing on in-depth interviews with 36 P-rated scientists in the period 1983 to 2022, we found that personal characteristics (such as work ethic), the right international networks, and strong departmental support are among the key factors that explain the research accomplishments of highly successful achievers.

Significance:
The research is significant for two reasons. It explains why so few promising young scientists in South Africa become world leaders in their respective fields and, in particular, why even fewer young black scientists achieve the highest ratings in their disciplines.

Introduction

In a companion study on young scientists (including social sciences and humanities scholars) with a rating from the South African National Research Foundation (NRF), we found that the P rating showed a poor predictive validity with respect to its granting assumption: that Ps were likely to become world leaders in their respective fields which, in NRF terms, means an A-rated scientist.[1] In fact, of the 136 Ps awarded since inception (1983 to 2022), only 20 (14.7%) became As. Of these Ps, 21 were still in their P cycle in 2022. If we exclude them from the total, then 20 of 115 eligible Ps became As (17.4%). Figure 1 illustrates the progression of Ps to higher ratings between 1983 and 2022.

This does not mean that the P is not a good differentiator in terms of future success when compared with the lower rating for young scientists, that is, those who obtain the Y rating, as Figure 2 shows.

In this regard, two distinct trends emerge for P- and Y-rated researchers. For P-rated researchers, the distribution is skewed towards the higher rating categories, peaking at B1 (31%). In total, 78% of P-rated researchers (excluding those without further ratings) ended up achieving a rating of B2 or higher, while only 13% received a C rating (C1–C3).

For Y-rated researchers, the distribution is skewed towards the lower rating categories, peaking at C2. In total, 77% of Y-rated researchers (excluding those without further ratings) went on to receive a C rating (C1–C3), while only 24% went on to receive a rating of B3 or higher. It should be said that obtaining a P rating as a young scientist is an impressive achievement in its own right – not many P ratings are awarded by the NRF, and most young applicants who are rated would begin their careers with a Y rating.

Background

The NRF is a statutory body mandated by government to fund and support research and development in South Africa. One of its core functions is to assess and rate the scholarship of individual scientists through a peer-review-based rating system. Younger scientists, under the age of 35, can achieve a Y (Y1 or Y2) rating or the rare P rating. More established scientists compete to be awarded a C (C3, C2, C1) or B (B3, B2, B1) or A (A1, A2) rating with the stated gradations (in brackets) for each of them.

Each category of award has its own careful description. The Y is a promising young researcher, while the P is a prestigious award. The C is awarded to an established researcher, the B to an internationally acclaimed researcher, and the A to a leading international researcher. Each gradation within a category has an even more refined description to distinguish, say, a C3 from a much higher rating, the C1.

In the NRF stipulations, P awardees are those young scientists "considered likely to become future international leaders in their field" and who, in the review process, are "recognised by all or the overwhelming majority of reviewers as having demonstrated the potential of becoming future international leaders in their field on the basis of exceptional research performance and output".

Given these heightened expectations, we wanted to know who exactly the Ps are and why so few of them became A-rated scientists.

Approach

This report represents qualitative research grounded in the etic or insider perspective on doing advanced research within universities. An initial interview protocol was piloted with non-participating young scientists and amended accordingly. The thick data generated from the 36 transcribed interview sets was qualitatively analysed for convergent and divergent themes, out of which emerged the seven key findings. This is a non-judgemental inquiry in that the words of the P-rated scientists represent their own experiences, methods, and ambitions.

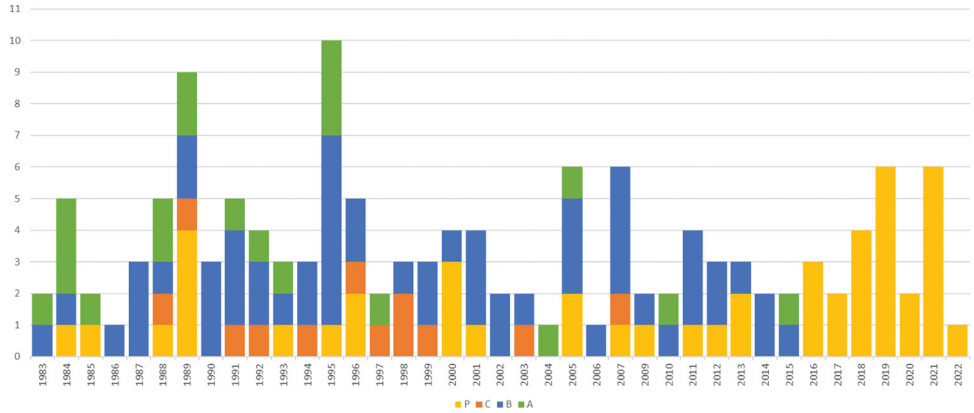
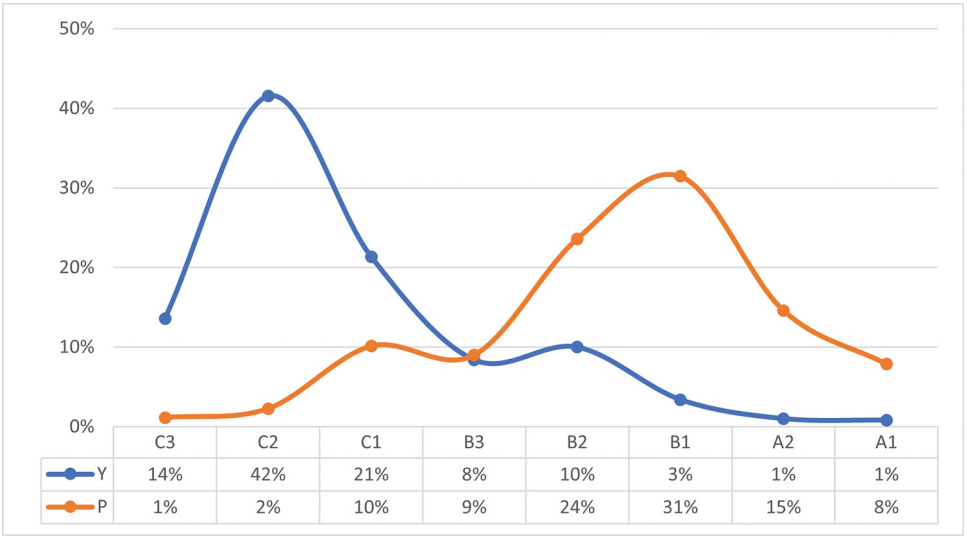


Figure 1: Highest rating achieved by P-rated researchers, by year in which the P rating was first awarded.



	C3	C2	C1	B3	B2	B1	A2	A1
Y	14%	42%	21%	8%	10%	3%	1%	1%
P	1%	2%	10%	9%	24%	31%	15%	8%

Figure 2: Comparing the senior ratings (A,B and C) eventually achieved by P- and Y-rated scientists.

The themes induced deductively from the qualitative interviews are not mutually exclusive. Nor do we claim that they represent the full range of explanations for success or otherwise of young scientists striving to become top-rated senior researchers.

To understand the low conversion rate of Ps to As, we interviewed 36 of the 136 Ps (26.5%) who were sampled based on their availability, their disciplinary diversity, and the extent to which they enabled a more or less equal distribution of numbers in each of the following three categories:

- In category 1, we interviewed Ps who actually became As over time (7 or 19.4% of this group). The purpose of the interview was to understand how and why they became As by asking questions about their work habits as researchers and their connections to the broader world of science collaboration.
- In category 2, we interviewed Ps who did not become As (15) and received their prestige rating 10 or more years ago. How did these scientists explain their lack of progress towards the highest rating for which they seemed destined?
- In category 3, we interviewed recent or new Ps (14) to understand what meaning the P held for them today, their work habits, and whether they would apply for re-rating when the time came.

Throughout, we anonymised the responses, with respect to both individual and institution.

We found seven key factors that explained the research trajectories of the P-rated scientists – for those who became As, those who did not, and those planning to become international leaders in their respective fields.

1. Work ethic

More than anything else, the single most important factor distinguishing 'Ps who became As' from other competitive young scholars is an extraordinary single-mindedness of purpose when it comes to research and publication. In other words, it is not primarily about the research environment or the availability of funding (external factors, things that can be built or supplied) but about the internal qualities of the P candidate. Those qualities are expressed through a dogged determination to succeed, a laser-focused attention on the research project, and an exceptional work ethic.

An A-rated plant scientist who has held that status for multiple cycles, estimated that he works

> *about 80 hours a week, though not every week. I'm probably an obsessive-compulsive kind of person. As I get older, I need to start scaling down, but I don't know what that means. I need to stop this.*

It is a story repeated among the Ps who became As – stories of long hours, working on weekends, writing on planes, and being driven. As an accomplished P-to-A female medical scientist also shared:

> *I work between 60–80 hours per week for as long as I can remember. I am a workaholic, punishing myself in terms of meeting deadlines. I am organised and extremely hardworking.*

This gruelling research schedule is by no means limited to the P-to-As group, but can be found also among the more recent Ps, as explained by this young microbiologist: "I work almost all the time, my hobby tends to be work which I am told constantly is not good, but I do work quite a lot." A more established P, who gained a B rating in the plant sciences, was interviewed during a research sabbatical in Europe:

> *On Sunday night I got home at 8pm and it's the earliest I have been home for 2–3 weeks. I get really passionate about what I do.* [As a younger researcher] *my wife would visit me in the lab over weekends so that we can have some time together.*

It is this relentless commitment to productive work that also explains why these young scientists become Ps in the first place. For some, this particular mode of work is taken as normative, as a rare P in the field of law surmised: "I don't know of a single academic who has done well who doesn't work weekends or in the evenings."

With such a determination to succeed among the Ps, it is no surprise that there is a strong passion for their science and an equally strong commitment to achieving the ultimate rating (the A). When this does not happen, or not immediately, there is intense emotional fallout. One scientist, who changed her field to molecular microbiology, was devastated when she went from a P to a mere B2 rating. "I was hammered by that; if you change fields you're messed up, ok? You are completely messed up." She would eventually obtain an A rating.

A tree pathologist steadily made his way from a P to a B1 to an A1, but then surprisingly found himself 'demoted' to an A2 when in fact his research and publications had soared before that: "I was furious, I was absolutely furious. It was highly offensive and upsetting and I asked for an appeal." He too would later regain and maintain an A1 rating to this day.

For these accomplished, passionate scientists, the evidence is clear that the groundwork for becoming an A is laid early through a highly active and productive work ethic during the years of doctoral study, as well as the immediate postdoctoral period. Put differently, the Ps obtain their prestigious rating because of a surge of publications before they even secure a permanent academic position. Consider the case of this highly productive young anthropologist, as she came up for her P rating:

> *I think I am right in saying that the P was awarded on the basis of two books, an edited collection, another book, 11 book chapters and 19 journal articles. It is interesting to read my CV this way!*

However, none of this could be achieved without a considered plan.

2. Strategy

Most Ps were identified early on, encouraged, and prepared for the rating by institutional mentors. One P had applied for a rating, but his application was intercepted by a senior academic reviewing the university's pool of applicants. The young scientist was called in to discuss delaying his submission until two or three additional research milestones had been achieved; in other words, the current application would likely get a Y rating but with a considered strategy, could very well become a P. Two years later, the candidate applied and was awarded a P. Another P had no intention of applying for rating at all, but his scientific work was noticed by a senior professor in his department. Together they worked on a strategy that would eventually lead to a successful P application.

The top research universities all have *institutional mentors* embedded within the system. These are senior professors who themselves enjoyed superior ratings in their academic careers and know 'what it takes' to become a P-rated scientist. However, the mentors are not formally appointed or even recognised in the administration; for them, it is their academic duty[2] – a service to up-and-coming scientists. What they have in common is a commitment to identify and nurture future stars of the academy.

Each institutional mentor has a more or less similar strategy to guide the potential P. Make sure you have enough quality publications in high-impact journals showing first authorship. Choose your reviewers carefully from your international networks, scientists who know you and your work. Do not rush; submit only when there is sufficient evidence of high-level academic outputs to merit P rating consideration. Take time to write a carefully crafted narrative that explains the singular focus of your research. Show evidence of what comes next in your research journey so that reviewers have a sense of your future trajectory.

Regardless of what the mentor advises, the finer points of strategy still depend on the drive and calculations of the P candidate, and no one better lays out the plan for success than this new P in philosophy whose intellectual interests lie in the field of computational linguistics. We summarise and paraphrase his strategic thinking here:

> *I knew I had to get my name into the* Stanford Encyclopedia of Philosophy. *But how would I do that? I needed to find a famous co-author, which I did. I then realised I needed to get an invitation to the top journal in the field,* Philosophy Compass, *which I did, and single-authored an article on the philosophy of linguistics. I was encouraged by my doctoral examination committee to put my new thinking into a book. I got a mentor who is an A-rated philosopher and he put me in touch with Oxford University Press. At the time, I also got the Pittsburgh Philosophy fellowship and prepared a proposal for another book to Cambridge. What this means is that I will hopefully have two books coming out in 2023 (Oxford and Cambridge).*

Few of the 36 Ps interviewed demonstrated such incredible clarity of thought and refinement of strategy as this young philosopher. While several of the new Ps were unclear, and sometimes even ambivalent, about pursuing the path towards an A rating, this philosopher had clearly done substantial work suggesting that he is on track to becoming one of only three Ps who got an A evaluation within one 5-year cycle. He certainly carries that expectation: "I would be extremely disappointed with myself if I were not able to achieve an A in the next round."

Central to the effectiveness of the strategy of the Ps is the extent and the quality of their international networks; on this they are all agreed.

3. Networks

Without exception, every P did their PhD and/or postdoctoral fellowship at a top international university. A few did all their degrees overseas at prestigious institutions such as Princeton, Harvard, Oxford, and Cambridge, but all the Ps had some connection to well-known universities, mainly in Europe and North America. It was during these periods of placement abroad that two vital things happened: they were at their most productive in research and publications, and they built close and enduring relationships with the leaders in their fields. Without those international networks, the respondents agreed, they would not have experienced the phenomenal growth that led to the P award, and the academic recognition that came with it.

One of the Ps who became an A, who did his PhD at a top university in his field, makes the point that "I was already connected to the stars" and that such "global connectedness was absolutely crucial" once he returned to South Africa. For another, the international placement gave her "unfettered access to time and people and resources". All the Ps maintained those critical networks, but it required hard work. "I would go once a year to talk to the doyens" explains another P-to-A scientist "and I benefitted merrily … and found myself in two of the leading labs in the world".

For all these P-rated scientists, maintaining those networks meant travelling a lot. One of the new Ps who recently became an A remembers that "I was out of the country for one week every month" before

slowing down to spend more time with his family. "If you want to go to an A-rating" insists one of the other Ps, "you need to be known in the international community – that is my strong advice [to prospective Ps]." As indicated earlier, the many hours of plane travel enabled productive, undisturbed work that many of the Ps would exploit as they went back and forth between their home universities and a laboratory or seminar room in a distant land.

What became clear through the interviews is that none of these international networks and collaborations was incidental, random, or the outcome of occasional visits. They were part of a systematic and strategic plan and therefore every network was carefully chosen and nurtured over time. One of the Ps, a tree mycologist, made the interesting point that "you just need to know five people" and that "if you know [them] everything changes, everything".

Consider the mechanisms that enable such productive introductions, as retold by this P in plant physiology (not their real names):

> *I did my* master's *with Michael, who introduced me to Trevor to host me at his lab in Tasmania. In the same way, I did my PhD with Dick, who had a close working relationship with Dave at Berkeley, in whose lab I did my postdoc work. So, the networks were fundamental. I owe my career to the networks that I have been able to take advantage of and develop.*

The scientists approached are all highly accomplished leaders in their fields, extremely busy and always in demand in their professional communities. An unknown young scientist from Africa would certainly not be able to command such attention, and this is where the introducer becomes so important in the life of a P.

Where the young scientist enters doctoral studies with a famous scientist as supervisor, a relationship develops over three or more years in which the novice and the leader often become friends. Smart Ps would invite their supervisor to South Africa for a seminar or conference keynote, and even do joint publications that further cement the relationship. The loyalty that develops over time means that the ex-supervisor or mentor now takes on the task of introducing the young scientist to stars in allied networks. The role of the introducer is therefore essential to the success of the future P. It is clear that these rich networks both reflect the aggregate resources for research in the Global North as well as the inequalities in relation to what is available in staffing and infrastructure in the Global South.

Nonetheless, when they did find themselves in those rarefied international research spaces, the Ps would exploit the resources and expertise to the full before returning home. As one P retells, "I did every single early career workshop. I signed up for every single opportunity in this well-resourced, creative environment." What these accounts underline is that the placement of the P is crucial for optimising the learning opportunities that come from international networks. A young P even observed that some colleagues were "working overseas to improve their subsequent ratings". Back home, it is the department that matters.

4. Department

Where a newcomer P 'lands' in an academic department plays a significant role in their ability to flourish – or not – as young researchers at the top of their game. One P enters her department as a lone astronomer eager to build a research group from scratch because there was no infrastructure. With her American PhD she finds herself in what she calls a staid English academic culture which is discouraging, even spiteful. P stands for *prima donna*, she would hear, and finds department colleagues to be indifferent at best and 'nasty' at worst. Shortly afterwards, she leaves that South African university.

One of the very first Ps remembers coming into a university without a secure job. In fact, "I came into a complete vacuum as a P awardee." At the time, his physics department had no postgraduate students and so it was always going to be difficult to build a research group. It was also clear to him that people in his department had no idea what exactly a P meant. Before long, he too abandoned an active academic research career.

On the other hand, when a P lands in an academic department with a strong research culture and a known record for high-level scientific work, the young scientist finds the necessary stimulation and support that buoys their own academic ambition. There are already active research groups and regular seminars and networks that bring top scientists in and out of the department. One P remembers entering her South African academic home being "surrounded by brilliant people with a Nobel Laureate next door" and speaks of the department as "this powerhouse of a place that ranks by certain metrics as number 1 in the world in tuberculosis research".

For another P, the relationship with the department was transactional: where the P was productive in the generation of research and publication, there would be more opportunities to find relief from the more burdensome tasks of teaching and administration. As he remembers,

> *because I was showing success, they allowed me certain freedoms to be able to focus more on my research … the more you can deliver, the more freedoms you have and the more support you get.*

However, even in well-resourced universities with communities of postgraduate students, where you land as a P depends entirely on how the head of department sees the prestigious award. Two contrasting experiences from interviewees are instructive.

When a young scientist in plant physiology attains a P rating, his head of department immediately begins to shape the work environment in such a way that enables his research to flourish. He would encourage grant applications and support the research-driven individuals. "I have been given a relatively light teaching load so I can focus on the research" said the appreciative P, adding that "my HoD has been incredibly supportive". What was striking about this focused support for the P is that he had just been appointed, which would normally mean that, as the 'newbie', he would be given a substantial teaching load. For this HoD, however, the research potential of his new appointment was to be optimally realised. In response, the new appointee's "main motivating driver at this point [is] to make a success of my P and to focus on the research".

At a neighbouring university less than an hour's drive away, another scientist recalls that after the initial fanfare around the P award there was little support, no mentorship, lots of politics, and a lack of responsiveness to personal research needs. His teaching of large classes came with a significant administrative load so that "I certainly burnt out and there was no recognition from the department that the research component should be prioritised over the teaching component". While he had grown a research group, won competitive funding, and published, it did not matter to the department leadership. In the end, the work became "too tiring", and the P-rated scientist emigrated with his family to another country.

5. Transformation

Only two black scientists ever progressed from a P to A: one in cardiovascular genetics (now deceased) and one in vertebrate palaeontology. The relatively small number of black rated scientists in general, and Ps in particular (7 out of 136, or 5%, until 2022), of course reflects the inequalities of social and scientific opportunities for black students and researchers over centuries.[3] But what explains the fate of the remaining Ps who were in the system long enough to have attained an A rating? They all shared a common experience: the pressure to lead transformation in senior administrative positions, which in turn had direct negative effects on their research performance.

Two of the seven black Ps won the president's rating, as it was first called, around the time of the country's transition from apartheid to a constitutional democracy. It was a period of great expectation for highly qualified black scientists – many of whom came under pressure to lead and transform the solidly white scientific establishment in the early post-apartheid years and to build strong faculties in the historically black universities. Here are vignettes or short stories of three black

Ps who went into leadership in universities and in science enterprises off-campus.

The first black P felt the pressure immediately. Barely out of doctoral studies and having just attained the P rating, he was definitely looking forward to a productive career in theoretical physics. But he was told that there was a real chance that the black university where he worked could lose its struggling engineering faculty. He answered the call and found himself "drawn into deanship to save the faculty of engineering". That the P scientist was a physicist and not an engineer did not seem to bother the university's leadership. They needed a leading scientist whose knowledge and reputation could rescue a faltering faculty. "I made those choices, not unwillingly", indicating that the lure of leadership through service was a conscious commitment.

Because of his success as a university leader, this P was soon afterwards drawn into leadership at the neighbouring white university as well. This was the institution where he studied as a minority on a then overwhelmingly white campus and his "terrible" experiences there as a student served as an additional incentive to want to lead there. As he recalls, "I did feel that the transformation of University X [the former white institution] was something I had to do; it was after all the late 1990s and there was pressure to change things in higher education."

Clearly, there would be little dedicated time for building a research career in physics and that sense of loss came with regret. "You see your [research] life just flitting away … I really do regret some of those years." It could have been very different. "If I had stayed in physics there is little doubt that I would be an A."

The second black scientist achieved his P in 2003 in the field of artificial intelligence during his first year as an academic. With a significant amount of funding at his disposal from both the NRF (ZAR100 000 per year over 5 years) and ZAR2.5 million that came with a prestigious research chair, he was ready to launch his scientific career "with money I could not possibly finish". He recalls that "as my rating expired (2008) I became Dean of Engineering".

By this time, his research was already taking strain and with the re-application for rating (2008) he received a disappointing C2 rating, which he read as "punishment for working in diverse areas". Once again, the P was identified as a leader in his university, but he insists "I did not seek to be a manager; I was called to consider the role and told I could return to being a scientist if it did not work out. I never came back."

In the interview, the former P drew our attention to his Google Scholar chart showing the frequency of publication by year in the form of a bar graph. "Every time I took a leadership position my publications went down, literally. Dean, Deputy Vice-Chancellor, Vice-Chancellor, down. There is definitely a cost to this which we cannot avoid." One of the consequences of immersion in management and leadership is that attendance at signal academic events came to an end. "I have literally never attended research conferences since I became a manager."

The third scientist whose vignette is shared here obtained his P in 1997 at the age of 35 after completing a PhD in physics under a Fulbright Award in the USA. Returning to his alma mater, there was some excitement generated around the new P, but this was not matched with a hospitable research context. As he recounts: "Through the P rating I was able to kind of aspire to something that was world-class but in reality, the local environment did not support that."

Raised in an era of activism, this P would soon feel the pressure in and outside this former white university to lead transformation in physics. Unlike others who were called on to lead by senior colleagues, this P felt an obligation to do so across a number of science fields at the same time. "I felt as a South African and as a scientist in South Africa, I had many more responsibilities to lead."

The P tried very hard to maintain his active research record during spells as a dean at two elite universities in South Africa, with some success. "I am still doing science, I have a PhD student, I give talks, but I am unable in my dean's role to continue at the highest levels of science."

The only P in education would reflect that when he took the deanship of his faculty, "without doubt it derailed the research machine, without doubt. You cannot do very good research in leadership, for it requires deep thinking for which there is no time. It has come at a personal cost … and I feel sore".

6. Motivation

In the early years of the evaluation system, the main reason for applying for a rating was that it was required in order to access research funding. One of the very first Ps remembers that his university at the time did not have money for research to support their researchers nor did his senior leaders understand the value, or for that matter the workings, of the nascent rating system. The young mineral and process engineer had no laboratory or equipment to speak of, so he applied for the rating and, as a consequence, could start building the beginnings of a research enterprise.

In today's value, the early rated researchers once received significant sums of money for their research. In 1984, a P received ZAR100 000 (ZAR2.04 million in today's money) and in 1991, ZAR750 000 (ZAR5.79 million) while today (2023) the individual P receives a mere ZAR50 000 per annum from the NRF. It should be said that it was difficult to pin down a clear or consistent value of NRF allocations to Ps (or other rated researchers) as the rationale and magnum of funding changed almost every year, including periods of no funding at all, as well as a period of 'incentive funding' that stood apart from the traditional allocations of award.

Regardless, in time it became clear that the motivation for applying for a P rating had little to do with accessing research funds through the NRF allocation. The process of applying is too onerous, as all the Ps agreed, and the size of the award too small if money was the only motivation. So why did Ps apply for rating?

For some it was quite simply a matter of obligation towards the department; in other words, academic staff were either encouraged or required to apply in a university eager to improve its standing as a research institution in the South African higher education landscape. These metrics are publicised on university websites and comparisons are often made with other public universities.

For other Ps it was more calculated, a personal decision quite apart from what the department or faculty or the university might require. "I got a sense it was a good idea, so I applied" says an ecological scientist who was attuned very early on to the world of research. She was exceptional: one of only two who started at P and progressed straight to an A rather than via the C, or more likely B, rating first. As an undergraduate student she was already co-publishing research papers, having grown up with parents who worked in the science community.

"I applied to establish myself," said a humanities P conscious of the value of this prestigious rating within his research-intensive university. For him, and others, the process of completing the online application might have been arduous, but it also offered the opportunity for self-reflection – such as composing the narrative that threaded together the various elements of the candidate's current and future research. "It was a self-actualising tool," offered one P.

There were other benefits too. "The P put me on the map of the university leadership," said a science P. Others spoke of being able to negotiate a more permanent position (bargaining power, in other words), the opportunity for promotion, and the "opening of doors" to influential people in the university. One P spoke movingly of the recognition that came with the award, saying that, "It was the first time in my life that somebody recognised the quality of the research work I'd done."

And, while the P award from the NRF in the 2000s might have come with a modest financial allocation, many awardees found unexpected contributions from their university. Some universities provided funds to match the NRF allocation. Others would add a 25% salary bonus, or an "exceptional achievers" award made annually for the duration of the P. One institution offered a generous multi-year institutional award, easily accessible for up to ZAR350 000 per annum. And of course, the P status

of the individual could be used to leverage external research funding for a distinguished research chair or a generous international grant.

7. Life

A sizeable number of Ps (47 out of 136, or 34.5%) did not pursue a further rating. The reasons vary considerably from one individual to the next. Some left for industry (this applied particularly to those in the applied sciences and engineering fields, although most maintained some foothold in the academic world); others felt disenchanted with the lack of support in the academic environment and found themselves moving jobs in and outside of universities simply to survive; one left the university environment altogether because he could not even secure an entry level job in his department with a P in-hand.

A recent P, a geochemist, was about to leave for her native country in Europe because of difficulties securing a visa extension. A few wanted to disconnect from the intensity of the research environment – very much holding the attitude expressed by one P, "I am not a hamster, I'm not jumping onto that wheel." In the latter case, the disengaging P often cites the prioritisation of children and family over the intense research demands made on high-flying young scientists.

There are also Ps who migrated because of conditions in the country. One of the first Ps left because he "could not see any opening of society" during the apartheid years. But others left because of concerns for their safety and security in the new South Africa. One P, a historian from Italy, was offered permanency and seniority at his university, but it was not enough. His new wife felt unsafe in a city known for high levels of crime, whereas "back home she likes to take long walks at night which she can do safely over there". Another P cites the hijacking of a family member and concerns over the future of his children for relocating to a research and development industry opportunity in Australia.

"Then life happened," mused one P in a lengthy email responding to our research questions. This fig biologist would suffer a series of chronic health challenges which included physical, psychological, and neurological problems. "My research group was destroyed, and I just could not get going again." There was no lack of effort, though, to restart an energetic research programme, but frailty of body and mind would limit his academic work to teaching large undergraduate classes.

And then there are the Ps who, through a combination of a disinterested academic department and a growing teaching load, simply abandon the pursuit of a second rating. A political science P recalls some initial excitement but then "a really, really reserved response" from her departmental colleagues. The promise of less teaching when the P was announced did not materialise. She suspects academic jealousy reflected in snide comments that she was not doing "real political science".

In the meantime, her class sizes doubled ($n = 320$ in one undergraduate third-year class) and suddenly "there was no time for slow, deep, profound work" required for advanced research. Of course, with the huge classes came heavy administrative loads, all of which "sucks up a lot of your time", alongside committee work and journal responsibilities. Why did she not walk away and concentrate on her research? "One wants to be a team player."

When this P and others reflect on the "life happens" explanation, they cite two major events in recent times – protests and pandemics. The historic student protests of 2015 onwards (decolonisation, free higher education) disrupted their research[4] and required that they attend not only to teaching but the mental and emotional anxieties of students[5]. A second major disruption was the pandemic that led to lockdowns starting in 2020. This event, too, derailed the research of especially those Ps who were bench scientists.[4] Said an atmospheric chemist,

> *I have a piece of laboratory equipment that stood for a year because technicians from Germany could not be sent to install it. Students did not graduate. Papers were slow in coming out. My work definitely took a hit.*

The fact that more than a third of all Ps did not go on to a senior rating does not show a particular trend or a cluster of factors that provide a causal explanation for the observation. Moreover, the relatively small sample of Ps means that one cannot make any firm generalisations beyond what is reported here.

Discussion

It is evident from this study that the Ps who become As are those with an extraordinary work ethic and focused determination, who devise fine-tuned strategies to advance their research (and therefore ratings). They would draw on high-quality international networks, which are enabled by supportive university leadership, while resisting the lure of senior administrative positions in order to flourish within productive research environments, all the while navigating the challenges of life and living in South Africa.

While the rating system has, since its inception, drawn both critics[6-8] and supporters[9-11], it is clear from this study that the P rating carries enormous value for the awardees that goes well beyond financial benefits. Apart from compliance, issues of status, recognition, promotion, and bargaining power all feature in the motivation of the Ps for their rating applications.

What this study also revealed is that the under-representation of world-leading black scientists in the global academy will continue unless the pipeline of young talent is increased; that the most promising of emerging researchers identified in their earlier years (doctoral and postdoctoral studies) are placed inside highly productive international networks; and that they are incentivised to continue doing advanced research rather than being lured into university administration.

This research holds at least three implications. One, the importance of institutional posture (attitude) towards and targeted support for talented young researchers. Two, the value of bringing in enabling international networks and affiliations for early career academics. And three, the need for a considered strategy that retains promising black researchers in high-level research for as long as possible.

Competing interests

We have no competing interests to declare.

Authors' contributions

J.J.: Conceptualisation, methodology, data collection, sample analysis, writing – initial draft, project leadership, project management. C.W.: Methodology, sample analysis, validation, writing – revisions, project management. A.W.: Methodology, sample analysis, conceptualisation, data curation. G.M.: Methodology, sample analysis, data curation.

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Selection, sequencing and progression of content in biology in four diverse jurisdictions

Selection of content for a school syllabus is important in achieving progress towards inclusive generalisations which characterise powerful knowledge. Biology as a discipline progresses from knowledge of individual facts to inclusive generalisations such as homeostasis, energy transformations, heredity, and evolution. The present study evaluated the selection of content in the official biology syllabus for the seventh and eighth years of schooling in four diverse jurisdictions: Kenya, South Africa, British Columbia (Canada) and Singapore. The purpose was to determine whether and how content selection enabled progression to inclusive generalisations in biology and to compare selection, sequencing and progression among the four jurisdictions. General Topic Trace Mapping was used to compare each syllabus to a generic reference syllabus structured according to inclusive generalisations. Although there was some agreement in the scope of topics selected, jurisdictions varied in the way it was organised. Kenya included more everyday knowledge than other jurisdictions. British Columbia and Singapore selected content according to unifying themes, whereas South Africa and Kenya did not. South Africa selected content that enabled progression towards inclusive generalisations, but did not explicitly identify the generalisations. This study supports the contention that powerful knowledge in biology may be construed differently in diverse jurisdictions.

Significance:

Recent curriculum developments have favoured choice of content for school subjects that enables students to progress towards powerful knowledge. The current study provides evidence of variation in selection, sequencing and progression towards powerful knowledge in the biology syllabi of four jurisdictions: Kenya, South Africa, British Columbia (Canada) and Singapore. British Columbian and Singaporean syllabi explicitly identify unifying themes and organise content according to those themes, whereas South African and Kenyan syllabi lack explicit unifying themes.

Introduction

The construction of a school subject syllabus entails selecting disciplinary knowledge and skills that will best achieve the overall purposes of the curriculum and transforming it for the age and stage of development of school students.[1-3] Powerful knowledge is characterised as specialised knowledge that is related to its disciplinary roots, from which it can generate new ideas. Biology has the potential to provide access to powerful knowledge if its content is selected to relate individual facts to broader concepts, which themselves link into more inclusive generalisations representative of the discipline.[4,5] The present study compared content selection and progression in the biology component of the science syllabus for the 7th and 8th years of schooling in four diverse jurisdictions: South Africa, Kenya, British Columbia (Canada) and Singapore. It evaluated each syllabus in terms of whether it enables progression towards inclusive generalisations characterising powerful knowledge.[4] In this paper, inclusive generalisations are also referred to as 'unifying themes' or 'big ideas'.

Social realism[6] and modest realism[7] recognise that many scientific concepts and theories successfully explain reality and are increasingly true, within the constraints of existing technology for observing natural phenomena and human ability to comprehend such phenomena. Knowledge production is regulated by peer review, leading to reliable but revisable knowledge.[4] There is therefore an established body of powerful knowledge that has the potential to achieve scientific literacy. Recent curricula in countries such as the United Kingdom, South Africa, some Australian states, some Latin American and European countries and the Organisation for Economic Cooperation and Development (OECD) have reinstated knowledge as the prime organiser[1,8], replacing previous frameworks which foregrounded generic skills and competences[9]. Nevertheless, the OECD framework has been criticised for not focusing on powerful knowledge per se, but prioritising the economic utility of knowledge.[9]

The social realist position, termed 'knowledge for its own end' by Deng[1], aims to promote access to powerful knowledge which provides reliable explanations and transformative ways of thinking. Powerful knowledge in science equips students with conceptual thinking by linking particulars into inclusive generalisations which may be universally true. It enables students to relate new observations to existing concepts and to generate and evaluate alternative connections between observations and concepts.[4,6] Powerful knowledge is fundamentally democratic in that it is non-discriminatory.[6] Schools can promote social equality by providing access to powerful knowledge, providing disadvantaged children with possibly their only opportunity to move, intellectually at least, beyond their local circumstances.[2,6]

Not all subjects link particulars into broader generalisations as described by Young and Muller[6] for powerful knowledge in science. Deng[1] criticises a curriculum that prioritises knowledge for its own end because it is indifferent to the social and economic needs of a society. He favours a Bildung-related curriculum that selects and uses knowledge as a vehicle to develop human powers for the future.[5,10] Mathematics, geography[11-13] and history[14] can be structured to develop human potential through powerful knowledge. A Bildung-centred curriculum should cultivate self-determination, imagination, critically reflected action, and a sophisticated and informed understanding of the world.[5] Content selection should be guided by the potential of the content to develop human powers. Deng[5] does not elaborate on how a Bildung-centred curriculum should vary according to socio-economic contexts.

Although powerful knowledge has been claimed to promote social justice and equality of educational opportunity[6], studies supporting such claims are rare. Limited success has been reported in the USA and the UK in schools that have adopted a discipline-based subject curriculum and a strict disciplinary code.[15,16] Improved social equity is less easily demonstrated in other countries that have adopted a strong content-focused curriculum.[8] A knowledge-rich curriculum has yielded limited improvement in equality of academic performance in South Africa.[17] Clearly, the relationship between school curriculum, achievement of social justice and academic achievement is multifactorial and difficult to demonstrate.[8,18]

The choice and structure of curriculum is influenced by the context of a country/region.[19] The primary science syllabi of developing countries such as Kenya[19], Malawi[20] and Uganda[21] include more everyday topics such as health education, agriculture, parenting and/or domestic tasks than equivalent syllabi of wealthy countries such as British Columbia and Singapore.[19] Everyday knowledge has application in the lives of students but has limited application beyond the students' context.[4] Therefore, school science should include knowledge of basic facts and concepts in science, how investigations are conducted in science, the nature of science and its social and environmental relations and responsible uses of scientific knowledge in everyday life.[22] The weighting of these components depends on the age, stage of development and context in which the curriculum is enacted.

A biology syllabus that aims to develop powerful knowledge begins by identifying the most inclusive generalisations and matching subsidiary concepts according to the target student group.[1] Mayr[23] proposed that biology was constructed according to 'what', 'how' and 'why' questions. 'What' questions provide descriptions of the elements of the biological world, 'how' questions refer to processes causing effects in living systems, corresponding to the concept of proximate causation. 'Why' questions address 'the historical and evolutionary factors that account for all aspects of living organisms that exist now or have existed in the past', commonly known as ultimate causation[23(p.115)].

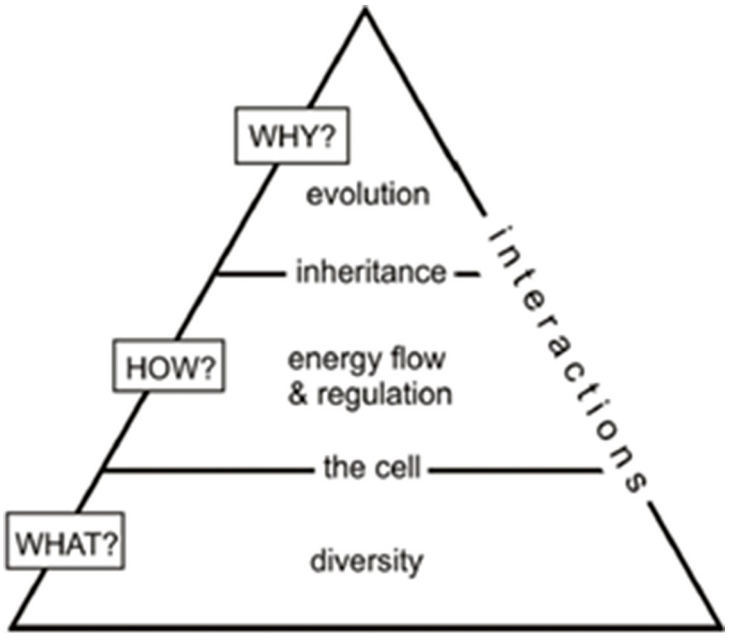
Johnson et al.[24] developed a model of the hierarchical knowledge structure of biology by mapping seven core concepts onto Mayr's[23] 'what', 'how' and 'why' questions. The model arranges the questions hierarchically and is reproduced as Figure 1.

The lowest level of the triangle in Figure 1 represents descriptive knowledge such as the diversity of life forms or the structures that constitute a living organism or the components of an ecosystem. The 'how' level represents functional biology, for example, how cells manage energy transformations and how organisms regulate their internal and external environment. The cell straddles what and how levels because its study is descriptive (what?) and functional (how?). 'Why' questions are generally answered in terms of unifying themes such as evolution and natural selection. Inheritance straddles the boundary between the 'how' and 'why' levels of the hierarchy because it controls an organism's functions and is ultimately responsible for evolution. Finally, interactions occur between the 'what', 'how', and 'why' levels and are therefore depicted straddling all three levels of the hierarchy; for example, structure is related to function, and both are linked through their evolutionary history.

Figure 1 presents a model of the academic discipline of biology, whereas a school subject should transform the main ideas but not exactly mirror its parent discipline. Junior secondary science, aimed at students aged approximately 12–15 years of age, is likely to be less specialised and more appealing to a general student body than science at upper secondary level. Scientifically literate citizens should be critical consumers of science, requiring scientific knowledge and understanding, knowledge of how science builds knowledge and knowledge of the social practices of the scientific community.[22]

In 2009, a group of 10 international experts in science education developed a set of principles to guide science education from age 5 to 17, which was revised in 2014.[22] The experts identified 15 'big ideas' in science, with associated content sequenced by broad age categories. Four of the 15 'big ideas' relate to disciplinary biology, while one relates to applications of science relevant to biology.[22] Harlen[25] added that science education should contribute to the Sustainable Development Goals (SDG) as expressed by the United Nations General Assembly[26], two of which are pertinent to biology education. The list of biologically relevant 'big ideas', their component topics and SDGs relevant to biology for ages 11–14 are:

1. **Living organisms are composed of cells and have a finite life span** (including structure and function of cells; cell specialisation; energy transfer in cells; tissues, organs and organ systems; structure and function of organ systems; homeostasis in cells).
2. **Living organisms depend on or compete with each other for a supply of energy and materials** (including ecosystem structure and functioning; nutrient cycling; transfer of energy and matter through an ecosystem; interspecific competition for resources; plant adaptations and effect of environmental change on populations).



Source: Johnson et al.[24] (under CC-BY-ND 4.0 licence)

Figure 1: Hierarchical model of knowledge in biology.

3. **Genetic information passes from one generation to another** (including chromosomes; DNA; genes; DNA replication during cell division; mutations; genetic mixing during sexual reproduction; genetic variation giving rise to phenotypic variation; natural selection acting on phenotypic variation).
4. **Evolution is responsible for the diversity of organisms, living and extinct** (including beneficial adaptations arising from genetic changes enhancing survival and reproductive success; increase in better adapted individuals in the population; speciation resulting from accumulated changes through natural selection; natural selection's role in the long history of life; biodiversity and classification).
5. **Applications of science often have ethical, social, economic and political implications** (including positive consequences, e.g. increased human life expectancy due to clean water, adequate food, improved medicine; negative consequences e.g. depleted natural resources due to increased demand for food, housing and waste disposal as human populations increase; habitat destruction causing extinction; benefits and disadvantages of improved transport networks, e.g. increased CO_2 levels, greenhouse effect; melting of polar ice, higher sea levels and disrupted weather patterns).

SDG3 Good health and well-being: Ensure healthy lives and promote well-being for all at all ages.

SDG13 Climate action: Take urgent action to combat climate change and its impacts (related to 'big idea' 5).

The list of 'big ideas' could be conceptualised quite differently by a different group of experts[25], but the curriculum should facilitate cognitive progression from concrete knowledge of facts towards deep conceptual understanding of abstract principles[22,27,28]. Only then can students engage with 21st century skills such as critical thinking and problem-solving.

The Trends in International Mathematics and Science Study (TIMSS) assessed syllabus represents content selected by a large proportion of participating countries, including developing and developed countries, up to and including the eighth year of schooling.[29] It is organised according to six knowledge categories, listed below with the closest matching big idea[24]:

1. Life processes of living things (Big idea 1)
2. Cells and their functions (Big idea 1)
3. Life cycles, reproduction and heredity (Big idea 3)
4. Ecosystems (Big ideas 2 and 5, SDG13)
5. Diversity, adaptation and natural selection (Big idea 4)
6. Human health (SDG3)

There is considerable agreement between Harlen's[22] 'big ideas' and the TIMSS assessed curriculum. Harlen's[22] outline provides some detail of how progression might be organised, but was developed from the perspective of developed countries, and may not be appropriate for developing countries. The present study compares the biology syllabus of two developing countries with that of two developed countries. Therefore, the TIMSS assessed syllabus represents the widest range of contexts available and was chosen as a starting point for constructing a reference syllabus for the present study.

The present study emerged from a project commissioned to benchmark the South African science syllabus for the Junior Secondary years (Grades 7–9 in South Africa) against the equivalent science syllabi of Kenya, Singapore and British Columbia (Canada). The original study was conducted in 2014, using syllabus documents in use at that time. The work presented here compares selection of content regarding progression towards powerful knowledge in the intended curriculum for the seventh and eighth years of schooling (Grades 7 and 8 of the Senior Phase of General Education and Training in South Africa). In all four jurisdictions, biology is incorporated into a combined science syllabus for years 7 and 8. Year 9 was excluded because biology is incorporated into combined science in South Africa and British Columbia, while it is a standalone subject in Singapore and Kenya.

The diverse contexts of the four jurisdictions included in the present study are illustrated by differences in the gross domestic product (GDP) per capita[30] and level of inequality measured by the Gini coefficient.[31] Singapore has a GDP of USD97 057 and Gini coefficient of 46, Canada has a GDP of USD48 720 and Gini coefficient of 33, South Africa has a GDP of USD12 032 and Gini coefficient of 63, and Kenya has a GDP of USD4926 and Gini coefficient of 41. South Africa and Kenya are poorer than Singapore and British Columbia, while South Africa has the highest level of inequality in the world, followed in the present study by Singapore, Kenya and Canada.

Inequality of educational opportunity in South Africa is evident in a marked difference between the academic performance of the relatively wealthy 20% of schools compared with the 80% of schools serving poorer communities.[17] Mathematics and science literacy as indicated by TIMSS has consistently been poor compared with other participating countries.[29] Singapore remains one of the best performers in TIMSS[29] and the Programme for International Student Assessment (PISA)[32]. British Columbia is a high performer in PISA[33], while Kenya does not participate in TIMSS or PISA. Although Kenya does not participate in international studies of science literacy, the relative health of its education system is indicated by its good performance in reading and mathematics in the Southern and Eastern Africa Consortium for Monitoring Educational Quality evaluation conducted in 2013.[34] Kenyan sixth-grade students outperformed their South African counterparts.

Students in the seventh to eighth years of schooling are approximately 12–15 years old, depending on the jurisdiction. In Singapore, the seventh and eighth years have a single syllabus called Lower Secondary, which cannot be divided into two separate years.[35] Other jurisdictions have a syllabus for each year of study. Science in all four jurisdictions includes a selection of content from biology, chemistry, physics, agricultural science, human health and/or earth and space science, depending on the jurisdiction. The present study focused on the biology-related components of each syllabus.

There is a limitation in that the intended curriculum, as expressed in policy documents, likely differs from the enacted curriculum in the classroom and the attained curriculum revealed through formal and informal assessment. Also, some content relevant to biology may be offered in other subjects. The research questions guiding the present study were:

- What biological knowledge has been selected in four science syllabi for the seventh–eighth years of schooling?
- How is knowledge organised so that it progresses to powerful knowledge in the four syllabi?

Methods

In South Africa and British Columbia, biology is a discrete component of the science syllabus called Life and Living[36] and Life Science, respectively.[37,38] In Kenya, biology is incorporated into six of ten units.[39] In Singapore, biology is integrated with physics and chemistry in four broad multidisciplinary themes, namely Diversity, Models, Systems, and Interactions.[35] For example, the theme Models includes Model of Cells – the Basic Units of Life, Model of Matter – The Particulate Nature of Matter, Model of Matter – Atoms and Molecules, and Ray Model of Light.

Statements describing the biology content were identified in each syllabus. In South Africa, content statements for Life and Living are listed as topics, for example: "Some inherited characteristics are height and tongue-rolling"[36(p.17-84)]. The content statements for Life and Living were analysed in the present study.

In British Columbia, each year of Life Science has an organising principle: Ecosystems in Year 7[37] and Cells and Systems in Year 8.[38] Content is listed as broad prescribed learning outcomes, for example, "It is expected that

students will analyse the roles of organisms as part of interconnected food webs, populations, communities and ecosystems", accompanied by more detailed suggested achievement indicators, for example, "Students….are able to identify populations of organisms in communities and ecosystems according to simplified food webs"[37(p.78)]. Prescribed learning outcomes and suggested achievement indicators were analysed in this study.

In Kenya, biological topics were located in science units entitled Human Body, Health Education, Environment, Plants, Animals, and Foods and Nutrition.[39(p.62–71)] Content is listed as specific objectives, for example, "By the end of this topic the learner should be able to explain fertilisation in human beings", and content, for example "fertilisation"[39(p.67)]. Specific objectives and content were used in the present analysis. Some content listed under the plant, animal and environment units was directly relevant to agriculture and was excluded, for example, signs of unhealthy crops, effects of livestock disease, soil conservation measures and ways of controlling air pollution. However, the boundary between biology and agriculture was blurred.

In Singapore, biology content and skills are described in three learning outcomes, which are Knowledge, Understanding and Application; Skills and Processes, and Ethics and Attitudes.[35] Content was extracted from the first and third learning outcomes.

The method of comparison identified elements present in one or more jurisdictions using a reference listing of content from the TIMSS Grade 8 assessed syllabus for 2011.[40] The 2011 TIMSS syllabus was selected because it was nearest in time to the present analysis. Biology constitutes 35% of the questions in the TIMSS tests. TIMSS recognises six knowledge categories, which are shown in Table 1. Topics give examples of content for each knowledge category.[40]

Table 1: Reference list of TIMSS 2011 knowledge categories and example topics[40(p.66–68)] matched with big ideas and Sustainable Development Goals (SDG).[22,25] Italics indicate added topics.

Knowledge categories	Example topics	Big idea
1. Life processes of living things	1.1 Locate major organs in the human body; identify the components of organ systems; explain the role of organs and organ systems in sustaining life.	1
	1.2 *Locate major organs in plants; identify components of plant organ systems; transport of water and other substances in a plant.*	1
2. Cells and their functions	2.1 *Identify and describe biologically important molecules.*	1
	2.2 Explain that living things are made of cells that carry out life functions and undergo cell division, and that tissues, organs and organ systems are formed from groups of cells with specialised structures and functions; identify cell structures and some functions of cell organelles; compare plant and animal cells; *transport of molecules by diffusion, osmosis and active transport.*	1
	2.3 Describe the process of photosynthesis and cellular respiration.	2
3. Life cycles, reproduction, and heredity	3.1 Compare and contrast how different organisms grow and develop; *describe human reproduction; describe plant reproduction.*	3
	3.2 Compare and contrast asexual and sexual reproduction.	3
	3.3 Relate the inheritance of traits to organisms passing on genetic material to their offspring; distinguish inherited characteristics from acquired or learned characteristics.	3
4. Ecosystems	4.1 *Describe the biosphere in terms of the hydrosphere, lithosphere and atmosphere.*	2
	4.2 Describe the flow of energy in an ecosystem; identify different organisms as producers, consumers, or decomposers; draw or interpret food pyramids or food web diagrams; *identify abiotic and biotic factors in an ecosystem.*	2
	4.3 Describe the role of living things in the cycling of elements and compounds through Earth's surface and the environment.	2
	4.4 Explain the interdependence of populations of organisms in an ecosystem in terms of the effects of competition and predation.	2
	4.5 Identify factors that can limit population size; predict effects of changes in an ecosystem on the available resources and the balance among populations.	2
	4.6 Recognise that the world's human population is growing and identify reasons why; discuss the effects of population growth on the environment.	5, SDG13
5. Diversity, adaptation and natural selection	5.1 State defining characteristics of major taxonomic groups and classify organisms according to these characteristics.	4
	5.2 Relate the survival or extinction of species to variation in physical/behavioural characteristics in a population and reproductive success in a changing environment.	4
6. Human health	6.1 Describe causes of common diseases, methods of infection or transmission, and the importance of the immune system.	SDG3
	6.2 Explain the importance of diet, exercise and lifestyle in maintaining health and preventing illness; identify the dietary sources and role of nutrients in a healthy diet; *understand and apply healthy sexual practice, dental hygiene, treatment of intestinal parasites, avoiding substance abuse.*	5, SDG3
	6.3 *Name and describe health issues related to human organ systems.*	SDG3

TIMSS knowledge categories and topics were adapted to accommodate content selection in all syllabi studied. The topic 'Characteristics and classification of organisms' was moved from 'Life processes of living things' to 'Diversity' and three TIMSS topics were omitted because they were absent in all four jurisdictions. Topics were added to accommodate content present in the syllabi but not in the TIMSS assessed syllabus.

Content topics present in each syllabus were mapped to the most closely related reference topic listed in Table 1. The process is similar to General Topic Trace Mapping used for cross-national comparison of mathematics and science curricula.[28,41] To ensure reliability, mapping was repeated several times over weeks and months until no further changes were made. Maps were scrutinised for progress towards inclusive generalisations reflecting the powerful knowledge of biology.[4,22,25]

Findings

Tables 2 – 6 show the content mapped onto topics identified in Table 1 linked to each TIMSS knowledge category and its associated big idea or SDG.[25] The purpose was to assess whether and to what extent each syllabus builds towards powerful knowledge in biology.

Table 2 shows that human organ systems, other than reproductive systems, are included in the syllabi of three of the four jurisdictions, with South Africa being the exception. Plant organ systems are present in only the Singaporean syllabus. Topics related to cells and their functions are absent in Kenya, while only the processes of photosynthesis and respiration are addressed in South Africa. British Columbian and Singaporean syllabi include cell structure and function, osmosis and diffusion, thereby contributing to big idea 1 far more comprehensively than the syllabi of Kenya and South Africa.

Table 3 shows that all four jurisdictions provide opportunities to build towards big idea 2, relating to interactions in ecosystems. Kenya provides the least exposure to topics related to ecological interactions, while South Africa, British Columbia and Singapore address ecosystems in some detail, nutrient cycles and some aspects of population dynamics. The topic Competition and Predation is indirectly addressed as interdependence among organisms.

Table 4 shows that three of the four jurisdictions provide foundations for big idea 3, which relates to heredity and reproduction, with British Columbia being the exception. Human reproduction is included in the syllabi of Kenya, South Africa and Singapore, with South Africa also including reproduction in flowering plants in considerable detail. Heredity is addressed only in South Africa and Singapore, with Singapore linking sexual reproduction to genetic variation. Thus Singapore provides the best access to big idea 3.

Table 5 shows that all four jurisdictions provide some access to the TIMSS knowledge category Diversity, Adaptation and Natural Selection, which forms the foundation of big idea 4, which is that evolution is responsible for biodiversity. Diversity and classification are present in the syllabi of three jurisdictions, with Kenya being the exception. South Africa provides the most comprehensive coverage of classification and the biological species concept. Variation and species survival as a topic lays a foundation for the process of natural selection. It is addressed through adaptations in three jurisdictions, British Columbia being the exception. South Africa and Singapore link intraspecific variation to survival and extinction. Overall, South Africa provides the most comprehensive access to big idea 4, although none of the jurisdictions mentions the term evolution. British Columbia provides the least opportunity to access big idea 4.

Table 6 shows progression towards the two SDGs. All four jurisdictions provide access to SDG3 relating to good health and well-being for all. Contraception and sexually transmitted infections and/or the link between pathogenic organisms and disease feature in all four jurisdictions. Contraception and STIs are related to the inclusion of human reproduction in three jurisdictions – Kenya, South Africa and Singapore. British Columbia provides less comprehensive coverage of human health than the other jurisdictions. Kenya and South Africa make specific mention of HIV and AIDS, which are omitted in other jurisdictions.

Climate action, which is the focus of SDG13, was not addressed in any syllabus, but topics related to the impact of human activities on the environment were identified in all four jurisdictions. The impact of pollution on the environment and the importance of conservation were common topics.

Table 7 summarises the selection of content in each jurisdiction. Singapore selects content matching 15 of the 17 topics and all six

Table 2: Selection and progression towards big idea 1: Living organisms are composed of cells and have a finite lifespan

Knowledge category		**1: Life processes of living things**		**2: Cells and their functions**		
Topics		**Structure and function of human organ systems**	**Structure and function of plant organ systems**	**Biologically important molecules**	**Cell structure and function**	**Photosynthesis and respiration**
Kenya	Std 7	Circulatory system; blood; blood vessels; heart				
	Std 8	Excretory organs' structure and functioning in humans				
South Africa	Gr 7					
	Gr 8					Descriptions and word equations; raw materials and products
British Columbia	Yr 7					
	Yr 8	Structure, function and interactions between selected human organ systems, eyes, immune system		Osmosis and diffusion	Cell theory; cell types; structure and function of organelles; microscope; tissue, organ, organ system	
Singapore	Lower Sec	Transport and circulatory systems and their interaction with other systems; digestive system	Plant transport system structure and function; diffusion and osmosis in plants	Digestive enzymes; diffusion in animals and plants	Structure and function of cells; tissues, organs, systems; plant and animal cells; division of labour in cells	

Table 3: Selection and progression towards big idea 2: Living organisms depend on or compete with each other for a supply of energy and materials

Knowledge category		4. Ecosystems				
Topics		**Biosphere**	**Ecosystems**	**Nutrient cycles**	**Competition and predation**	**Population dynamics**
Kenya	Std 7		Biotic and abiotic components of the environment; simple food chain		Interdependence between organisms; parasites	
	Std 8		Mammalian feeding habits – herbivores, carnivores, omnivores			
South Africa	Gr 7	Components of biosphere				
	Gr 8		Ecosystems; biotic and abiotic components; energy and matter flow during photosynthesis and respiration; trophic levels; food chain; food webs; energy pyramids	Microorganisms' role in recycling		Balance in an ecosystem; limiting factors; imbalance
British Columbia	Yr 7		Food webs; habitats; food pyramid; energy transfer; interactions between biotic & abiotic factors.	Decomposers and nutrient cycles	Interdependence of plants, animals and decomposers	Suitable environment for organisms; factors favouring healthy populations and ecosystems; effects of habitat loss
	Yr 8					
Singapore	Lower Sec		Ecosystem definition; abiotic factors; role of photosynthesis and respiration in energy flow through food chains and food webs	Decomposers and nutrient cycles	Interactions among organisms in a community	Reasons for depletion or extinction of species

Table 4: Selection and progression towards big idea 3: Genetic information passes from one generation to another

Knowledge category		3: Life cycles, reproduction and heredity	
Topics		**Reproduction, growth and development**	**Heredity**
Kenya	Std 7		
	Std 8	Human reproduction	
South Africa	Gr 7	Sexual reproduction in humans and angiosperms	Inherited characteristics
	Gr 8		
British Columbia	Yr 7		
	Yr 8		
Singapore	Lower Sec	Puberty; human reproduction; menstruation	Heredity and genetic variation through sexual reproduction; genetic material

Table 5: Selection and progression towards big idea 4: Evolution is responsible for the diversity of organisms, living and extinct

Knowledge category		5: Diversity, adaptation and natural selection	
Topics		**Diversity and classification**	**Variation and species survival**
Kenya	Std 7		
	Std 8		Plant adaptations; bird adaptations to feeding and movement
South Africa	Gr 7	Species concept; Linnaean classification system; diversity of animals and plants	Intraspecific variation; adaptations
	Gr 8	Classification of viruses, bacteria, protists and fungi	Adaptations, survival and extinction
British Columbia	Yr 7		
	Yr 8	Characteristics of living things; kingdoms	
Singapore	Lower Sec	Biodiversity and its importance; classification	Intraspecific variation; adaptations and survival

knowledge categories – a wider range than any other jurisdiction. South Africa selects content that matches 12 topics, omitting the knowledge category Life Processes entirely and giving scant attention to Cells. British Columbia restricts content selection to the theme for each year of study, being Ecosystems in Year 7 and Cells and Systems in Year 8. It addresses 10 topics, omitting the knowledge category Reproduction and Heredity. Kenya addresses eight topics from five knowledge categories, making it the narrowest syllabus of the four jurisdictions. It omits Cell Structure and Function.

Discussion

The biology syllabi for the seventh and eighth years of schooling in all four jurisdictions is dominated by specialised knowledge rather than biology for everyday living. They fit the description of social realism[6] or modest

Table 6: Selection and progression towards SDG3 (Good health and well-being), big idea 5 (applications of science) and SDG13 (Climate action)

Knowledge category		6: Human Health (SDG3)		4: Ecosystems (big idea 5 and SDG13)
Topics		**Diseases**	**Nutrition and health education**	**Human population growth and effects on the environment**
Kenya	Std 7		Types and effects of drug abuse; HIV and AIDS myths and misconceptions; care of HIV-positive people; controlling intestinal worms	
	Std 8	Causes and symptoms of STIs; food poisoning	Nutrition for specific needs; prevention of STIs; controlling HIV and AIDS; preventing food poisoning	Soil pollution; soil conservation; air pollution
South Africa	Gr 7		Concept of contraception	
	Gr 8	Disease-causing organisms	Hygiene; medicines; yoghurt	Human effects on ecosystem balance
British Columbia	Yr 7			Effects of forestry, pollutants and Aboriginal communities on environment
	Yr 8	Effects of pathogens and toxins	Correcting defects in human vision	
Singapore	Lower Sec	Effects of gut bacteria; transmission and treatment of STIs	Ethics and organ donation; hygiene and food; contraception; ethics and abortion and premarital sex	Importance of conservation; sustainable living; human population growth and impact on the environment

realism[7] more closely than human-centred curricula as described by Deng[1]. Powerful knowledge[4] predominates in all four syllabi, although human health and human effects on the environment are present in all jurisdictions.

There is overall agreement in the broad knowledge categories selected in the seventh and eighth years of study in biology, but considerable diversity in the range of topics included. Three topics – ecosystems, disease and human effects on the environment – were represented in all four jurisdictions. By contrast, three topics were addressed in only one jurisdiction: plant organ systems and their functions in Singapore, the processes of photosynthesis and respiration and the components of the biosphere in South Africa. Big idea 2 featured prominently in all four jurisdictions, indicating general agreement that students at this age and stage of schooling should be exposed to the basic concepts of ecosystems, including human effects on the environment. There was also agreement among at least three jurisdictions that students should learn about human life processes, reproduction, diversity and/or classification, variation and survival, and health education.

Big ideas 3 and 4 correspond with the apex of Johnson et al.'s[24] triangle showing the hierarchical organisation of knowledge in the discipline of biology. The most inclusive generalisation applicable in biology is evolution by natural selection (big idea 4) which is mediated through heredity (big idea 3). While adaptations were included in three jurisdictions, South Africa and Singapore provided the best foundations for big ideas 3 and 4. Nevertheless, all four jurisdictions omitted the process of natural selection and the nature of genetic material. Thus, there was general agreement that those topics were not appropriate for the seventh and eighth years of schooling.

With regard to progress towards powerful knowledge, Singapore emerged as the jurisdiction that provided access to the widest range of unifying themes as represented by Harlen's[22] big ideas. However, the biology content is scattered in multidisciplinary themes and progress towards big ideas may not be evident to students. They experience the biology content as isolated topics, thereby losing their potency to fit those facts into inclusive generalisations of biology.[4] Nevertheless, Singapore has been successful in achieving high levels of scientific literacy as indicated by performance in international studies.[30,31]

South Africa provides comprehensive access to three of the four big ideas, omitting most of the topics related to big idea 1. It does not identify a theme for each year of study, thereby concealing the relationship between individual topics and inclusive generalisations. Students may experience the curriculum as a list of facts to be remembered thereby reducing the potency of this knowledge-rich syllabus.[4,28] The South African curriculum contains abstract concepts such as the species concept, inheritance, intraspecific variation and considerable detail of the Linnean classification system in Grade 7 while Grade 8 is more concrete. This is contrary to the expected sequence of concrete to abstract.[27] Despite its strongly knowledge-focused curriculum, South Africa has had limited success in improving scientific literacy.[8,17]

British Columbia achieves access to powerful knowledge by explicitly centring content around a unifying theme[4] in each year of study. Restricting the breadth enables the topics to be dealt with in considerable detail, but it reduces the scope of big ideas that may be addressed. Thus British Columbia devotes considerable attention to big ideas 1 and 2 but little attention to big ideas 3 and 4 in years 7 and 8. The unifying themes identified in British Columbia do not closely match Harlen's[22] big ideas, supporting the contention that big ideas may be identified differently by different groups of experts.[22] The knowledge-focused syllabus in which breadth is limited in favour of depth, is associated with successful acquisition of scientific literacy in this jurisdiction.[33]

Kenya covers few topics scattered across knowledge categories without an evident unifying theme. Although it provides foundations for three of the four big ideas, the topics lack the depth of the other three jurisdictions. The knowledge is discipline-centred and organised around topics rather than concepts. Biology is interspersed with agricultural science and health education, making it difficult for students to link facts into inclusive generalisations. Kenya omits most of the foundational topics for big ideas relating to the cellular basis of life, inheritance and diversity and classification (big ideas 3 and 4). Variation and survival, the foundation of natural selection, are addressed only through several examples of adaptations. Thus Kenya's syllabus for Standards 7 and 8 provides limited access to powerful knowledge.[4]

Kenya's content selection is markedly different from those of the other jurisdictions in that it includes so many topics relevant to agriculture and/or everyday life. These topics relate to the SDGs and have worth in the context of rural Kenyan students, but do not apply beyond those contexts.[4,5] The syllabus is not future-oriented, nor does it fully cultivate human powers in the same way as deep engagement with disciplinary knowledge can do. Although Kenya does not participate in international studies of scientific literacy, its success in the foundational skills of reading and numeracy surpass those of South Africa and indicate a healthy education system.[34]

Table 7: Selection of biology topics for years 7–8 in four jurisdictions. Shaded blocks show omitted topics.

		Kenya		South Africa		British Columbia		Singapore
Knowledge category	**Topic**	**Std 7**	**Std 8**	**Gr 7**	**Gr 8**	**Yr 7**	**Yr 8**	**Lower Sec**
1. **Life processes**	1.1 Human organ systems		✓				✓	✓
	1.2 Plant organ systems							✓
2. **Cells**	2.1 Molecules						✓	✓
	2.2 Cells						✓	✓
	2.3 Photosynthesis and respiration				✓			
3. **Reproduction and heredity**	3.1 Reproduction, growth and development		✓	✓				✓
	3.2 Heredity			✓				✓
4. **Ecosystems**	4.1 Biosphere			✓				
	4.2 Ecosystems	✓	✓		✓	✓		✓
	4.3 Nutrient cycles				✓	✓		✓
	4.4 Competition and predation	✓				✓		✓
	4.5 Population dynamics				✓	✓		✓
	4.6 Human population growth and effects		✓		✓	✓		✓
5. **Diversity, adaptation and natural selection**	5.1 Diversity and classification			✓	✓		✓	✓
	5.2 Variation and survival		✓	✓	✓			✓
6. **Health**	6.1 Disease		✓		✓		✓	✓
	6.2 Health education	✓	✓	✓	✓			✓

British Columbia and Singapore provide the best access to specialist knowledge and greater depth of engagement with the topics included in biology. The British Columbian curriculum has been revised since 2014[42], as has the Singaporean curriculum.[43] The two poorer countries, South Africa and Kenya, expect less depth than the two wealthy countries. The Kenyan curriculum does not progress towards inclusive generalisations. In terms of Young and Muller's[6] concept of the powers of powerful knowledge, the developing countries provide less opportunity for academic equity and social justice than the wealthier countries.

Should Kenya and South Africa increase the depth of their biology syllabi with a view to contributing to the development of citizens' human potential?[5] The Kenyan Integrated Science curriculum was revised in 2022 and separates agriculture and health education from integrated science, which encompasses physics, chemistry, biology and technology.[44,45] More detailed analysis will indicate whether the revision provides better access to powerful knowledge than its predecessor. South Africa is the only jurisdiction that has not revised its syllabus since the study was conducted in 2014 and this study shows that its biology syllabus for Grades 8 and 9 adequately addresses concepts that lead to inclusive generalisations, although the sequence could be revised. Both South Africa's and Kenya's 2014 syllabi would benefit from explicit identification of unifying themes.

Biology is a small but potentially powerful component of the school curriculum because it enables access to specialist knowledge. Curriculum alone does not explain success in science. Other factors such as widespread poverty, teacher quality and professionalism, and school resources affect academic success.[17,34] Classroom pedagogies such as rote learning and whole-class teaching detract from the potential of the curriculum to enhance social equity.[8,34] Nevertheless, this study illustrates how biology is selected, sequenced and how it progresses towards powerful knowledge in different ways in four diverse jurisdictions.

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Competing interests

I have no competing interests to declare.

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Climate finance across sub-Saharan Africa: Decision trees and network flows

The structure of climate finance flows from donors (multilateral sources) to recipients (sub-Saharan African countries) was studied. This is the first study to provide a comprehensive network structure of the climate finance flows into Africa, based on the global public climate finance governance system. Network theory and decision tree techniques were employed. The results obtained generally fit the multilateral funding units (MFUs) into two categories: central funding units (CFUs), which simultaneously attend to the climate-related projects of many African countries, and the boundary funding units (BFUs), which cater to only a few countries at once. An isolated region with no BFUs was identified. African countries within this group could be more exposed to climate financial risk as they rely on only the CFUs. In general, with the exception of mitigation REDD (reducing emissions from deforestation and forest degradation) climate finance, a disproportionate distribution of climate themes, with particular reference to adaptation finance, was observed across sub-Saharan Africa. This has real implications for equitable resource allocation of climate funds. The need for African-bred region-wide MFUs is recommended.

Significance:

Insights from this analysis expose the presence of contagion effects within the sub-Saharan African climate finance network structure and, consequently, the flow of climate finance-related risks. This knowledge is critical for future planning as it can provide African governments and interested stakeholders with informed evidence upon which they can make reliable and justifiable decisions, such as shaping of sectoral strategies and improving of climate finance flow coordination.

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC)[1,2] defines climate finance as the local, national or transnational financing that seeks to support both mitigation and adaptation actions, with the underlying aim of addressing climate change. A similar definition given by Watson and Schalatek[3] refers to climate finance as the financial resources mobilised to fund actions that mitigate and adapt to the impacts of climate change, including public climate finance commitments by developed countries under the UNFCCC. According to the Intergovernmental Panel on Climate Change (IPCC)[4], the core objectives of climate funds are low carbon transition-related transformations; establishing a platform upon which developing countries can be assured of an unflinching support from developed nations; and an environment for nurturing technological innovation. This implies that climate finance is necessary for achieving sustainable development, most especially for developing countries, given the adverse impact of climate-related risks on the economy, society and governance. Moreover, climate finance is also owed to developing countries because developed countries are responsible for most emissions. Hence, African governments and policymakers, including climate stakeholders, need to fully understand the dynamics of climate finance distribution in order to develop better climate finance negotiations in regard to the scale of the finance required and the need for additional finance where gaps exist, and the type of finance needed. This solid grasp of climate finance dynamics also plays a major role in the aspect of accountability and planning of sustainable policies.

One core aspect that has received very little attention is climate finance flows across sub-Saharan Africa. According to the IPCC[5], one of their key themes is the need for insights into scenarios of and needs for investment, and financial flows that are connected to mitigation tracks and climate change actions both at the global and regional levels. However, although millions of dollars are disbursed periodically to different African countries to cater for climate change mitigation and adaptation projects, the quantitative studies needed to aid African governments and stakeholders in understanding how the flow of these financial resources is structured are virtually non-existent. This study aims to fill this gap. The scarcity of academic literature on climate finance has been further stressed by Working Group III (WGIII) of the IPCC, which is working on integrating climate finance research undertaken by different researchers and other actors, as highlighted by Thomson et al.[6]

The funds involved are drawn from different sectors – public, private and alternative sources. Noting that climate finance flows, from financially buoyant sources (mainly from developed countries that are responsible for the majority of emissions) to less endowed and vulnerable target groups (mainly in developing countries), are central to accomplishing the Paris Agreement[5] and in actualising climate-resilient development, it is necessary for investors, lenders, insurers, policymakers and other stakeholders across sub-Saharan Africa to possess a sound knowledge of climate finance because it affects every one of them. Such insights can be made possible through research.

The perspectives of the few existing studies on climate finance vary and are mostly qualitative. Banga[7] investigated the relationship between climate finance and structural transformation in developing countries. With the aid of the DEPSAE (driver - exposure - pressure - state - action - effect) model, Banga argued that climate finance has the potential to hasten the drive towards achieving sustainable structural transformation only if it is allocated to sectors within the environmental sphere. Bird et al.[8] examined international climate funds in terms of their governance, while Steckel et al.[9] and Bowen[10] delved into the strategies for raising climate funds. A few studies have explored the distribution, supervision and tracing of climate finance.[11-14] Additionally, others[15,16] have focused on the ethical aspects of climate finance. A total of 160 reports (consisting of 188 parties) from the Intended Nationally Determined

Contribution (INDC) climate action communications were aggregated by Zhang and Pan[17]. Of these, 28 parties concluded that the overall mitigation and adaptation demand ratio is 1: 4. With respect to quantitative studies, Bowen et al.[18] employed a number of integrated assessment models to determine the financial transfers required to equalise climate mitigation efforts across regions. They indicated a threshold of at least USD400 billion as the required amount of climate financial transfer needed to attain equality across the distributed regions. Halimajaya[19] assessed the relationship between the characteristics of 180 developing countries and the allocations they received with regard to climate mitigation from 1998 to 2010. The attributes used to characterise the nations were CO_2 intensity, volume of carbon sinks, gross domestic product (GDP) and governance. The conclusions drawn indicate that those countries that receive more climate mitigation finance have the following attributes: higher levels of CO_2 and carbon sinks, lower per capita gross domestic product, and good governance.

Empirical research focused solely on sub-Saharan Africa is limited, if at all available. This presents numerous gaps that deny African players who are actively or passively participating in climate-related issues the opportunity of completely grasping the concept of climate finance, what it entails, and how they can fully take advantage of the opportunities it presents moving forward. Quantitative mapping of adaptation finance into individual African countries and regions was undertaken by Savividou et al.[20] They found that finance targeting adaptation in Africa is a far cry from what is required to cater to the scale of the problem. Doku et al.[21] employed regression techniques to characterise recipient countries and concluded that sub-Saharan African countries with a high poverty rate, high population growth rate, and a weak corruption control system, amongst others, are more likely to attract climate finance. This result, however, seems to be at variance with that of Halimajaya[19]. From an insurance modelling point of view, Chukwudum et al.[22] examined the frequency and severity of approved climate public funds flowing into sub-Saharan Africa with the aid of various probability distribution models, highlighting the need for a risk-adjusted distribution modelling process. Bird et al.[23] give reasons why spotlighting sub-Saharan Africa is vital. The region is the most vulnerable to the adverse effects of climate change, even though it is the least responsible. Several actors are involved in channelling funds to the region, which are employed to accomplish mostly mitigation and adaptation projects in agriculture, energy and environmental policy, to mention a few. For example, Watson and Schalatek[24] note that about 42% of the global adaptation finance goes to sub-Saharan Africa. Furthermore, grants play a major role in the overall climate finance sector as donors seek to balance the gender narrative, which involves taking into account the gender perspective when developing resource mobilisation strategies and climate finance instruments. These reasons underline the urgency for more (particularly, quantitative) studies on sub-Saharan Africa climate funding, undertaken in this study.

Thus, the contribution of this paper is its analysis of the network system of donors and recipients using network theory techniques in order to characterise the static and dynamic structures of the climate finance network in sub-Saharan Africa. Further, an assessment of the balance between the different themes/objectives of climate change finance cash inflows was carried out. The fund themes are: Mitigation general, Adaptation, Mitigation REDD, and Multiple foci.

Data

The data set used in this study was obtained from the Climate Funds Update website (climatefundsupdate.org), maintained by Heinrich-Böll-Stiftung Washington DC and ODI. It provides information and data from 2003 to 2020 on the different multilateral climate finance initiatives designed to help developing countries address the challenges of climate change. The data are not time series data. The variables within the project data subset which were used in this study were: Fund, Fund Type, Country, World Bank Region, Income Classification, Name of Project, Theme/Objective, Sector (OECD), Sub-Sector, Approved Year, End Year, Amount of Funding Approved (USD millions) and Disbursed (USD millions).

All data relating to sub-Saharan Africa were extracted, giving 693 observations of country recipients only (no multi-country and regional recipients). Country entries without any stated year for their approved funds were omitted. The final data used comprised a sample size of 667 made up of 48 African countries and 20 multilateral funds (Table 1). Each fund was assigned an identity serial number. A similar identification process was done for African countries, which started from number 21 (not displayed here).

Scaling the data region-wise, the region of each country was included. These regions are southern Africa, western Africa, eastern Africa (EA) and central Africa (CA). For funding units, 'multilateral' is assigned under the 'region' column. Table 2 displays an extract.

Table 1: Multilateral funding units with their associated numeric codes

Fund	Fund's numeric code
Adaptation for Smallholder Agriculture Programme (ASAP)	1
Adaptation Fund (AF)	2
BioCarbon Fund Initiative for Sustainable Forest Landscapes (BioCarbon Fund ISFL)	3
Forest Carbon Partnership Facility – Readiness Fund (FCPF-RF)	6
Forest Investment Program (FIP)	7
Global Climate Change Alliance (GCCA)	8
Global Environment Facility (GEF4)	9
Global Environment Facility (GEF5)	10
Global Environment Facility (GEF6)	11
Global Environment Facility (GEF7)	12
Green Climate Fund IRM (GCF IRM)	13
Least Developed Countries Fund (LDCF)	14
MDG Achievement Fund (MDG AF)	15
Partnership for Market Readiness (PMR)	16
Pilot Program for Climate Resilience (PPCR)	17
Scaling Up Renewable Energy Program (SREP)	18
Special Climate Change Fund (SCCF)	19
UN-REDD Programme	20

Table 2: Region-wise categorisation of funding units/countries

Fund code	Funding unit / Country	Region
18	SREP	Multilateral
19	SCCF	Multilateral
20	UN-REDD	Multilateral
21	Angola	Southern Africa
22	Benin	Western Africa
23	Botswana	Southern Africa
24	Burkina Faso	Western Africa
25	Burundi	Central Africa
26	Cabo Verde	Western Africa

Techniques used

Here, only a brief overview of the techniques used is provided, and the technically minded reader is referred to more appropriate sources.

Networks

Social networks can be thought of as a set of individuals in which the relationship between any of the two individuals is accounted for. Let $V = \{v_1, v_2, ..., v_n\}$ be a finite set of unspecified elements. We denote the set of all ordered pairs $[v_i, v_j]$ as $V \otimes V$. The subset $A \subseteq V \otimes V$ then defines a relation to the set A. The pair $G = (V, A)$ is called a simple graph, where V represents the set of finite nodes and A represents the edges. These edges have a symmetric and anti-reflexive relation to V. An anti-reflexive edge implies that the vertex does not have an edge to itself. Several network metrics exist, such as network centrality (which is used to estimate how important a given node is, based on its level of connectivity. Key players can therefore be identified. This further gives rise to the various types of centrality measures, namely, degree, closeness, betweenness and eigenvector. Additionally, different structures of network patterns exist, like the core-periphery structure, which is a network pattern with a dense core of tightly connected nodes and a sparse periphery of nodes that are loosely connected to the core. Others include the layered and the hub-and-spoke structures.

In this study, directed networks $G = (V, A)$ were used, where A is no longer symmetric. Here, V denotes the set of all individuals present (donors and recipients) and A represents the financial linkages, that is, the set of arcs (ordered pairs). Arc $(i, j) \in A$ implies that $i \in A$ can make direct contact with $j \in A$. The flow of climate finance pledges is then tracked from donors to recipients. The multilateral climate change funds are used as proxies for the donors, given that most of these funds are funded by several countries simultaneously. A few of these countries include the UK, Germany, the USA and Sweden. Other sources of funding, such as bilateral donors[3,25], were not considered. Hevey[26] can be consulted for a deeper understanding of network theory.

Decision trees

For easy visualisation and interpretation, tree-based techniques can be employed. They basically partition the predictor variable into different portions. This method adopts an iterative process of repeated splits that are then displayed as a tree. Both regression and classification analyses can be carried out using decision trees. For the former, quantitative data are required, while the latter uses qualitative responses. In this study, the classification tree approach was adopted as it works best when predicting discrete class labels. Kotsiantis[27] gives a more detailed review of decision trees.

The modelling process and application

This section seeks to unravel the structural relationships within the climate finance flows across sub-Saharan Africa.

Network analysis of climate finance flow

In designing the network model for the data, the nodes (or vertices) represent both the donors (funding units) and the recipients (African countries) of climate finance. The edges represent the flow of climate finance, and the network describes the total relationship structure of the actors who exhibit some attributes. The main assumption is that no self-edges exist. This means that the nodes do not form ties with themselves.

For the static network, the node attributes include the funding unit/country, the region, and the amount of funding approved, which indicates the numeric node level variable. The latter is chosen instead of the amount of funds disbursed because of the problem of missing values. The summary statistics indicating the number of countries in each region are 8, 15, 8, 17, and 20 for CA, EA, SA, WA and multilateral, respectively.

However, funds approved does not automatically imply that the target countries will receive the stated funds. For example, in Supplementary table 1, although the GCF IRM fund ranks the highest in approving funds, confirming Watson and Schalatek's[23] assertion of the GCF IRM multilateral unit's approval of the largest amount of adaptation projects (in 2019), it ranks about the lowest with respect to the proportion of total climate funds disbursed to the countries to which it caters. Conversely, funding units like SCCF, MDG AF and GEF4 have completely disbursed their approved funds. This result was computed based on the assumption that there are no disbursed funds (that is, zero value) for the few missing values observed.

In order to build the dynamic network, time points are incorporated to understand the temporal nature of how the climate finance flow system is evolving. The onset, which indicates the time at which the actor came into the climate finance network, represents the year that the first project was approved, while terminus, which indicates when it left the network, represents the very last year the last project (within the period of analysis) was approved for a given African country. With respect to the funding units, this refers to the total time it distributed climate funds to different countries in Africa. The duration represents the total time spent in the network. For example, the funding unit GEF4 approved/distributed funds from the year 2006 to 2010. Thus, the onset is 2006, the terminus is 2010 and the duration is 4 years. With respect to Angola, funding for different projects was approved by different funding units from the year 2008 (representing the onset) to the year 2018 (representing the terminus). This gives a duration of 10 years.

In constructing the attributes for the dynamic network edge, all the funding units sending climate funds to a given African country were extracted. Given that the number of years taken to complete a specific project was missing for many entries, a set of standard time periods was adopted – 3 years, 5 years and 10 years, to cater for short-term, medium-term and long-term projects, respectively. The entry (onset) period therefore represents the first time a project was approved by the specific funding unit, while the terminus period makes use of the standard time adopted. The duration is the total time spent. Other attributes include the tail and head, which respectively refer to the donor and the recipient. For instance, in Supplementary table 2 (the Angola case), for GEF5, number 10 represents the tail while number 21 represents the head. In total, there were 67 node and 667 edge observations.

The static network plot is shown in Figure 1. It incorporates the labels and colour codes the donors (light blue) and the recipient countries (maroon). The outlier (number 5) in both figures refers to the Congo Basin Forest Fund (CBFF). The R packages used were ndtv and tsna.

Different network runs consistently show that the funding units can be broadly categorised into two – those at the middle and those at the boundaries. These are respectively denoted as central funding units (CFUs) and boundary funding units (BFUs) (Table 3). Furthermore, the whole network displays portions that are more dense (or connected) and portions that are less dense (sparse) at the boundaries, that is, connected boundary zones and isolated boundary zones. The more dense portions are characterised by the presence of different BFUs and the isolated zones have no BFUs. This interesting observation indicates that, while the CFUs climate finance flows to many African countries, it is the only source of funding for countries in the less dense region of the network.

A closer look at the countries at the outermost parts of the isolated region reveals that western African countries constitute more than half. These countries include Benin (21), Burkina Faso (23), Gambia (37) and Senegal (55). Those from other regions are Ethiopia (35), Sudan (61) and South Africa (59).

The CTF multilateral fund falls under the BFUs. This finding directly confirms Watson and Schalatek's[28] statement which clearly states that the CTF benefits only a small number of emerging economies. They also point out that GEF 4, 5, 6 and 7 cover most developing countries. With the exception of GEF 7, this study's findings are also in agreement, as GEF 4–6 fall under the CFUs (Figure 1), which indicates that they fund a large proportion of African countries. From the foregoing, it is safe to generalise that BFUs cater to only a few African countries while CFUs cater to many African countries simultaneously.

When the finance approved is taken as the weights, it was observed that GEF7 (with numeric code 12) is the largest BFU and South Africa (59) is

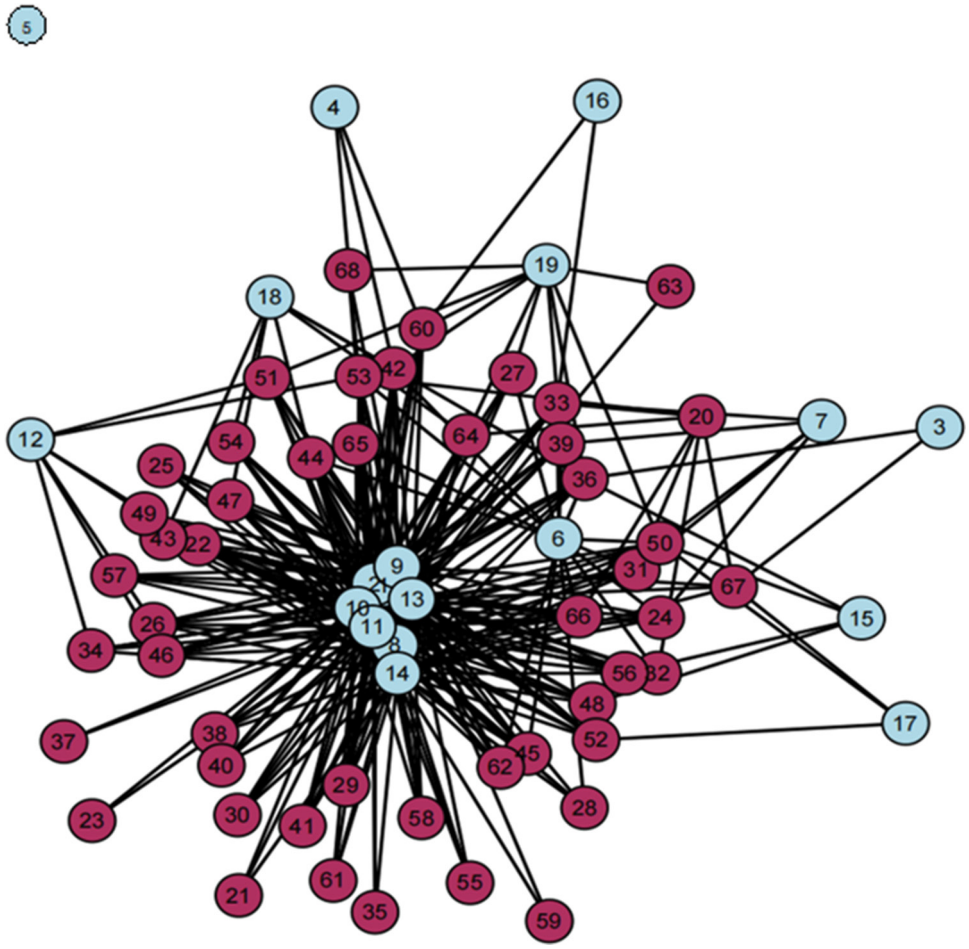

Figure 1: Static network based on climate fund transfer from multilateral funds (light blue) to different African countries (maroon).

Table 3: Boundary and central multilateral funding units

Boundary funding units	Numeric code (BFUs)	Central funding units	Numeric code (CFUs)
BCF-ISFL	3	ASAP	1
CTF	4	AF	2
FIP	7	GCCA	8
GEF7	12	GEF4	9
MDG AF	15	GEF5	10
PMR	16	GEF6	11
PPCR	17	GCF-IRM	13
SREP	18	LDCF	14
SCCF	19		

the country with the largest portion of climate finance, all coming from the CFUs (Figure 2).

To visualise the dynamic nature of the network, the filmstrip function in the ndtv R package was applied. It breaks the network up into successive temporal slices, giving us a view of the network as it develops over time (Figure 3). Hence, we get to see snapshots (that is, static plots) at a few key moments of the dynamic networks, over the lifetime of the projects.

It can be observed that longer-term project networks tend to 'mature' (or transform) faster than 5-year or 3-year duration projects. There is a persistent pattern of a sparse neighbourhood emerging around the year 2010 for the 3- and 5-year duration projects only. This pattern persists for a while up to the year 2014, for only short-term projects. In both the medium- and long-term projects, however, more dense subgroups can be observed in the latter years of formation where the transition behaviour from the year 2012 follows a similar pattern. Figure 4 denotes how centrality changes over time, year on year, based on the rolling aggregated betweenness centrality. This is an example of crucial node types which capture how much a specific node lies in between other nodes (serving as a key broker). It measures the fraction of the least paths that are passing through a given node. High values of betweenness centrality are generally used to identify vertices that preserve the whole network's connectivity. The climate finance flow network (Figure 4) experienced its lowest dip around 2007, and although it has risen since then, it has not approached its 2004 peak (or thereabout). This suggests that the connectivity of the financial flows across sub-Saharan Africa was at its lowest during the period of the global financial crisis which started in 2007 and lasted until 2009, most probably because the major key players (donors) temporarily stopped or drastically reduced funding. By 2010, after the crisis, it had stabilised a bit, but was not yet fully recovered.

Decision tree analysis of climate finance flow

The theme/objective of the data set entries was used as a guide. The four themes are Mitigation General (Mitigation G for short), Adaptation, Mitigation REDD and Multiple foci. The amount of funding approved for each country under each specific theme was then extracted as shown in Table 4 (for the first 15 countries).

Overall, across the 48 sub-Saharan African countries, a total of USD1437.95 million has been approved for projects under the Mitigation G theme, USD2038.27 million for Adaptation, USD565.58 million for

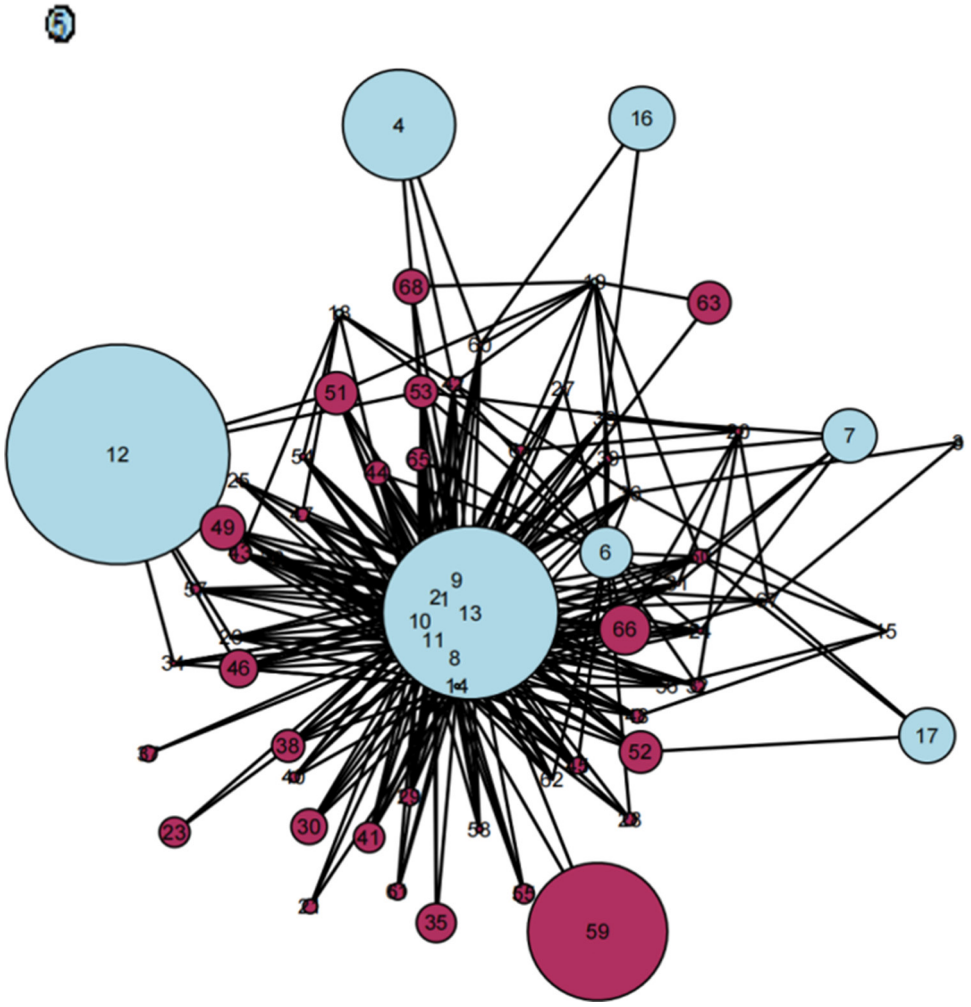

Figure 2: Weighted static network of climate finance flows from multilateral funds (light blue) to different African countries (maroon). The approved funds serve as the weights.

Mitigation REDD and USD383.85 million for projects leaning towards Multiple foci objective. This finding underlines the fact that mitigation finance dominates the total climate finance flowing into sub-Saharan Africa, as previously noted by Savividou et al.[20] This is not a healthy path for the region. The summary statistics for each objective are denoted in Supplementary table 3.

Setting region as the target variable, each variable's univariate and bivariate distribution was examined with respect to the target variable using simple histogram representations. The R packages used in this analysis were plyr, dplyr, ggplot2, caret, rpart, rpart.plot, e1071 and stringi. The univariate distributions are displayed in Figure 5.

All the themes display right-skewed distributions and possess extreme outliers. Adaptation, however, is less skewed and there are fewer very high and low values in comparison with the other objectives. Most of the Mitigation G funds fall between 0 to USD100 million (Figure 5a). The bivariate distribution is created by converting the variable region to a factor variable where the region's numeric code features are used to represent the factor levels. Region 1 refers to western Africa, region 2 southern Africa while central and eastern Africa are represented by regions 3 and 4, respectively. Each of the continuous variables (the themes) was then examined in relation to the target variable (Figure 6).

From Figure 6a, countries in region 3 (central Africa) are more likely to receive a higher proportion of Mitigation G finance if the projects fall within the range of USD100 million. However, the countries in region 2 (southern Africa) get a disproportionately high amount of Mitigation G funds as indicated by the extreme outlier. With Adaptation finance (Figure 6b), a much more evenly distributed mechanism is at play (specifically when the funds are less than USD50 million). The histogram takes the form of a bimodal distribution, where the first mode is approximately normal. In the case of Mitigation REDD, an even distribution is also observed in general, with the exception that funds greater than USD100 million are more likely to go to countries in region 3 (Figure 6c). Finally, countries that fall under region 4 (eastern Africa) are more likely to receive higher Multiple foci climate finance if it is above USD25 million (Figure 6d). These patterns also speak loudly about the kinds of climate-related projects that are more dominant in a given sub-Saharan African region.

To further classify the themes of climate finance region-wise, decision trees were built. The plots are shown in Figure 7.

Train/test split approaches were implemented in the cases of Figure 7(b–d). One node remained unused in all cases, with the exception of Figure 7d where the leaf size was lowered. Although the test accuracy for the latter is lower than that in plot c, it will be adopted because it makes use of all the nodes (regions); however, Mitigation G is not used. It should be noted that these results may not be reliable enough, given the small sample size of 48 that was used. Figure 7d indicates that region 4 (eastern Africa) fully dominates when Adaptation finance is greater than USD55 million. This aligns with the bivariate plot in Figure 6b where we see region 4 showing up 4 out of 7 times when funds are greater than USD50 million and 1 out of 7 times when less than USD50 million. This finding was observed by Atteridge et al.[29] as well. They expressed concerns over the concentration of Adaptation finance in only a small number of sectors, noting that this could hinder the broader impact of the objective.

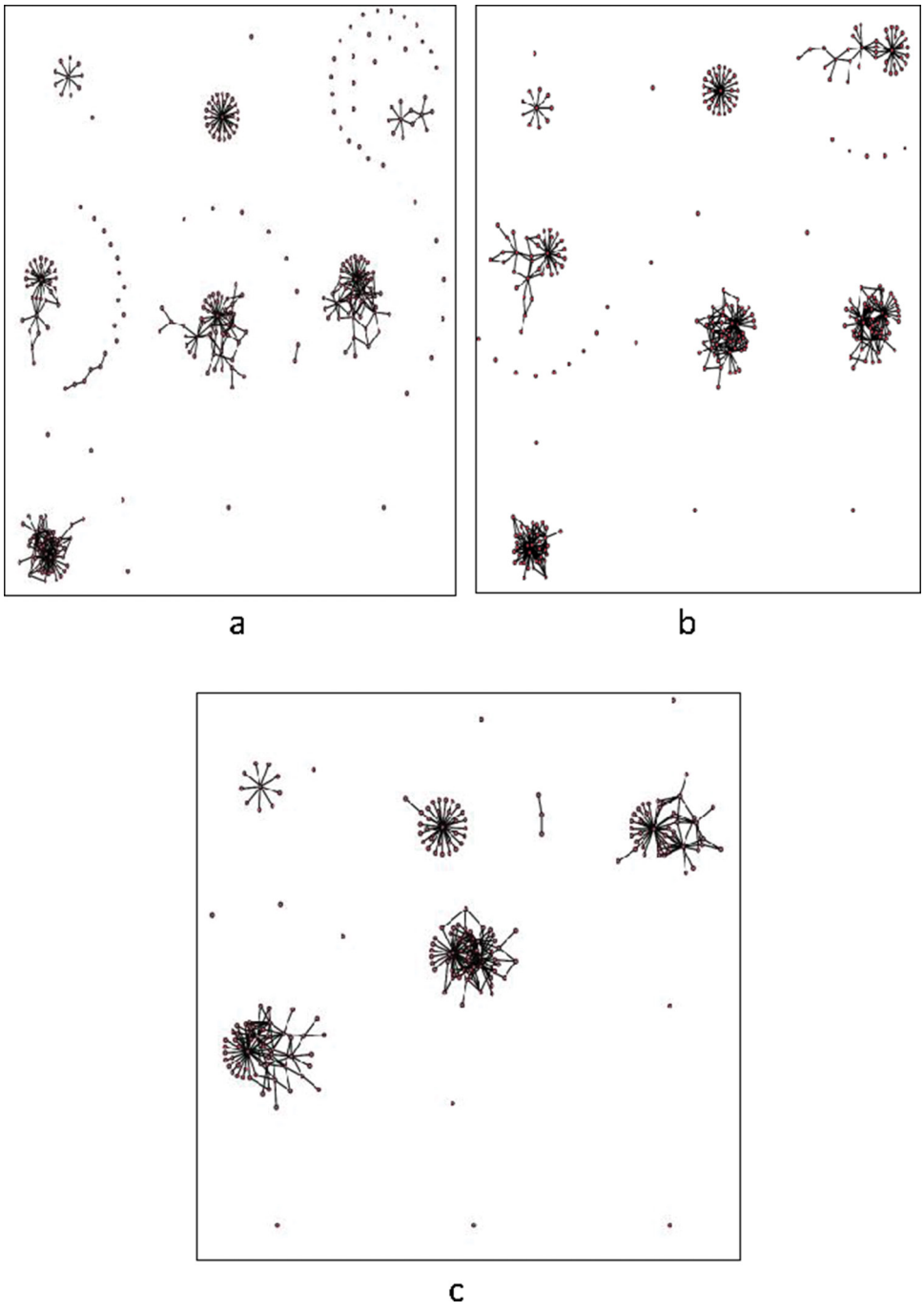

Figure 3: The (a) 3-year, (b) 5-year and (c) 10-year duration of the temporal snapshots for the dynamic network. Moving across the rows (three in each case) from left to right, the times of occurrence of the static projections of the temporal networks are t= 2003, 2005.375, 2007.75, 2010.125, 2012.5, 2014.875, 2017.25, 2019.625, 2022 for (a); t=2003, 2005.625, 2008.25, 2010.875, 2013.5, 2016.125, 2018.75, 2021.375, 2024 for (b); and t=2003, 2006.25, 2009.5, 2012.75, 2016, 2019.25, 2022.5, 2025.75, 2029 for (c).

Region 2 (southern Africa) is characterised by lower (less than USD55 million) levels of Adaptation finance with projects under Mitigation REDD costing less than USD0.98 million, and for Multiple foci, less than USD5.1 million. Region 3 (central Africa), however, gets more than USD0.98 million with regard to Mitigation REDD, even though it receives less than USD55 million in Adaptation funds. Their Multiple foci quota share is much less (less than USD1.8 million).

Implications for practitioners, policymakers, donors and regulators

About 63% of the multilateral climate funding units (studied in this paper) are yet to disburse up to 50% of their approved funds for climate-related projects in sub-Saharan Africa. This generally signifies the very slow pace at which the low-carbon, climate-resilient goal is being achieved. This is also a wake-up call to the African regions. More African regional-based multilateral funding units are needed. Both the private and public sectors should be fully involved in coordinating such climate finance pools with the associated required regulations.

Implications from network analysis: The less dense region of the network reveals some sort of vulnerable position for the countries (up to 16 of them) located therein. With the exception of South Africa, which gulps in the largest share of climate funds, the others in the sparse region have to share what is left with the countries in the denser region. Secondly, this brings to the fore the issues surrounding equitable

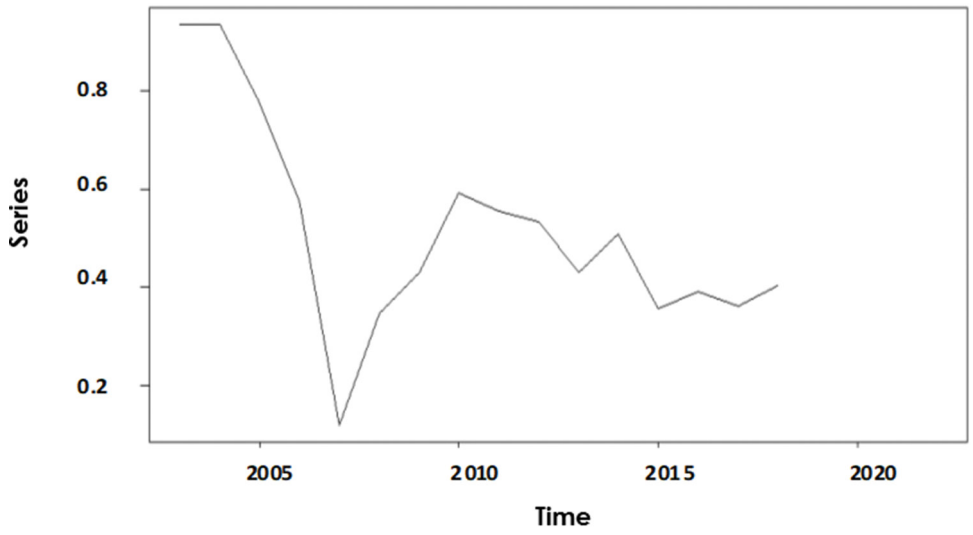

Figure 4: Year-on-year aggregated betweenness centrality changes for the temporal network.

Table 4: Approved funds for sub-Saharan African countries based on the themes

Country	Region	Region's numeric code	Mitigation G (USD millions)	Adaptation (USD millions)	Mitigation REDD (USD millions)	Multiple foci (USD millions)
Angola	Southern Africa	2	8.16	25.67	0	0
Benin	Western Africa	1	7.52	51.1	2.63	1.89
Botswana	Southern Africa	2	2.63	0	0	0.95
Burkina Faso	Western Africa	1	29.65	49.3	53.07	5.92
Burundi	Central Africa	3	3.4	22.86	0	0
Cabo Verde	Western Africa	1	4.53	7.28	0	8.12
Cameroon	Central Africa	3	3.73	4.03	13.99	0.34
Central African Republic	Central Africa	3	2.65	10.12	7.6	0.63
Chad	Central Africa	3	4.99	35.84	0	14.64
Comoros	Eastern Africa	4	5.91	69.93	0	3.76
Congo, Democratic Replubic of	Central Africa	3	28.15	26.86	120.91	0.96
Congo, Republic of	Central Africa	3	5.07	10	22.78	0.66
Cote d'Ivoire	Western Africa	1	8.35	6.34	49.31	4.24
Equatorial Guinea	Central Africa	3	4.36	0.2	5.93	0.9
Eritrea	Eastern Africa	4	0	15.77	0	8.26

resource allocation of climate funds, given the scarcity of BFUs allocating funds to a number of African countries. A situation in which the CFUs are overburdened might ensue, leading to the unexpected accumulation of approved funds if this type of setup tarries for a long time. An example of such a situation might be during a financial crisis. In the absence of alternative (boundary) multilateral funding units, the isolated regions are bound to suffer the most.

It must also be noted that while South Africa is the largest emitter of carbon in Africa, hence requiring more climate funds (particularly mitigation finance), the climate change issue remains a global problem. The attainment of low carbon across African countries will as well impact South Africa positively, judging from the extremal dependence of climatic variables that may be present in African regions, eastern Africa for example.[30] This therefore implies that a fair balance for climate fund allocation needs to be struck by the donors. Thirdly, the presence of this gap presents opportunities for practitioners seeking to engage in the global/continental climate fund negotiation processes, as the entry of more multilateral funding units can help limit the monopolisation of African countries' access to international funds. Fourthly, the structure of the network seems to suggest a greater coordination between CFUs than BFUs, although this may not be reflective of the real situation. Nevertheless, there is need for greater coordination between the funding units at the boundaries and at the centre to enable every African country to benefit from both sources.

Implications from decision tree analysis: Although eastern Africa is arguably the hardest hit region in terms of the adverse effects of climate

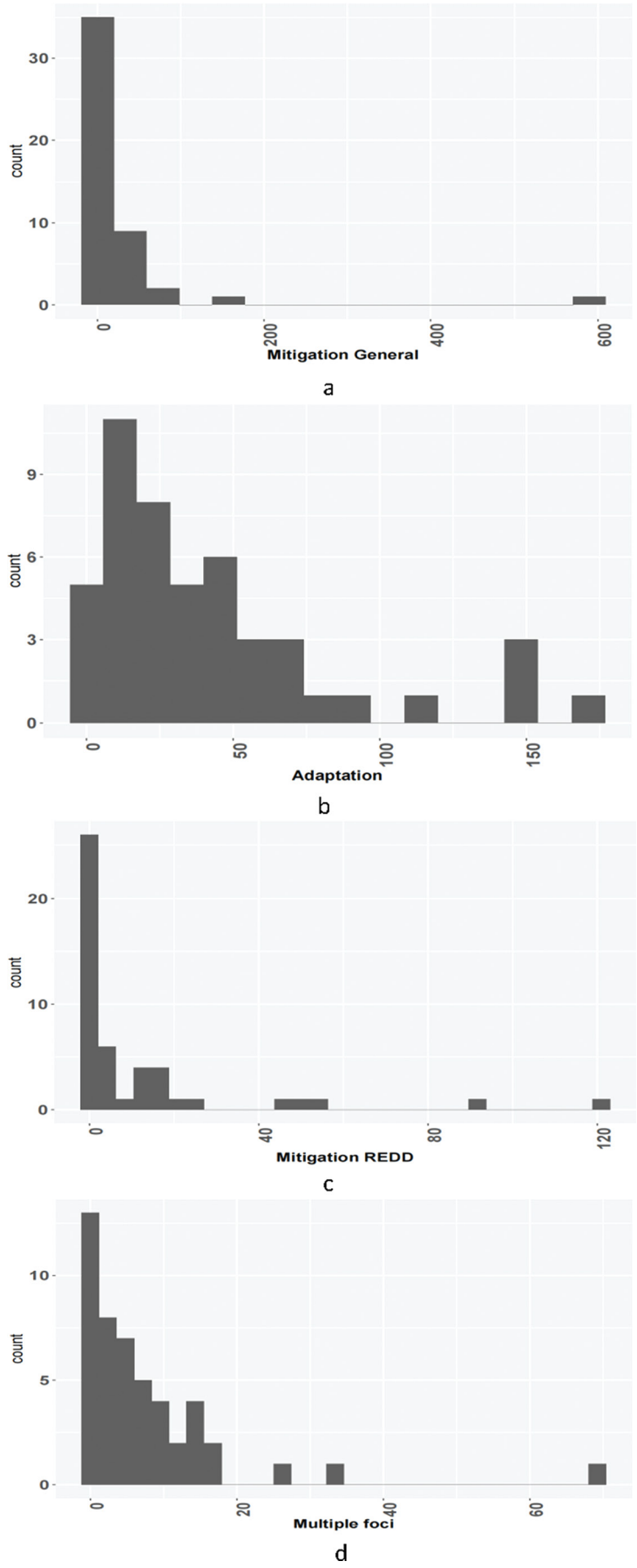

Figure 5: Univariate distributions of themes (a) Mitigation G, (b) Adaptation, (c) Mitigation REDD and (d) Multiple foci, with respect to the different African regions.

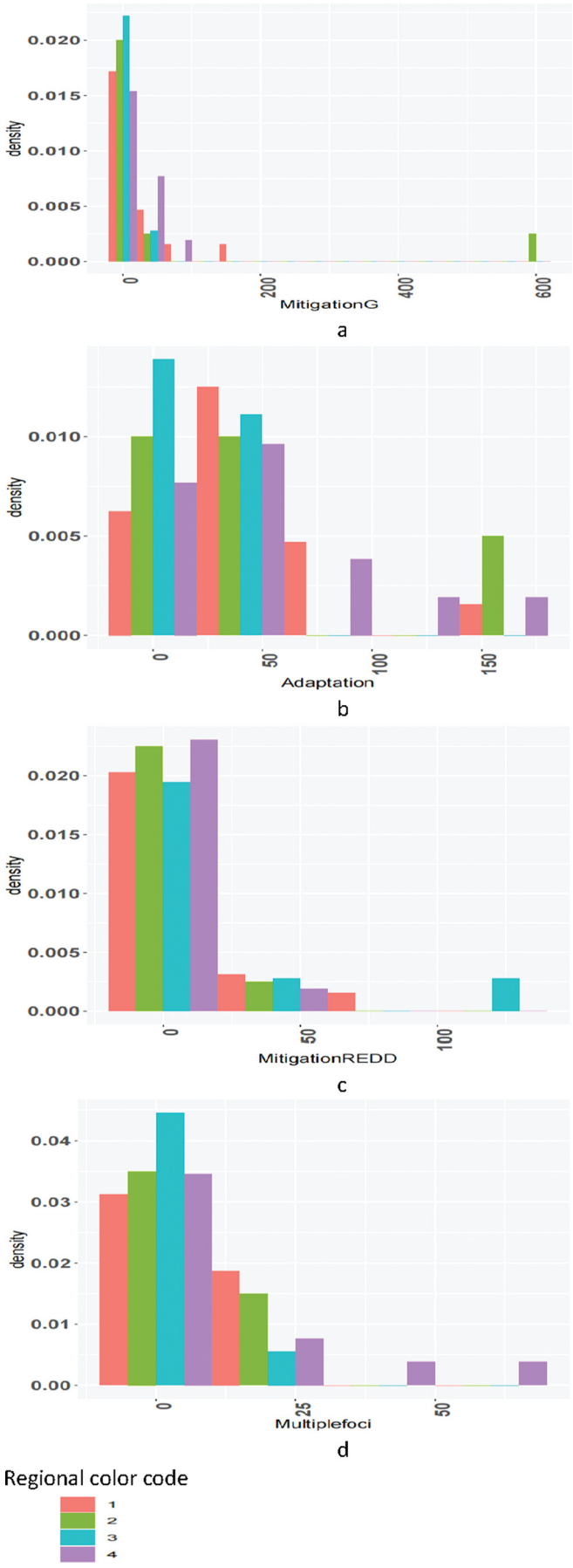

Figure 6: Bivariate distributions of themes with respect to the countries' regions: western Africa = 1, southern Africa = 2, central Africa = 3, and eastern Africa = 4 in the colour-coded key.

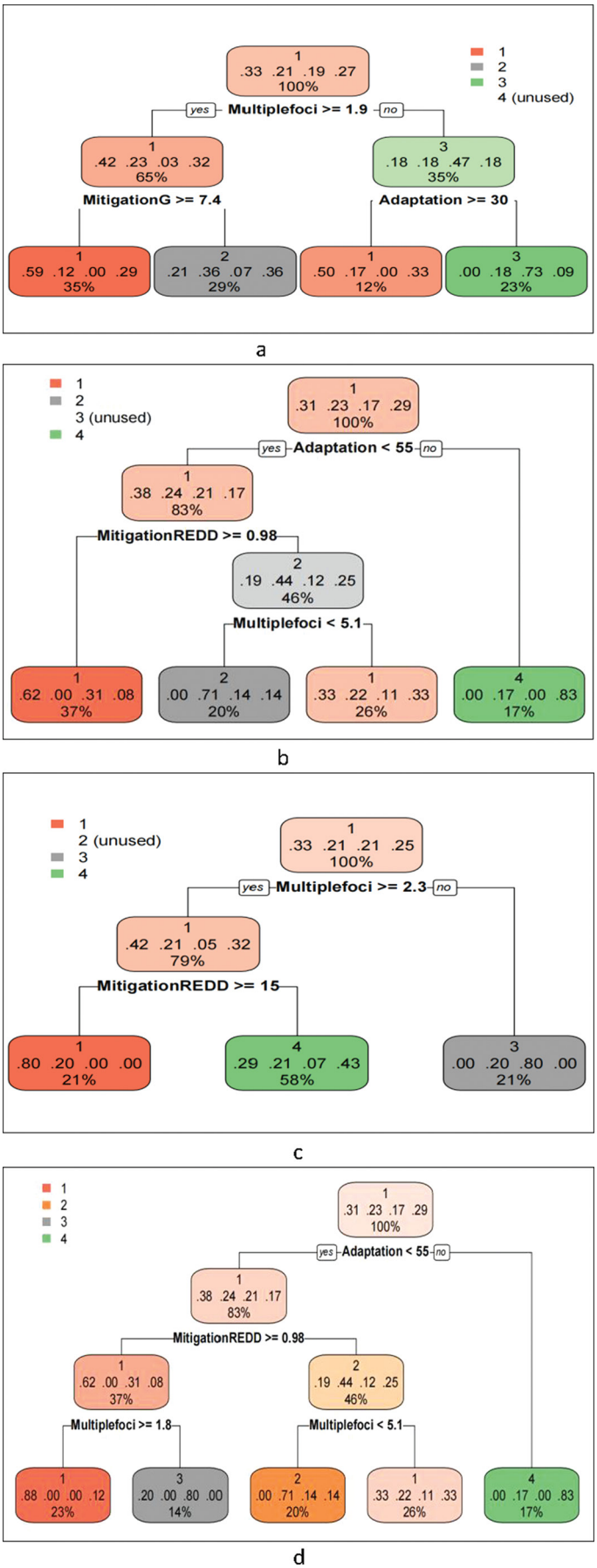

Figure 7: Decision trees classifying the climate finance themes region-wise. (a) No partition, (b) 70/30 partition with test data accuracy=7%, (c) 50/50 partition with test data accuracy=33%, (d) 70/30 partition with a lowered leaf size and test data accuracy=23%.

change in Africa, the highly unequal distribution of Adaptation finance for funds greater than USD50 million may be a matter of concern. This is due to the critical assistance other African countries currently need (particularly in the area of agriculture) in order to adapt to the rapid increase in the impacts of climate change already being experienced as a result of droughts and floods. Rapid desertification, for instance, lies at the base of the farmer–herder violence in northern Nigeria, which has since reached crisis levels, leading to the loss of thousands of lives and property, massive internal displacements, and heightened food insecurity.[31-33] Adequate adaptation funds will definitely go a long way in resolving this problem (all else being equal).

Conclusion

Climate finance holds the key to obtaining the goals set for achieving a low-carbon world. However, the complexities involved in monitoring its flow across sub-Saharan Africa have not been thoroughly dealt with. This study was an in-depth critical look at how the flow is structured. The results obtained generally fit the multilateral funding units into two categories: the central and boundary funding units. Although more African countries have the opportunity of a boundary funding source which supplements the central source, a substantial number of countries remain in the isolated region at the boundary as they rely only on the central funding units, thus increasing their vulnerability. This vulnerability can become even more evident when shocks such as pandemics and financial crises are introduced into the system, as the flow of money declines significantly during such periods. Hence, there is a need for the major stakeholders in the concerned countries to highlight these issues when negotiating for climate finance. Plus, other alternatives can be prepared ahead of time because mitigation and adaptation strategies for climate change demand huge amounts of finance.

Nevertheless, further studies are required to understand the evolution of this vulnerable group when other climate funding sources are accounted for, such as multilateral, bilateral, grant-type, national and local government sources. Additionally, the diverse nature of the countries in Africa implies that each has their own special climate-related problems, risks, and solutions. The complexities of how climate money is distributed within individual countries and each country's unique needs and efforts may be overlooked if countries are grouped into broad regional groupings. Other variables such as political links, past obligations, and the success of national climate policy also affect how climate financing is allocated. Hence, country-specific analyses of climate finance flows and their effects might offer a more perceptive viewpoint on the matter. To this end, African governments are encouraged to give keen attention to data collection and data storage. There is also a need to understand if there are any patterns emerging that differentiate projects into fully disbursed finance versus those that have partially disbursed finance, the regions affected and the reasons for failure to disburse funds.

Competing interests

I have no competing interests to declare.

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AgERA5 representation of seasonal mean and extreme temperatures in the Northern Cape, South Africa

Over regions with sparse observation networks, including South Africa's Northern Cape Province, gridded data sets represent valuable supplementary data sources enabling spatially detailed climate investigations. Their performance is, however, influenced by regional characteristics, thus a performance assessment should be a prerequisite for any regional application. Through a pairwise comparison with eight point-based temperature records, we evaluated the AgERA5 data sets representation of mean summer (November–March; Tms) and winter (May–September; Tmw) temperatures and respective seasonal heatwave and coldwave characteristics across the Northern Cape for 1980–2020. Correlations ranging from 0.48 to 0.92 for Tms and from 0.38 to 0.94 for Tmw reflect relatively strong, but varying, temporal correspondence between the AgERA5 data and stations. Low biases, averaging –0.08 (0.17) °C and ranging from -0.79 to 2.10 (-0.40 to 1.47) °C for Tms (Tmw) were evident. Biases for the heatwave (coldwave) magnitudes were low, averaging -0.38 (0.19) °C^2, and ranging from -1.55 to 1.47 (-2.05 to 2.91) °C^2. Biases for the heatwave (coldwave) frequency were also low, but typically overestimated, averaging 1.19 (0.73) days, and ranging from -1.33 to 5.60 (-1.61 to 3.39) days. Biases for the heatwave (coldwave) number were low and typically overestimated, averaging 0.27 (0.08) events, and ranging from -0.28 to 1.40 (-0.39 to 0.39) events. Despite some stations depicting consistently poor performance, the study results support further application of the AgERA5 product for spatiotemporal analyses of mean and extreme temperatures across the Northern Cape, provided limitations are adequately acknowledged. Further application of the fine-resolution AgERA5 product will greatly inform impact-based studies exploring mean and extreme temperature influences over the Northern Cape Province.

Significance:

- The AgERA5 product was assessed on its performance in representing average and extreme temperature characteristics over South Africa's Northern Cape Province.
- Good comparability between the AgERA5 product and point-based observations supports further application of the AgERA5 across the Northern Cape.
- The AgERA5 product offers a spatially detailed picture of mean and extreme temperatures across the Northern Cape, which is valuable for regions where weather stations are not available.
- The AgERA5 product is thus important for impact-based studies assessing, for instance, the impact of extreme temperatures on livestock and human health.

Introduction

Southern Africa is expected to experience above global-average warming, which will lead to drastic changes in regional extreme temperature event (ETE) characteristics.[1-3] Historical trends and future projections indicate that, compared to other South African provinces, the Northern Cape Province (Figure 1) has and will likely continue to experience among the largest increases in surface air temperature and hot ETE characteristics (e.g. heatwaves).[1,4] Conversely, historical trends and future projections over southern Africa typically show decreasing trends in the cold ETE characteristics (e.g. coldwaves).[5-7] During ETEs, prolonged exposure to thermal stress can have devastating impacts which can influence agricultural productivity, by reducing crop yields and potentially causing livestock mortalities, and human health, by exacerbating illnesses (e.g. headaches and asthma) and potentially leading to mortality.[7-9] These impacts are of concern, because in developing regions, such as the Northern Cape, associated implications are exacerbated due to a high reliance on weather and climate-sensitive activities (e.g. agriculture), and high levels of poverty and unemployment.[10,11]

Across the Northern Cape Province, interactions between tropical, temperate and subtropical weather systems, the regional topography, and the cold Benguela Current (and the Benguela Upwelling System) are known to drive the occurrences of cold and hot ETEs.[12] Through westerly troughs, cut-off lows and mid-latitude cyclone cold fronts, the mid-latitude westerlies and cold Benguela current (and the Benguela Upwelling System) contribute to the advection of cold air, from the southern Atlantic Ocean, over the Northern Cape and are known to be associated with cold snaps and coldwave events.[12-14] Typically, heatwaves are associated with mid-to-lower tropospheric high-pressure systems, limited cloud coverage, and enhanced incoming longwave radiation.[15,16] Troughs extending from the tropics transport warm air from the farther northern tropical regions and are also known to induce hot ETEs across South Africa and the Northern Cape.[17-19]

Weather station records have been the primary data source for investigations regarding ETEs across South Africa, yet large parts of South Africa, especially mountainous and remote regions, have sparse station network coverage.[20] Thus, station data alone cannot provide detailed spatial pictures required for climate studies. Station data sometimes have data quality issues and are not typically temporally complete due to technical issues and, in some cases, closure of stations.[20] There is thus an increasing need for an alternative, or supplementary data

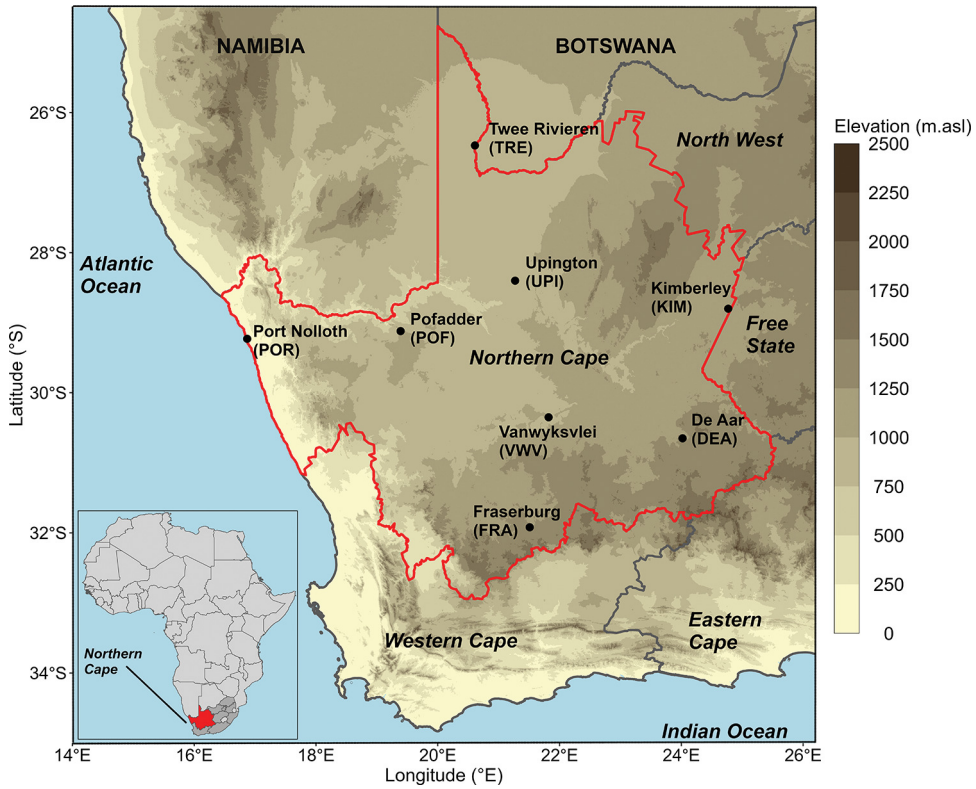

Figure 1: Study site map depicting elevation, neighbouring countries and provinces, bordering oceans, and locations of weather stations used across the Northern Cape Province. Details of the weather stations are presented in Supplementary table 1.

source, and gridded data sets offer such an alternative.[21,22] Various gridded temperature data sets exist which are generated using different methods, such as interpolating station data, analysing satellite imagery, and assimilating observations from stations and/or satellite imagery through simulations.[23-27] There is, however, uncertainty as to whether gridded data accurately represent temperature and ETEs, especially in regions adjacent to oceans, with steep near-surface temperature gradients, elevation gradients and/or precipitation gradients.[21,22] The Northern Cape represents a region with steep elevation gradients, where the high-lying interior plateau and low-lying coastal plain are separated by the mountainous region of the western Great Escarpment (Figure 1). The Northern Cape has a complex rainfall climatology, with a summer rainfall zone towards the east, a year-round rainfall zone from the central parts to the edge of the western Great Escarpment, and a winter rainfall zone across the coastal plain.[28] Therefore, over a region like the Northern Cape, a fine resolution data set should provide a more detailed representation of the region's climate, as studies demonstrate that finer resolution data sets often, but not always, provide improved climate representations compared to coarser products.[20,29]

Among the available gridded temperature products, the ERA5, and specifically products downscaled from it (i.e. AgERA5), offer the highest resolution temperature data sets.[25,26] Although recent research has assessed the AgERA5 data set in representing mean and extreme temperatures across the Northern Cape, a gridded observation-based product was considered. Thus, there is still uncertainty as to whether the AgERA5 area-averaged grid cells accurately compare to point-based temperature records.[20] Therefore, using point-based weather station records from the South African Weather Service (SAWS), we aimed to apply comparative statistics to explore the performance of the AgERA5 data set in representing mean summer (Tms) and winter (Tmw) temperatures and respective seasonal heatwave and coldwave characteristics across the Northern Cape for 1980–2020. Considering the adverse implications associated with ETEs and the importance of reliable gridded data sets for spatial investigations of ETEs, the evaluation of such a data set is relevant as a prerequisite for further studies utilising the AgERA5 product over the Northern Cape.[29]

Data and methods

Data and pre-processing

The AgERA5 daily maximum and minimum temperature (Tx and Tn, respectively) outputs for 1980–2020 were utilised for this study; AgERA5 data are freely available for download from the Copernicus Climate Data Store.[26] The AgERA5 data set is a statistically downscaled and bias-corrected product that is available at a 0.1° resolution.[26] It is derived from the hourly ERA5 reanalysis which is available at a 0.25° resolution and combines numerical model, satellite and observation data using the European Centre for Medium-Range Weather Forecasts' Integrated Forecast System (ECMWF).[25,26] Before calculating the temperature indices using the AgERA5 data, several pre-processing steps were undertaken to prepare the data using the Climate Data Operators software.[30] This preparation included the temporal merging of daily NetCDF files, spatial clipping to the study domain extent (i.e. 25–33° S and 17–25°E), converting units from K to °C, and changing of variable names according to the Climpact user manual.[31]

To evaluate the performance of the AgERA5 data set across the Northern Cape, daily Tx and Tn spanning 1980–2020 were utilised from eight SAWS weather stations (Supplementary table 1), purposively selected following van der Walt and Fitchett[32], to produce an evenly distributed network of stations across the province (Figure 1). For inclusion, stations were required to have >90% data availability for 1980–2020.[33] Before statistical analyses, data quality was examined and cleaning was performed.[32,33] All dates were checked for duplication and gaps, and values were rounded to two decimal places for consistency.[33] Repetition and duplication of temperature values and where Tx $\leq$ Tn were among the errors identified, while outliers were identified using box plots and then verified through comparison with nearby stations.[28,32,33] All errors and outliers identified were deleted and recorded as missing values.[28,34,35] Missing values were filled with data from nearby stations if they were located within a 50 km radius and had a Spearman Correlation Coefficient (CC) of >0.70 between the existing records of both stations.[32,35-37] If there were still missing values for less than five consecutive days, a five-day running average was used to estimate these.[28,32]

Table 1: Tabulated results, per location mapped in Figure 1, of the comparison between the AgERA5 and SAWS data sets for average daily summer temperatures (Tms) and daily winter temperatures (Tmw). CC represents the Spearman Correlation Coefficient; RMSE represents the Root Mean Square Error; MD represents the Modified Index of Agreement. CC values denoted in bold represent statistically significant correlations at the 5% alpha level.

Index	Station	CC	MD	RMSE	Bias
Tms	DEA	**0.92**	0.79	0.34	-0.21
	FRA	**0.86**	0.46	0.87	-0.79
	KIM	**0.85**	0.72	0.51	0.08
	POF	**0.90**	0.70	0.38	-0.26
	POR	**0.48**	0.21	2.19	2.10
	TRE	**0.68**	0.57	0.76	-0.50
	UPI	**0.84**	0.58	0.52	-0.36
	VWV	**0.85**	0.45	0.79	-0.70
Tmw	DEA	**0.84**	0.64	0.52	-0.40
	FRA	**0.84**	0.71	0.41	-0.11
	KIM	**0.70**	0.56	0.70	0.49
	POF	**0.94**	0.72	0.57	-0.29
	POR	**0.38**	0.23	1.57	1.47
	TRE	**0.68**	0.51	0.74	0.52
	UPI	**0.78**	0.68	0.37	-0.16
	VWV	**0.84**	0.64	0.40	-0.27

Heatwave and coldwave indices

To calculate ETE indices we utilised the R Climpact package, developed by the World Meteorological Organisation (WMO) Expert Team on Sector-specific Climate Indices (ET-SCI).[31] Among the available heatwave and coldwave definitions, the Excess Heat Factor (EHF) and excess cold factor (ECF) were applied herein for the heatwave and coldwave calculations for the extended summer (November–March) and winter (May–September) seasons for 1980–2020, respectively.[38,39] The EHF/ECF incorporates two components based on average daily temperatures, representing acclimatisation and significance, which are combined into one factor: the EHF/ECF.[39] Heatwaves (coldwaves) are defined when the EHF (ECF) value is positive (negative) for at least three consecutive days.[31,39] More information about the EHF, ECF and respective heatwave and coldwave calculations are detailed in Herold and McComb[31] and Nairn and Fawcett.[39]

Duration, magnitude and frequency are heatwave and coldwave characteristics frequently used to describe such events.[4,6,38,40] Thus, similar heatwave and coldwave indices were computed as seasonally averaged outputs for the AgERA5 and SAWS data sets. These include: (1) heatwave (coldwave) frequency (HWF [CWF]) which represents the total number of days contributing to annual summer (winter) heatwave (coldwave) events, (2) heatwave (coldwave) magnitude (HWM [CWM]) represents the average temperature of summer (winter) heatwaves (coldwaves) per year, measured as °C^2 due to the EHF (ECF) definition and (3) heatwave (coldwave) number (HWN [CWN]) which represents the total number of summer (winter) heatwave (coldwave) events per year.[38,39]

Evaluation analysis

To evaluate the AgERA5 in representing Tms and Tmw, and respective seasonal ETE characteristics, we first explored the data sets' performance in characterising daily average Tms and Tmw, using the summer and winter periods for the heatwave and coldwave calculations. Tms and Tmw are fundamental as they can dictate underlying factors influencing the performance of seasonal ETE characteristics.[20] Thereafter, performance was explored for the respective ETE indices. In all instances, four pairwise statistical metrics were calculated to compare the AgERA5 and SAWS data sets; single grid cell values corresponding to the station coordinates were extracted to compute the evaluation metrics (Supplementary table 1). CC was used to measure the level of temporal consistency between the AgERA5 and SAWS data sets, where output values range between zero and one, and one is optimal.[28] Information on the standard metric errors, measuring deviation between the data sets, were calculated as Root Mean Square Error (RMSE) values, where outputs range between zero and one, with zero as the strongest score.[22] The bias metric was used to determine the tendency of the AgERA5 data set to overestimate or underestimate values compared to the SAWS data set, where positive (negative) bias values indicate an overestimation (underestimation) by the AgERA5 data set, while a value of zero is optimal.[41] The Modified Index of Agreement (MD) was used to identify both additive and proportional disparities in the SAWS and AgERA5 mean and variance ranges.[42,43] This provides a valuable skill score for the data; the resulting value ranges between zero and one, with one being the desired value.[42,43]

Results

AgERA5 representation of mean summer and winter temperatures

Box plots illustrating the distribution of Tms and Tmw across the weather stations and AgERA5 grid cells in the Northern Cape for 1980–2020 indicate that there is strong agreement between the data sets, with mean values deviating by <1 °C for most locations (excluding POR; Figure 2a–b). Excluding POR, the overlapping boxplot boxes for the stations and AgERA5 cells further indicate a high degree of agreement and strong correspondence between the two data sets (Figure 2a–b). For Tms, the box plots reveal that KIM and POR exhibit higher temperature values (i.e. warm bias) in the AgERA5 data set, whereas the remaining locations exhibit lower temperatures (i.e. cool bias; Figure 2a). This pattern is indicative of a predominant negative (cool) bias in the AgERA5 Tms proxies, which is apparent in the Supplementary figure 1 time series plots and the bias values (Table 1). Similarly, for Tmw, the box plots

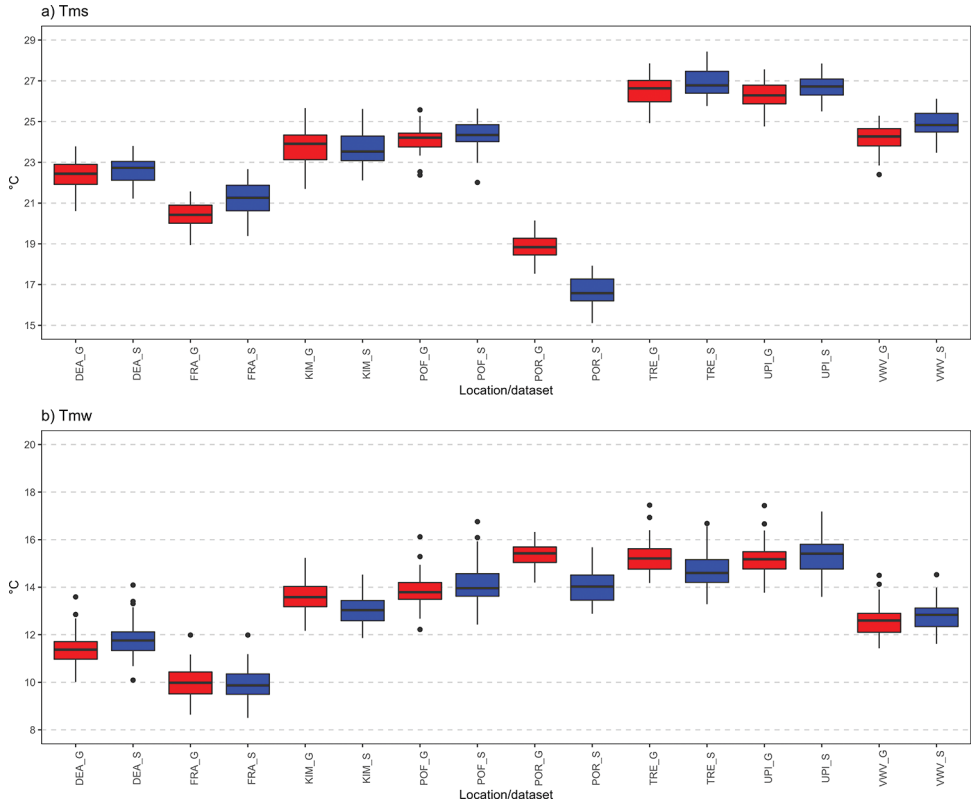

Figure 2: Box plots depicting the distribution of (a) average daily summer (Tms) and (b) winter (Tmw) temperatures for the AgERA5 (red) reanalysis and SAWS (blue) weather station data sets from 1980 to 2020 for locations mapped in Figure 1.

reveal that the AgERA5 cells exhibit higher temperatures (i.e. warm bias) at KIM, POR and TRE, while lower temperatures (i.e. cool bias) are observed at the remaining locations (Figure 2b). This indicates a predominant negative (i.e. cool) bias in the AgERA5 Tmw data, which is also evident in the time series plots and tabulated bias values (Table 1; Supplementary figure 1). Compared to SAWS data, most locations depict lower AgERA5 box plot tail ends, which may translate to an underestimation of AgERA5 extremetemperatures (Figure 2). Among the stations, POR consistently depicts weaker correspondence as mean values deviate by >1 °C and the spread of the data does not overlap consistently for both Tms and Tmw (Figure 2).

Strong temporal consistency between the AgERA5 and station data sets is supported by the statistically significant CC values, demonstrating consistent interannual variability patterns, and the time series plots, which demonstrate consistent temporal tracking between the two data sets (Supplementary figures 1 and 2; Table 1). The CC values are moderate to strong in magnitude, further indicating strong consistency between the data sets (Table 1). CC values range between 0.48 (POR) and 0.92 (DEA) for Tms and from 0.38 (POR) to 0.94 (POF) for Tmw, with stronger temporal correspondence for Tms as reflected by higher correlation values for most stations (Table 1). Located along the western coast and farthest north, POR and TRE exhibit the lowest degree of temporal agreement for Tms (Tmw), with CC values of 0.48 (0.68) and 0.38 (0.68), respectively (Table 1). The MD values further indicate strong agreement between the data sets, with Tms values ranging between 0.21 (POR) and 0.79 (DEA) and Tmw values from 0.23 (POR) to 0.72 (POF; Table 1). The low, but varying, deviation in seasonal temperatures between SAWS and AgERA5 for Tms is characterised by RMSE values ranging from 0.34 °C (DEA) to 2.19 °C (POR), while for Tmw RMSE values range from 0.37 °C (UPI) to 1.57 °C (POR; Table 1). The AgERA5 Tms values are overestimated by 0.08 °C and 2.10 °C at KIM and POR, respectively, and Tmw values are overestimated by 0.49 °C, 1.47 °C and 0.51 °C at KIM, POR and TRE, respectively (Table 1). In general, for most stations, the AgERA5 data set underestimates Tms and Tmw, as evidenced by the mostly negative bias values and the time series plots per station (Table 1; Supplementary figures 1 and 2). Specifically, bias values range from -2.10 (POR) to 0.79 °C (FRA) for Tms and from -1.47 (POR) to 0.40 °C (DEA) for Tmw (Table 1). Despite these biases, their magnitudes are relatively small, which is consistent with the low RMSE values evident across the stations (excluding POR; Table 1).

AgERA5 representation of mean summer season heatwave characteristics

Box plots depicting the distribution of heatwave characteristics and time series plots illustrating temporal patterns across the stations and corresponding AgERA5 grid cells in the Northern Cape for 1980–2020 depict strong consistency between the data sets, as is evident from the overlapping boxes of the box plots, similar temporal variability patterns and consistent tracking for each time series (Figures 3–5; Supplementary figure 3). Specifically, the box plots indicate that most locations deviate, based on mean values, by <3 days for HWF, <1 °C² for HWM and <1 event for HWN (Supplementary figure 3). However, the box plots of heatwave characteristics at different locations show different degrees of overlap, less so for POR, suggesting that the data distributions for these variables differ across various locations and characteristics (Supplementary figure 3).

Moderate to strong statistically significant CC values (>0.5) for all heatwave characteristics supports that there is strong agreement between the AgERA5 and SAWS data sets (Table 2). For HWF, CC values range from 0.60 (TRE) to 0.87 (KIM), while for HWM, CC values range from 0.53 (POR) to 0.93 (VWV), and HWN CC ranges are from 0.53 (POR) to 0.85 (KIM; Table 2). CC values for POR, UPI and TRE are generally weaker for all heatwave characteristics (Table 1). This observation is consistent with relatively little overlap observed between the corresponding boxplot boxes and weaker MD values for POR, UPI and TRE (Supplementary figure 3). The degree of agreement between the SAWS and AgERA5 data sets, as measured by MD values, is moderate to strong and is generally higher in magnitude compared to Tms (Tables 1–2). MD values for HWF range between 0.47 (POR) and 0.80 (KIM), while for HWM the range is from 0.51 (KIM) to 0.77 (FRA), and for HWN the range is between 0.44 (POR)

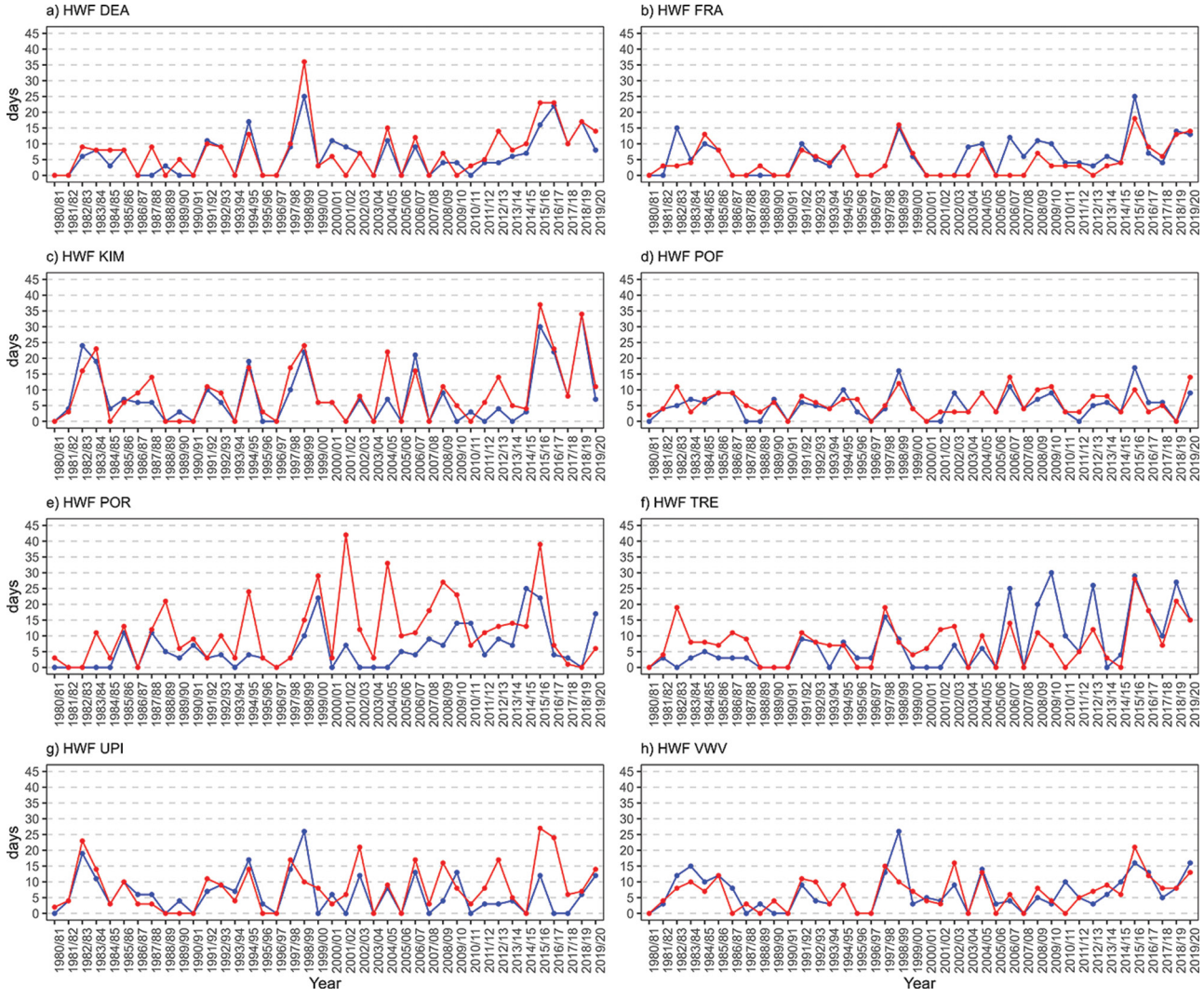

Figure 3: Time series plots depicting the total number of days contributing to annual summer heatwave events (HWF) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for locations mapped in Figure 1.

and 0.80 (KIM; Table 2). KIM shows the highest MD values for HWF (0.80) and HWN (0.80), but the lowest value for HWM (0.51; Table 2). The consistency observed in the moderate to strong MD values reflects a high degree of temporal consistency between the data sets (Table 2). Relatively low deviation across the data sets is also evident from the RMSE values, which are relatively low for all heatwave aspects (Table 2); despite this, these RMSE values are higher than that for Tms (Tables 1–2). The RMSE values provide support for the consistency and general deviation observed in the box plots (Supplementary figure 3; Table 2). Specifically, the HWF values range from 2.80 (POF) to 10.92 (POR) days, while HWM ranges from 1.34 (TRE) to 6.45 (POR) °C², and HWN ranges from 0.71 (POF) to 2.40 (POR) events (Supplementary figure 3; Table 2). A larger degree of deviation exists between the stations and corresponding AgERA5 for HWF, and a smaller degree of deviation is evident for HWN (Table 2). Overall, the AgERA5 data set typically overestimates HWF and HWN, and consistent with the Tms biases, it typically underestimates HWM (Tables 1–2). For HWF, biases range between -1.33 (POR) and 5.60 days (FRA), while for HWM biases range from -1.55 (POR) to 1.47 °C² (KIM), and for HWN the range is between -0.28 (POR) and 1.40 events (FRA; Table 2). This pattern in the biases is also evident in the time series plots and box plots (Figures 3–5; Supplementary figure 3).

AgERA5 representation of mean winter coldwave characteristics

Box plots and time series plots for coldwave characteristics of the weather stations and AgERA5 grid cells in the Northern Cape from 1980 to 2020, demonstrate a high degree of agreement between the data sets, albeit to a lesser extent than for Tmw (Supplementary figure 4; Figures 2a, 3–5). Strong agreement for the coldwave aspects is evidenced by typically overlapping boxes in the box plots and comparable temporal variability in the time series (Supplementary figure 4; Figures 6–8). However, for some locations (e.g. POR), the box plots show less overlap and less temporal agreement in the time series plots (Supplementary figure 4; Figures 6–8). Specifically, the box plots indicate that most locations deviate, on average, by <2 days for CWF, <2 °C² for CWM and <0.5 events for CWN (Supplementary figure 4).

The mostly moderate to strong CC values (>0.5) for coldwave characteristics provide additional support for the conclusions drawn from the box plots and time series plots (Supplementary figure 4; Figures 6–8; Table 2). Lower CC values for CWM show that CWM was characterised by the weakest performance and CWM is the only index that has CC values that are statistically insignificant (Table 2). Specifically, for CWF, CC values range from 0.45 (POR) to 0.92 (DEA), for CWM, CC values range from 0.17 (POR) to 0.80 (UPI), and for CWN, the range is between 0.47 (POR) and 0.89 (DEA; Table 2). CC values generally suggest that the AgERA5 and SAWS data sets agree the most for CWF compared to CWM and CWN (Table 2). Additionally, the MD values demonstrate a similar pattern where the CWM aspect depicts the weakest performance (Table 2). For both the CC and MD values, weaker agreement for CWF and CWN is evident at KIM, POR, and TRE, whereas, for CWM, KIM has higher MD and CC values, and FRA has lower MD values compared to KIM for CWF and CWN (Table 2). More specifically, the MD values for CWF range from 0.40 (POR) to 0.80 (DEA), for CWM, values range from

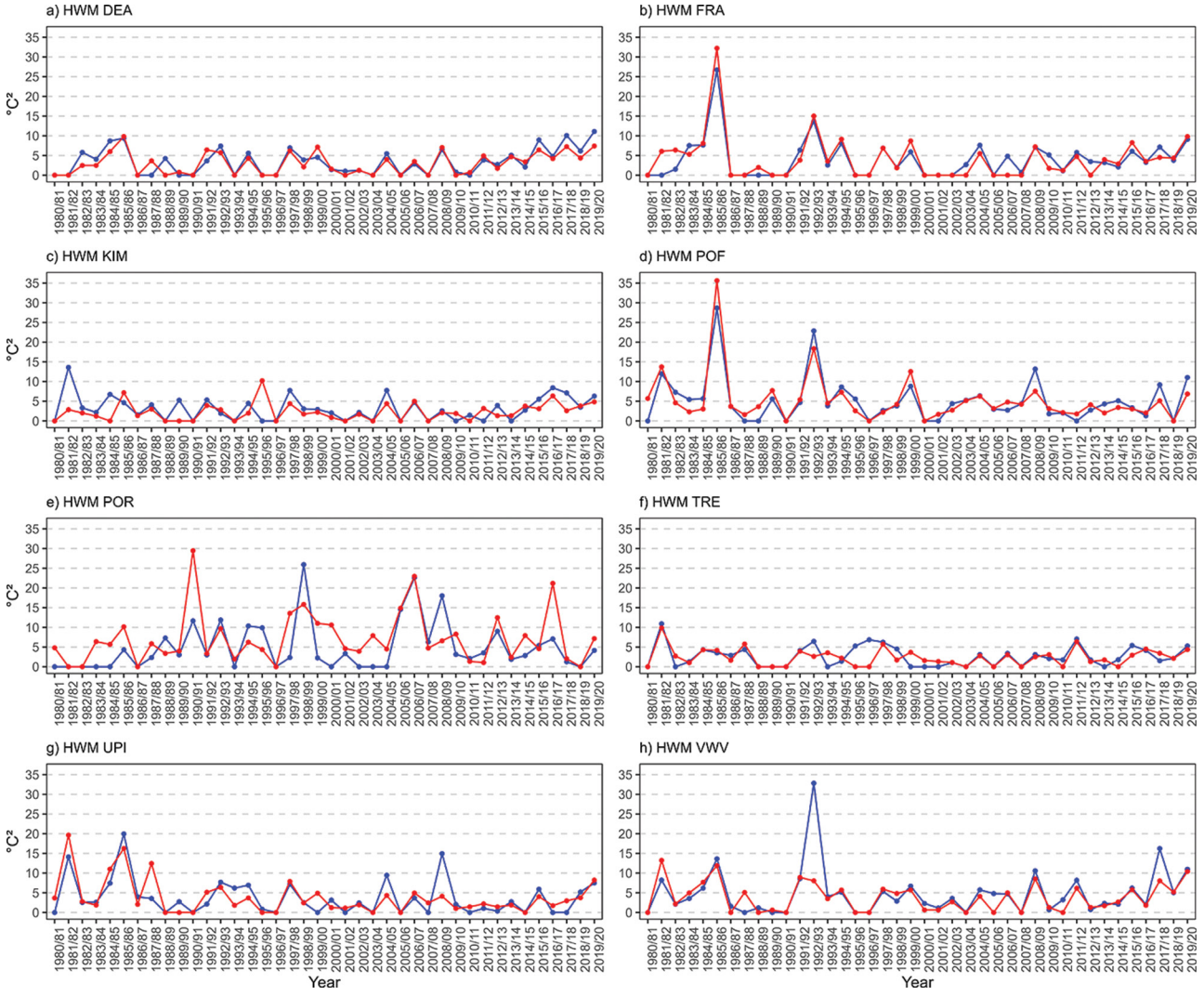

Figure 4: Time series plots depicting the average temperature of annual summer heatwave events (HWM) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for locations mapped in Figure 1.

0.35 (POR) to 0.68 (POR), and for CWN, values range from 0.48 (POR) to 0.84 (DEA; Table 2). Deviation between coldwave characteristics, as inferred from the AgERA5 and SAWS data sets' RMSE values, generally tends to be highest for CWF and lowest for CWN (Table 2). Regarding CWF, the RMSE values range from 3.25 (DEA) to 8.09 (POR) days, whereas for CWM, the range is from 2.32 (VWV) to 5.26 (KIM) °C², and for CWN, values range from 0.73 (DEA) to 1.52 (POR) events (Table 2). Box plots in Supplementary figure 4, patterns observed in the time series plots (Figures 6–8), and the positive bias values in Table 2 suggest that the AgERA5 data set overestimates coldwave characteristics to a greater extent than Tmw (Tables 1–2); positive biases for CWM are consistent with that for Tmw (Tables 1–2). Specifically, the biases for CWF range from -1.61 (FRA) to 3.39 days (POR), for CWM the range is from -2.05 (FRA) to 2.91 (KIM) °C², and for CWN the range is between -0.39 (FRA) and 0.71 (POR) events (Table 2). Bias values for POR and TRE are highest and lowest, respectively, for CWN and CWF, while the highest and lowest values for CWM are shown by POR and FRA, respectively (Table 2). This pattern is also apparent in the values calculated for CC and MD (Table 2).

Discussion and conclusions

Through a comparative analysis between weather stations and corresponding AgERA5 grid cells, we evaluated the accuracy of the AgERA5 representation of seasonal average and extreme temperature characteristics over the Northern Cape for 1980–2020. This study builds on research by Roffe and van der Walt[20] by evaluating the AgERA5 data set's ability to represent Tms and Tmw, and the respective seasonal heatwave and coldwave characteristics, against point-based SAWS station data, as opposed to such evaluations using a gridded observation data set. This approach is advantageous as fewer biases are introduced into the evaluation as the point-based weather station data used herein has not been interpolated.[20,44] We do, however, acknowledge that the station-based temperature data are not completely without biases due to, for instance, missing data and the methods used for estimation thereof, changes in station location and monitoring instrumentation, and land use/cover.[44] Despite the weather station data limitations, their use for evaluation provides a robust understanding of the AgERA5 performance over the Northern Cape. Thus, the insights gained from this comparative analysis highlight limitations and advantages of using the AgERA5 product over the Northern Cape; these are important to consider for future research applying this data set to the Northern Cape.

The results presented herein reveal that the AgERA5 data set performs quite well over the Northern Cape, and is thus an invaluable data set to apply for future temperature-related research over the region. Over this data sparse region, the AgERA5 data set can be used, for instance, to analyse ETE impacts for areas with no existing weather station infrastructure.[45] This would be particularly valuable to understand the temperature patterns over Kakamas (a town without a weather station) for instance, where, in January 2023, anomalously hot temperatures caused seven fatalities.[46] This is not the only example in which ETEs have caused fatalities in South African regions where there are no weather

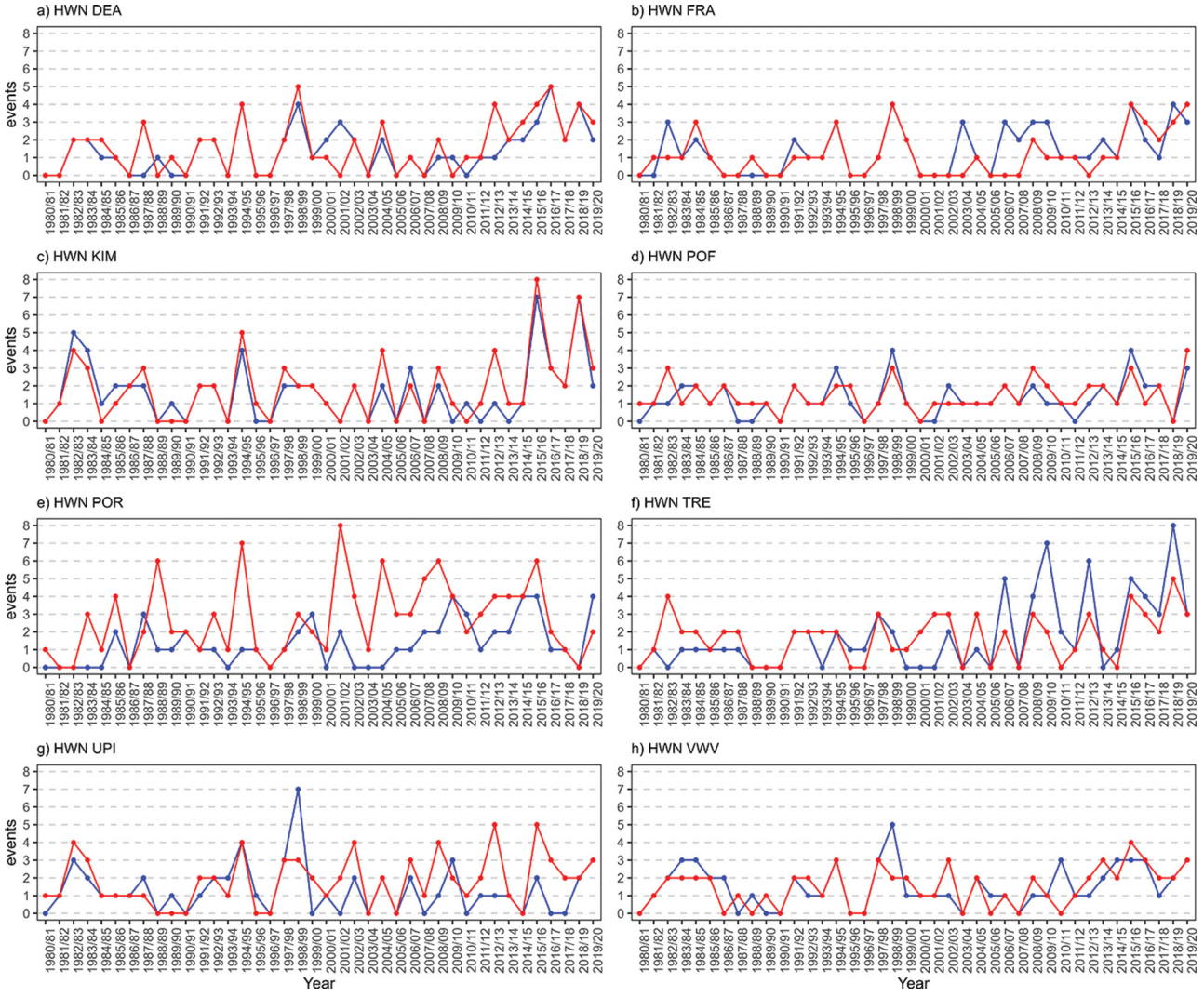

Figure 5: Time series plots depicting the total number of summer heatwave events (HWN) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for locations mapped in Figure 1.

Table 2: Tabulated results, per location mapped in Figure 1, of the comparison between the AgERA5 and SAWS data sets for the total number of days contributing to annual summer (winter) heatwave (coldwave) events (HWF [CWF]), the average temperature of annual summer (winter) heatwave (coldwave) events (HWM [CWM]), and the total number of summer (winter) heatwave (coldwave) events (HWN [CWN]). CC represents the Spearman Correlation Coefficient; RMSE represents the Root Mean Square Error; MD represents the Modified Index of Agreement. CC values denoted in bold represent statistically significant correlations at the 5% alpha level.

Index	Station	CC	MD	RMSE	Bias
HWF	DEA	**0.80**	0.76	4.04	1.28
	FRA	**0.72**	0.75	3.84	-1.33
	KIM	**0.87**	0.80	4.40	1.53
	POF	**0.78**	0.69	2.80	0.50
	POR	**0.66**	0.47	10.92	5.60
	TRE	**0.60**	0.64	6.96	0.10
	UPI	**0.65**	0.60	6.76	2.18
	VWV	**0.78**	0.69	4.26	-0.33

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Table 2 continued...

Index	Station	CC	MD	RMSE	Bias
HWM	DEA	**0.74**	0.63	1.85	-0.74
	FRA	**0.79**	0.77	2.17	0.37
	KIM	**0.68**	0.51	2.90	-1.55
	POF	**0.73**	0.76	2.61	-0.51
	POR	**0.53**	0.54	6.54	1.47
	TRE	**0.69**	0.72	1.34	-0.41
	UPI	**0.66**	0.64	3.69	-0.51
	VWV	**0.93**	0.70	5.13	-1.19
HWN	DEA	**0.74**	0.78	0.99	0.23
	FRA	**0.68**	0.74	1.01	-0.28
	KIM	**0.85**	0.80	0.87	0.20
	POF	**0.74**	0.70	0.71	0.15
	POR	**0.53**	0.44	2.40	1.40
	TRE	**0.56**	0.59	1.64	-0.10
	UPI	**0.60**	0.58	1.48	0.50
	VWV	**0.68**	0.69	1.00	-0.05
CWF	DEA	**0.92**	0.80	3.25	0.83
	FRA	**0.73**	0.69	4.43	-1.61
	KIM	**0.71**	0.59	5.64	0.88
	POF	**0.78**	0.74	3.78	1.10
	POR	**0.45**	0.40	8.09	3.39
	TRE	**0.59**	0.62	6.59	-0.34
	UPI	**0.90**	0.77	3.45	1.41
	VWV	**0.82**	0.74	3.46	0.15
CWM	DEA	**0.52**	0.58	3.28	0.02
	FRA	0.25	0.36	3.67	-2.05
	KIM	**0.57**	0.56	5.26	2.91
	POF	**0.76**	0.68	2.05	0.23
	POR	0.17	0.35	3.08	0.74
	TRE	**0.52**	0.57	3.85	-0.59
	UPI	**0.80**	0.65	2.73	0.71
	VWV	**0.75**	0.64	2.32	-0.45
CWN	DEA	**0.89**	0.84	0.73	-0.10
	FRA	**0.70**	0.71	1.08	-0.39
	KIM	**0.62**	0.57	1.31	0.10
	POF	**0.78**	0.76	0.91	0.20
	POR	**0.47**	0.48	1.52	0.71
	TRE	**0.53**	0.63	1.47	-0.17
	UPI	**0.85**	0.76	0.81	0.17
	VWV	**0.66**	0.64	1.05	0.12

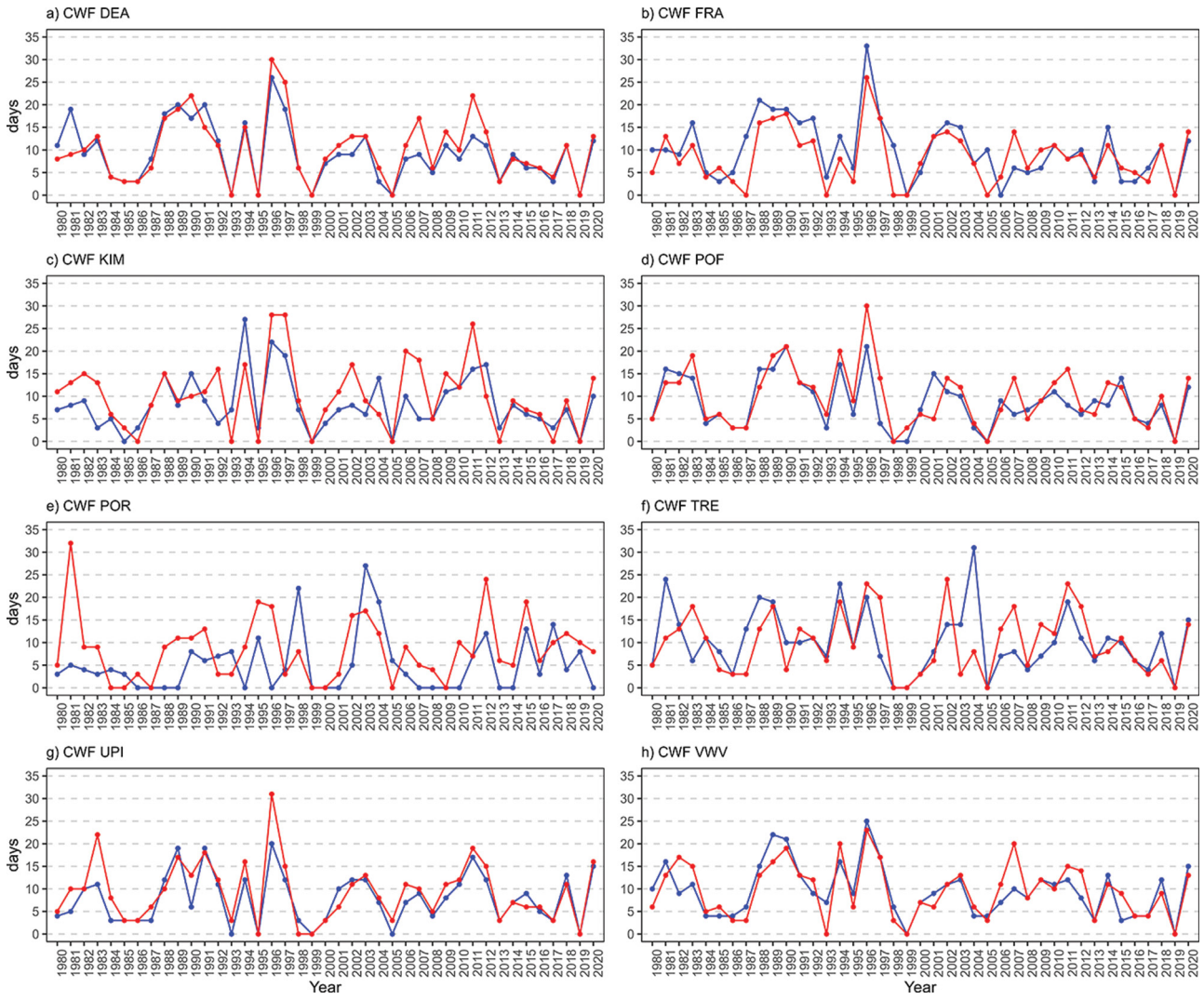

Figure 6: Time series plots depicting the total number of days contributing to annual winter coldwave events (CWF) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for locations mapped in Figure 1.

stations[47]; this highlights the value of a reliable gridded data set like the AgERA5. Moreover, by analysing ETEs with the AgERA5 data set, one can derive valuable information that can aid in developing efficient and prompt adaptive measures and strategies, which can aid in mitigating the negative impacts of ETEs, such as preventing heat stress, optimising crop management techniques, and enhancing infrastructure.[7-9,48]

In terms of the AgERA5 performance over the Northern Cape, general findings suggest strong, but varying, correspondence spatially, which is a result that is in agreement with the findings of similar studies.[20-21] Mean seasonal temperatures correspond and perform better than heatwave and coldwave characteristics from AgERA5 (Tables 1–2). This is likely due to differences at the temperature distribution extremes between the station and AgERA5 data sets (Figure 2). Furthermore, a common limitation in statistical comparisons, known as the double penalty problem, of fine-resolution data based on point-to-point analysis also contributes to the weaker performance detected for the ETE characteristics.[49] For instance, a temperature proxy may be penalised for a spurious observation due to imprecise station location, while an ETE proxy will be doubly penalised for issuing a false alarm for an ETE.[49] Based on daily to annual temperature averages, it is evident that Tms performs slightly better than Tmw (Table 1). Across the stations, Tms is characterised by higher CC and MD values, indicating better correlation and agreement between predicted and observed values (Table 1). The present analysis demonstrates a predominant underestimation of Tms and Tmw by the AgERA5 temperature proxies (Table 1), which is a finding that corresponds to results presented by Roffe and van der Walt[20] and Velikou et al.[21] Observed negative bias values between station and AgERA5 Tms and Tmw proxies can be considered a plausible explanation for the underestimation of HWM and CWM in the AgERA5 data set (Tables 1–2).[20] Among the heatwave and coldwave indices, HWM and CWM represent the ETE characteristics with the poorest performance (Table 2), and this is a finding that aligns with previous research.[20,21,29] While the AgERA5 data set performed well in representing heatwave and coldwave characteristics, these results highlight the need for caution when utilising the AgERA5 data set to examine HWM and CWM over the Northern Cape. The suboptimal performance of HWM and CWM therefore suggests that there is much room for improvement in the AgERA5 data set representation of temperatures at the tail ends of the temperature distribution. In contrast to HWM and CWM, HWF, HWN, CWF, and CWN exhibit positive biases relative to station data and demonstrate CC and MD values of greater magnitude (Table 2). While performance variations exist among different locations, and the difference in the performance of summer and winter ETE indices is relatively small, mean CC and MD values indicate superior performance for summer ETE indices compared to winter ETE indices (Tables 1–2). Stronger performance in summer ETE indices has also been observed in other studies.[20]

Although the overall performance was strong, some locations (i.e. POR, located along the western coast, and TRE, located in the Kalahari Desert) were consistently characterised by poorer performance (Tables 1–2), likely because these regions contain fewer stations compared to other parts of the Northern Cape.[20] Moreover, mean and extreme temperatures

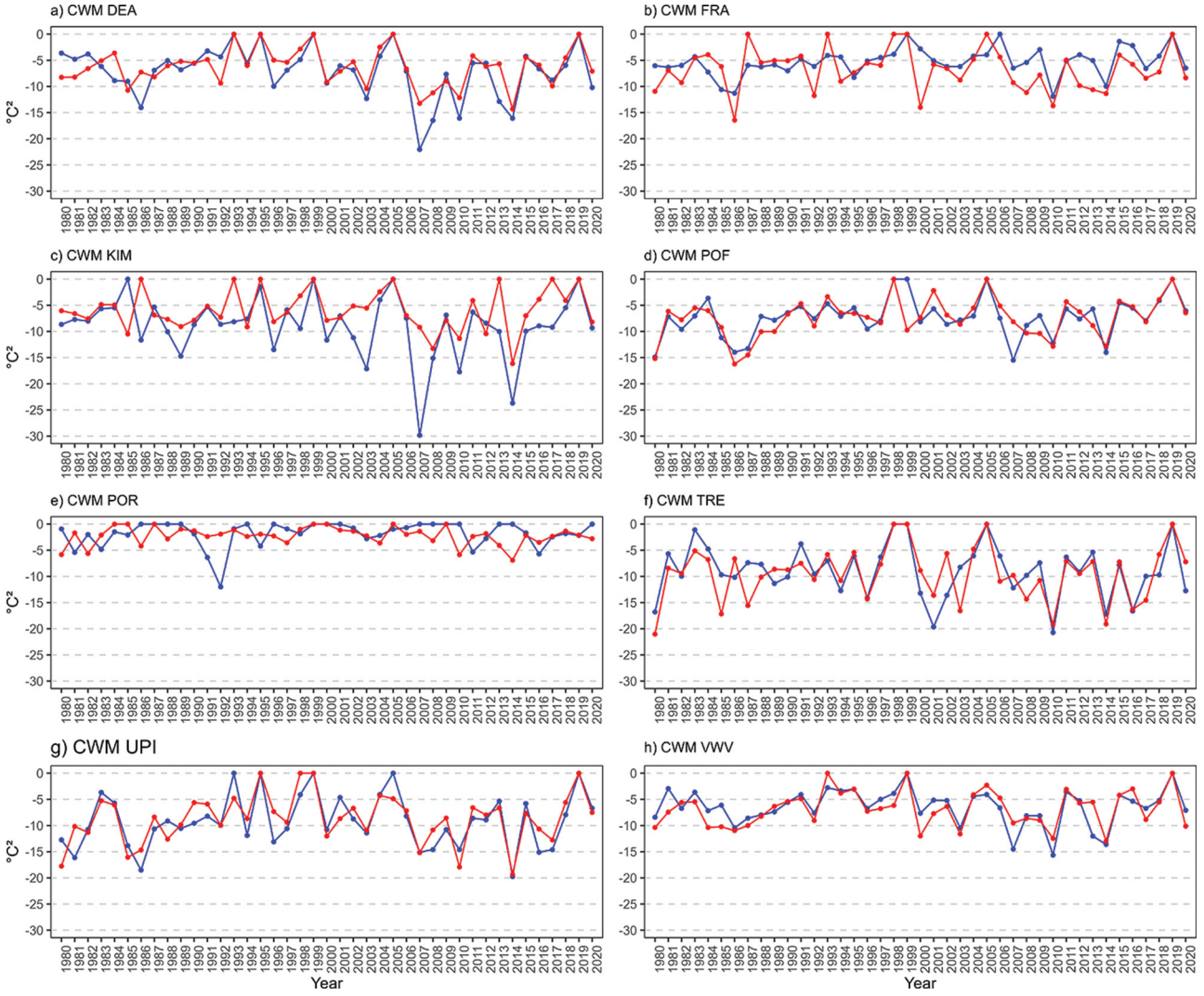

Figure 7: Time series plots depicting the average temperature of annual winter coldwave events (CWM) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for locations mapped in Figure 1.

at locations bordering the Atlantic Ocean are strongly influenced by the cold Benguela Current (and Upwelling System) which proves to be a phenomenon that is not accurately simulated by the ECMWF modelling system.[20,50] For TRE, in the Kalahari Desert region, the desert surface influences mean and extreme temperatures through cloud development mechanisms, which could also lead to parameterisation difficulties in the ERA5 reanalysis methods.[16,50] Grid cells bordering the cold Benguela current or falling within the Kalahari Desert regions should be treated with caution, and limitations and uncertainties should be appropriately acknowledged. A better understanding of these weaknesses is critical for improving future parameterisation methods for the underlying ECMWF model used for the ERA5 reanalysis; this will undoubtedly lead to better accuracy for calculated indices and long-term trends. Despite the weaknesses identified herein, this ERA5 reanalysis product has shown strong improvement based on its predecessor (ERA-Interim) and will likely improve still in the foreseeable future.[50] Furthermore, according to previous research comparing the AgERA5 data set to others, like AgCFSR and CPC, the AgERA5 outperforms these in terms of accuracy and reliability.[51,52]

The strengths and limitations of the AgERA5 presented herein support further application of the AgERA5 data set for characterising average and extreme temperatures over the Northern Cape. Findings suggest, based on moderate to strong CC values, that AgERA5 can effectively capture interannual variability patterns in the Northern Cape, and in turn will likely provide reliable trend results despite conflicting thoughts regarding the application of reanalysis for trend calculations.[20] This underscores the potential of AgERA5 as a valuable tool for studying long-term changes in the Northern Cape climate. Progressing forward, it would be important to utilise the ERA5 reanalysis to investigate synoptic-scale circulation patterns associated with the occurrence of coldwaves and heatwaves across the Northern Cape. Comprehending this using numerical weather prediction models can play an important role in the predictability of these events, ultimately informing better early warnings of ETEs over the Northern Cape.[53]

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Competing interests

We have no competing interests to declare.

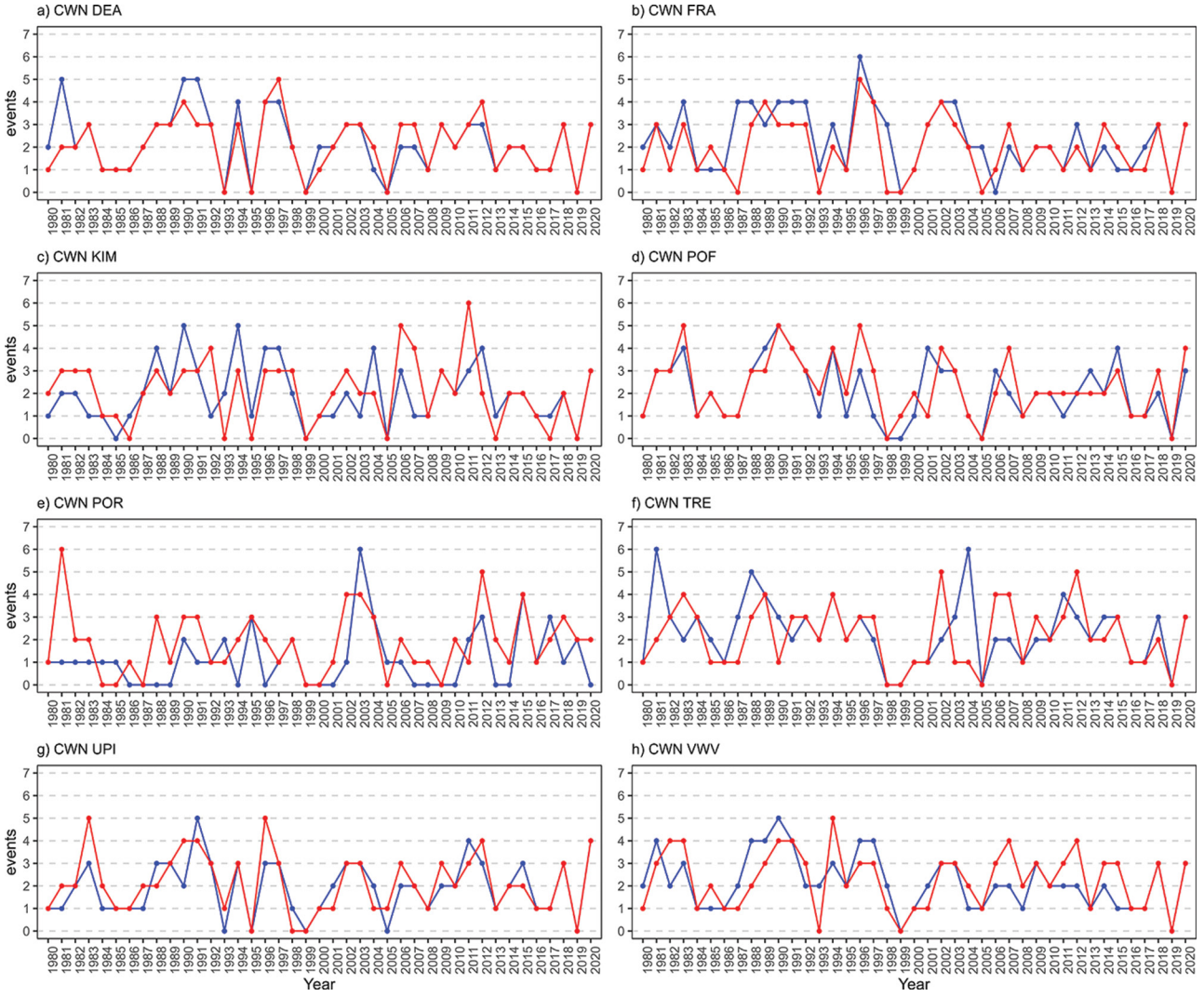

Figure 8: Time series plot representing the total number of winter coldwave events (CWN) for the AgERA5 (red) and SAWS (blue) data sets from 1980 to 2020 for all locations mapped in Figure 1.

Authors' contributions

J.A.K.: Conceptualisation, methodology, data collection, data analysis, data curation, student project management, validation, writing – initial draft. S.J.R.: Conceptualisation, methodology, data collection, data analysis, data curation, student project management, validation, writing – revisions, student supervision. A.J.v.d.W.: Conceptualisation, methodology, student project management, validation, writing – revisions, student supervision.

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Analysing patient factors and treatment impact on diabetic foot ulcers in South Africa

In the South African public healthcare sector, 28% of diabetic patients present to primary healthcare clinics with diabetic foot ulcers (DFUs), often presenting in advanced stages of ulcer severity. In this study, we aimed to categorise factors predisposing individuals to developing a DFU and to identify the potential shortcomings in existing treatment plans in the South African healthcare system. In addition, the use of preventative measures in the management of DFUs was examined as well as the influence of past treatment practices. A total minimum sample size of 50 DFUs was required for this study. Participants who were selected for this study had their past records reviewed in order to determine the likelihood of previous DFU infections, as well as to determine the occurrence of co-morbidities. The treatment protocol implemented was recorded. Twelve-month patient records were used to identify the infection frequency and past treatment protocols. A total of 48.9% of patients reported that they did not make use of any preventative measures. The most frequent concurrent medical conditions were hypertension, dyslipidaemia, and peripheral neuropathy. Polypharmacy was prevalent, with 55% of the population prescribed five or more medications. Potential medication interactions were examined and a total of 210 interactions were documented. An analysis of past and current treatment practices revealed that 52.1% of the treatment protocols did not comply with local treatment guidelines. This study highlights the urgent need for updated DFU treatment protocols in relation to the overall management of DFUs, taking into account existing international guidelines.

Significance:

We determined that the South African treatment guidelines and DFU classification system do not align to international standards. Furthermore, the use of preventative measures among DFU patients was poor and polypharmacy was present in the patient cohort. We emphasise the need for all members of a healthcare team, including podiatrists, clinicians, microbiologists and pharmacists, to work together in order to identify at-risk patients, prevent possible DFUs and effectively treat existing DFUs in a manner that does not contribute to antimicrobial resistance and provides the best possible outcome for the patient.

Introduction

Diabetic foot syndrome, a complication of diabetes mellitus, is the most common cause of hospitalisation and lower limb amputation among diabetic patients.[1] A foot ulcer is defined as a full-thickness wound below the ankle on a weight-bearing or exposed surface that involves at least the epidermis layer and part of the dermis layer of the skin.[2,3] By definition, a diabetic foot ulcer (DFU) is a foot ulcer in a person with diagnosed diabetes mellitus and typically presents alongside neuropathy or peripheral artery disease in the lower extremity.[3] Neuropathic DFUs often result in the formation of open wounds, the primary risk factor for the development of infections of the DFU.[4] It is estimated that over 50% of DFUs become infected, which increases the risk of amputation and mortality.[4]

South Africa is trying to move towards universal health coverage; however, at the time of this study, provision of health care in South Africa consisted of an unequal two-tiered system. The first is the public sector, which is state funded and services the majority of the population, and the second is the private sector, which is funded mostly by individual contributions to medical aid schemes or health insurance.[5] This study focused on patients within the public healthcare system. In the South African province of KwaZulu-Natal, there are approximately 1.4 million diabetic patients who access public health care, with approximately 2400 amputations performed annually.[6] A five-year audit of the amputations that occurred in one KwaZulu-Natal hospital found that 53.1% of amputations were due to diabetes mellitus.[7] A more recent study in KwaZulu-Natal determined that 53.7% of amputations were attributable to diabetes mellitus.[8] The high rate of amputation in KwaZulu-Natal corresponds to the findings of another study undertaken in 2018 whereby patients presented to rural healthcare facilities with advanced stages of DFU severity, requiring amputations as a result.[9] A study undertaken in the Gauteng province of South Africa ascertained that 1565 DFU-related amputations occurred over a period of 30 months.[10] These findings highlight the seriousness of the consequences of DFUs and the need to reduce their prevalence and improve treatment protocols.

Knowledge and practice regarding DFUs, as well as the ability to identify individuals at risk of developing a DFU, are vital in reducing complications and subsequent lower limb amputation. Thus, an understanding of the treatment of DFUs in the South African public healthcare sector by all healthcare professionals is necessary in order to improve patient outcomes through improved treatment guidelines. The aim of this study was to categorise factors that predispose individuals to develop a DFU and to identify the potential shortcomings in existing treatment plans. In addition, the use of preventative measures and past treatment practices in the management of DFUs was examined.

Methods

Ethical considerations and setting

Ethical clearance was obtained from the Human Research Ethics Committee (HREC) of the University of the Witwatersrand (M210431) and study site approval was obtained from two tertiary public healthcare institutions in Johannesburg, South Africa. The study design chosen was an observational cross-sectional study with retrospective analysis. Patient confidentiality was maintained through the use of key numbers which were ascribed to all participants (for example, A001, A002). The patient information leaflet was given to the patient before they gave informed consent to participate in the study. In addition, consent was garnered from all participants for the capture and use of photographs relating to the patient's DFU wound. The principal investigator of this study, unless otherwise stated, was responsible for capturing all photographic evidence. The research project was registered with the South African National Health Research Database (GP_202108_026).

A total of 45 patients with 50 DFUs were recruited for this study, thus meeting the expected sample size for this cohort. This sample size was calculated based on a 95% confidence interval and a 50% drop-out rate. The decreased prevalence of DFUs in this setting due to the COVID-19 pandemic was considered in the sample size calculation. Participation was on the day of study enrolment and no follow-up visits were required.

Patient selection and classification

All patients attending the study site's podiatry and wound clinics were selected and invited to participate in this study. Subjects identified to participate had to be diagnosed as diabetic and present with a DFU. Paediatric patients were excluded from participation in this study. Patient selection was based on purposive, homogeneous sampling as the goal of this research is to understand the influence of patient-specific factors on DFU development and subsequent treatment plans.

Patients were classified as having type 1 or type 2 diabetes based on the patient's history obtained from the file review or interview. Once classified by diabetic type, patients were further classified by level of DFU infection. This classification is dependent on the severity of the ulcer and is mild, moderate or severe as per the South African Antimicrobial Stewardship guidelines (Table 1).[11] The patient's DFU was subsequently classified according to the Wagner classification (Table 1) in order to compare the most commonly used classification system worldwide to the South African guidelines on DFU classification.

Table 1: The Wagner and South African Antimicrobial Stewardship classification systems[4,11,12]

The Wagner classification system	
Grade	**Lesion**
0	No open lesions; deformity or cellulitis may be present
1	Superficial ulcer; partial or full thickness
2	Ulcer extension to ligament, tendon, joint capsule, or deep fascia without abscess or osteomyelitis
3	Deep ulcer with abscess, osteomyelitis, or joint sepsis
4	Gangrene localised to portion of forefoot or heel
5	Extensive gangrenous involvement of the entire foot
The South African antimicrobial stewardship classification system	
Classification	**Description**
Mild	Limited to skin/superficial subcutaneous tissue <2 cm beyond ulcer margin
Moderate	Cellulitis >2 cm, deep fascial involvement, gangrene, abscess, osteomyelitis
Severe	Systemic complications

Patient record review and administration of a structured questionnaire

Participants who were selected for this study had their past records reviewed in order to determine the likelihood of previous DFU infections as well as to determine the occurrence of co-morbidities. The treatment protocol implemented was recorded alongside the number of infections treated and if sample cultures were taken. Twelve-month patient records were used to identify the infection frequency, the causative micro-organism (if identified) and the antimicrobial used to treat the DFU. This information assisted in determining the prevalence of DFU and the prescribing patterns of antimicrobials, which guided the development of the treatment policy. A short, structured questionnaire was used in order to determine the use of preventative aids that had been prescribed, or had not been prescribed but were independently initiated by participants. The structured questionnaire contained a section on demographic information in order to establish if certain patients were more likely to present with DFUs. Next, a section on concurrent conditions and chronic medication use was included in order to establish the effect of these factors on ulcer severity. A section on preventative measure use was included in order to establish both the frequency of their use and patient compliance. Rather than using a self-administered questionnaire, the patients were interviewed in order to overcome any language or understanding barriers.

Validating the retrospective review tool

The retrospective review tool was adapted from a South African study which looked at resistance patterns in urinary tract infections.[13] Validation of the retrospective review tool, in order to ensure its reliability in the context of its use, was completed by means of a pilot study. Two patients from the Charlotte Maxeke Johannesburg Academic Hospital podiatry unit were randomly selected. This site was used as it had been approved by both the hospital and ethics committee.

The two patients who participated in the pilot study comprise an acceptable sample size as the established sample size for the study was limited. The two patients proved the reliability of the retrospective review tool by answering all the questions without needing assistance or further explanation. Conducting the pilot study led to the addition of different preventative measures that were not previously included, for example, a walker. These changes were approved by the HREC prior to the commencement of the study.

Results

Patient demographics

An understanding of patient demographics is required for all members of a healthcare team in order to identify at-risk patients timeously. Non-modifiable factors like age and gender play a role in the development of DFUs.[14,15] The results from this study demonstrate a higher prevalence of DFU among male participants (60%) in comparison to female participants (40%). Table 2 depicts the age groups of participants in the study. The oldest participant was 80 years old, while the youngest was 36 years old. The median age of participants was 59 (n=45).

The use of classification systems in the treatment of DFUs

A patient-specific comparison of ulcer classification, with photographic reference to each ulcer, is provided in Supplementary table 1. In this study, the majority of patients presented with Wagner grade 1 DFUs (33.3%) and Wagner grade 2 DFUs (33.3%). Wagner grade 3 ulcers were seen in 17.6% of patients while Wagner grade 4 ulcers were seen in 13.7% of patients. Only one patient presented with a Wagner grade 5 ulcer. When comparing the South African classification system to the Wagner classification system, it is noted that the systems are very different in relation to detail and diagnosis. For example, the South African Antimicrobial Stewardship Programme (SAASP) 'mild' classification includes DFUs from Wagner grades 1, 2 and 3. This suggests that the Wagner classification system is more descriptive than the SAASP

Table 2: The age groups of participants in this study

Age	Number of participants	Percentage
30–40 years	2	4
41–50 years	6	13
51–60 years	18	40
>60 years	19	42
Total number of patients	45	100

guidelines and allows for more selective categorisation of different ulcers based on their severity. As a result, 60.8% of participants presented with mild ulcers (Wagner grades 1, 2 and 3), 37.3% with moderate ulcers (Wagner grades 2, 3 and 4) and 1.9% with severe ulcers (Wagner grade 4) according to SAASP guidelines.

The presence of co-morbidities and complications

Understanding the influence that co-morbidities have on the pathogenesis of DFUs is important as it enables healthcare professionals to screen, prevent or treat in a manner that does not worsen or promote DFU formation. Hypertension was found to be present in 84.4% of patients – making it the most common concurrent medical condition amongst this cohort. Table 3 provides a summary of the co-morbidities identified in the patient cohort.

In this study, 93.3% of patients presented with at least one chronic condition in addition to diabetes mellitus, 80% presented with at least two concurrent chronic conditions, and 40% presented with more than four co-morbidities. The highest number of concurrent conditions reported was eight; while the most frequently seen number of concurrent chronic conditions was two. The average number of co-morbidities in addition to diabetes mellitus seen in this patient cohort was $3.9 \approx 4$.

Patients who exhibited either Wagner grade 1 or 4 ulcers presented with the highest average number of chronic co-morbid conditions. The largest proportion of ulcers were classified as grade 1 or grade 2 in severity, and these patients presented with an average number of 4.1 and 3.8 co-morbidities, respectively.

Medication use and the incidence of polypharmacy

Diabetic patients are twice as likely as non-diabetic patients to experience a drug-drug interaction due to the presence of multiple co-morbid conditions in the diabetic population.[16] The most commonly used medication was found to be metformin (850 mg) taken either twice or three times daily. In total, 68.9% of patients were taking metformin. Insulin was used by 62.2% of patients, with the most frequently used form being actraphane, a biphasic human insulin. Of the medications that are not anti-diabetic in nature, the most frequently used include simvastatin (for hyperlipidaemia treatment), enalapril and amlodipine (both used in the treatment of hypertension), with 40% of patients found to be using these medications. Thereafter, the use of hydrochlorothiazide (a diuretic used in the treatment of hypertension) and paracetamol (an analgesic and antipyretic) was the next most frequently noted (33.3%). Table 4 summarises the total number of medications taken per patient, per day.

In this study's sample population, 44.4% of patients were found to be prescribed between one and five medications. Within this group, 15.5% of patients were prescribed two medications, making it the most frequently used number of medications. Thereafter, 11.1% of patients were found to be prescribed either seven or nine chronic medications. The highest number of medications used by a single patient was 14 and the lowest was 1. The majority of the sample population (55.5%) were noted to be prescribed more than five medications.

A total of 210 potential drug-drug interactions were observed in the patient cohort. The most frequently seen type of interaction in this study was moderate drug interactions (55.2%). The mean number of drug interactions per patient was 4.7. Only 35.6% of participants in this study did not present with any potential drug-drug interactions, while 60% and

Table 3: Co-morbidity prevalence

Concurrent condition	Number of patients presenting with the condition (%)	Average Wagner score of patients presenting with the concurrent condition
Hypertension	38 (84.4)	$2.4 \approx 2$
Dyslipidaemia	15 (33.3)	$2.1 \approx 2$
Peripheral neuropathy	12 (26.7)	$2.2 \approx 2$
Cardiovascular disease (including heart failure, atrial fibrillation, angina and dilated cardiomyopathy)	8 (17.8)	$2.8 \approx 3$
Metabolic syndrome	5 (11.1)	$2.6 \approx 3$
Gout	3 (6.7)	$2.7 \approx 3$
Hypothyroidism	3 (6.7)	4
Renal disease	3 (6.7)	2
Asthma	2 (4.4)	$2.5 \approx 3$
Chronic obstructive pulmonary disorder	2 (4.4)	2
Eczema	2 (4.4)	2
Visual impairment	2 (4.4)	1
Gastro-oesophageal reflux disorder / peptic ulcers	2 (4.4)	1
Depression / generalised anxiety disorder	2 (4.4)	$2.5 \approx 3$
Myasthenia gravis	1 (2.2)	2
Chronic kidney stones	1 (2.2)	3
Venous insufficiency	1 (2.2)	3
Rheumatoid arthritis	1 (2.2)	1
Iron deficiency anaemia	1 (2.2)	2

Table 4: The number of different medications taken daily by the patient cohort

Number of medications	Frequency of patients (%)
1–5	20 (44.4)
6–10	20 (44.4)
>10	5 (11.1)

57.8% of patients presented with moderate or severe interactions. The largest number of potential drug interactions seen per patient was 21. This number of interactions was seen in one patient and the same patient was noted to be on the highest number of medications (n=14). The average number of medications used in patients presenting with both Wagner grades 1 and 2 DFUs was six (Table 5). The highest average number of medications used (n=7) was seen in those with DFUs of Wagner grade 3 severity.

Non-pharmacological management: Preventative measures and pressure offloading devices

The prevention of DFUs should be the primary goal of all healthcare practitioners treating diabetic patients. It is at this stage that educating

the patient on preventative measures is important and can be done by all healthcare professionals. In this study, 48.9% of patients did not make use of any preventative measures. The frequency and type of preventative measures used by patients in the study cohort are given in Figure 1.

The results regarding the use of preventative measures were used to determine if there was a correlation between the use of these interventions and ulcer severity. Table 6 compares the severity of the DFU, according to the Wagner classification, to the use of preventative measures.

From Table 6, it can be seen that the most commonly used method of pressure off-loading for all grades of ulcer severity is crutches, which were used by 32.4% of patients overall. Except for those patients with DFUs classified as Wagner grade 2, the average number of preventative measures used is less than one for all grades of ulcer severity. The only instance in which crutches are not the most frequently used off-loading measure is in those patients with Wagner grade 3 ulcers. In those instances, removable walkers are more frequently used.

Pharmacological management and treatment practices

By evaluating the past treatment plan of patients in this cohort, gaps and missed opportunities in past treatment practices could be identified. This allows for the improvement of DFU treatment plans in the future. Table 7 describes the treatment protocols observed in the study population and compares the treatment practices observed to both local and international guidelines. South African guidelines suggest oral antimicrobial therapy of amoxicillin/clavulanic acid, flucloxacillin and clindamycin in the case of penicillin allergy. Due to missing files, and new patients with no file history, seven patients (15.6%) did not have comprehensive records of treatment protocols for previous or current DFUs. From the information available from the remaining 38 patient files, 48 treatment protocols were recorded. Of these, 47.9% complied with those set out in the South African guidelines. Only 14.6% of treatment protocols were partially compliant, 33.3% were not compliant and the remaining 4.2% of the protocols could not be assessed for compliance due to a lack of record keeping or because of treatment of unrelated foot conditions (onychomycosis). While the majority of patients were treated in a manner that adhered to the local guidelines, the repeated treatment

Table 5: The average number of medications and potential interactions observed as classified by the Wagner classification system

Wagner classification	Number of patients	Average number of medications	Average number of interactions
1	17	6	4
2	17	6	4
3	9	7	5
4	7	6	5
5	1	7	4

Table 6: Comparison between ulcer severity and preventative measure use

Wagner grade	Most frequent preventative measure used	Number of DFU patients	Average number of preventative methods used per patient	Number of patients not using preventative measures
1	Removable walker (25%); walker (16.7%); wheelchair (16.7%)	12	0.7	7
2	Crutches (41.2%); wheelchair (29.4%)	16	1.1	5
3	Removable walker (28.6%); walker, wheelchair, crutches, specialised footwear (14.3% each)	9	0.8	6
4	Crutches (60%); removable walker (20%); wheelchair (20%)	7	0.6	3
5	No preventative measures used	1	0	1

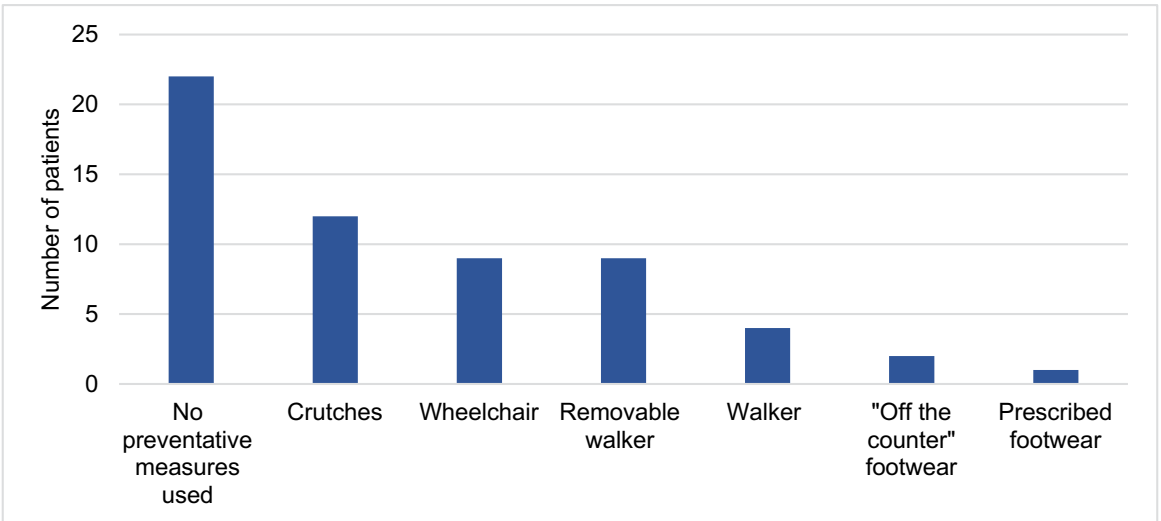

Figure 1: The use of preventative measures.

Table 7: Comparison of treatment protocols recorded in patient files to South African and international guidelines as well as to the incidence of polypharmacy

Patient code	Date of current and previous treatments	Wagner grade at most recent date	Antibiotic prescribed	Alignment to the STG or SAASP	Alignment to international guidelines	Number of chronic medications prescribed
A001	21/04/2021	2	Yes	C	PC	7
A002	07/03/2021	2	Yes	NC	NC	2
A003	12/03/2021	2	No	NC	NC	10
	20/08/2021	1	Yes	C	PC	
A004	20/08/2021	1	Yes	C	PC	2
A005	06/08/2021	2	Yes	C	PC	9
A006	[a]	2	[a]	[a]	[a]	2
A007	01/04/2019	1 & 4	No	NC	NC	6
	02/09/2019		Yes	NC	NC	
	30/07/2021		Yes	C	PC	
A008	23/08/2021	2	Yes	C	PC	2
A009	21/06/2021	3 & 1	No	NC	NC	6
A010	17/02/2020		Yes	C	PC	12
	11/08/2020	3	Yes	C	PC	
A011	13/07/2021	2	Yes	C	PC	8
A012	03/06/2021	2 & 1	Yes	PC	PC	4
A013	13/09/2021	2	No	NC	NC	5
A014	[a]	3	[a]	[a]	[a]	1
A015	09/2021	2	No	NC	NC	4
A016	[a]	3	[a]	[a]	[a]	9
A017	07/12/2021	2 & 4	Yes	C	PC	4
A018	16/11/2021	3 & 1	Yes	C	PC	1
A019	[b]	4	[b]	[b]	[b]	2
A020	20/12/2021	2	Yes	NC	NC	14
A021	Feb-21	1	No	NC	NC	2
A022	25/12/2021 - 31/12/2021	1	Yes	Unknown	Unknown	5
A023	[c]	1	[c]	[c]	[c]	3
A024	[c]	1	[c]	[c]	[c]	7
A025	7/02/2022	1	Yes	C	PC	3
	29/12/2020		Yes	PC	PC	
A026	[b]	1	[b]	[b]	[b]	7
A027	03/03/2022	4	Yes	PC	PC	14
A028	22/02/2022	2	Yes	N/A	N/A	7
	24/03/2022		Yes	PC	PC	
A029	08/03/2022	4	Yes	NC	C	8
A030	07/03/2022	4	Yes	C	PC	5
A031	07/03/2022	3	Yes	C	PC	4

...Table 7 continues on next page

Table 7 continued...

Patient code	Date of current and previous treatments	Wagner grade at most recent date	Antibiotic prescribed	Alignment to the STG or SAASP	Alignment to international guidelines	Number of chronic medications prescribed
A032	07/03/2022	4	No	NC	NC	6
A033	13/03/2022	5	Yes	NC	C	7
A034	09/03/2022	3	Yes	C	PC	9
A035	03/03/2022	2	No	NC	NC	8
A036	18/03/2022	2	Yes	C	PC	3
A037	13/03/2022	3	Yes	C	PC	11
A038	26/02/2021		Yes	C	PC	10
	12/03/2022	1	Yes	PC	C	
A039	09/02/2022	3	Yes	C	PC	8
	21/03/2022		Yes	C	PC	
A040	22/03/2022	1	Yes	PC	PC	12
A041	01/04/2022	2	Yes	PC	PC	9
A042	16/07/2016	2	No	NC	NC	9
	10/06/2022		No	NC	NC	
A043	10/06/2022	1	No	NC	NC	2
A044	23/08/2021	1	Yes	C	PC	10
	17/06/2022		Yes	C	PC	
A045	21/06/2022	2	Yes	C	PC	5

Key: *STG, Standard Treatment Guidelines; SAASP, South African Antimicrobial Stewardship Programme; C, compliant; PC, partially compliant; NC, non-compliant*

[a] *patient file unaccounted for*

[b] *new patient, no file history*

[c] *new file created as previous file was lost due to a fire at Charlotte Maxeke Johannesburg Academic Hospital*

plans observed, and the number of patients with chronic wounds, suggest that these guidelines do not cover the most commonly isolated pathogens.[17] It was further found that 60.4% of the treatment protocols implemented complied only partially to international guidelines.

Discussion

In this study, the greatest rate of incidence of ulceration occurred in those over the age of 60 years (42%), while only 17% of DFUs were seen in patients younger than 50 years of age. These results are consistent with the findings of a systematic review and meta-analysis carried out in 2022, in which increasing age, and subsequent longer duration of diabetes, was found to be a consistent risk factor associated with DFU incidence and consequent lower limb amputation.[18] According to a meta-analysis evaluating the influence of epidemiologic and patient behaviour related predictors on amputation rates in diabetic patients, the male sex was found to be a significant risk factor for amputation.[19] A higher prevalence of DFUs among male patients in this study was consistent with previous studies carried out across India.[1-3] The prevalence of DFUs has been suggested to be greater among the male population due to an increased incidence of peripheral neuropathy, a higher likelihood of exposure to trauma in comparison to female patients, as well as a greater tendency for female patients to carry out foot care regimens more frequently than male patients.[18,20-22]

Comparing the South African classification system to the Wagner classification system suggests that the Wagner classification system allows for more selective categorisation of different ulcers than the SAASP guidelines based on ulcer severity. As a result, patients presenting in the South African public healthcare sector with varying degrees of ulcer severity are treated in the same broad manner with very little difference in treatment between degrees of severity. The use of the SAASP guidelines in conjunction with the Standard Treatment Guidelines and Essential Drug List results in no difference in the treatment plans of Wagner grades 1 through 5 DFUs to account for increasing severity. It is thus important to consider changing the South African guidelines, to those which are more capable of discerning DFUs of different severity, and subsequent treatment plans, such as those provided for by the International Working Group on the Diabetic Foot (IWGDF).[23]

Many South African patients with diabetes are managed in primary healthcare clinics where healthcare providers are responsible for playing a role in the prevention of disease and education of patients.[24] Should screening for diabetes-related complications not occur effectively, individuals presenting with these complications will be missed, resulting in delayed treatment, increased healthcare cost and poor patient outcomes.[24] Patients in this study were expected to present on a monthly basis in order to monitor the progression of their DFU as well as track the management of diabetes and related co-morbidities. In this study, hypertension was found to be present in 84.4% of patients, making it

the most common concurrent medical condition amongst this cohort. This result is consistent with another South African study in which it was found that 85.7% of DFU patients presented with hypertension.[25] Hypertension is a critical co-morbidity in patients presenting with DFUs as it results in atrial wall stiffening and thus further promotes the advancement of peripheral artery disease and subsequent DFU development. The proportion of patients with hypertension in our study is greater than that of previous studies which had 58.3–69.9% of patients presenting with hypertension.[24,26] This result is congruent with the World Health Organization's findings that low- to middle-income countries have a higher incidence of hypertension amongst their population.[27] Dyslipidaemia (total cholesterol: >5.2 mmol/L; LDL cholesterol: >2.6 mmol/L; HDL cholesterol: <1.6 mmol/L or triglycerides: >1.7 mmol/L) was reported in 33.3% of patients. A study undertaken in Egypt concluded that the presence of dyslipidaemia significantly increased the risk for DFU development.[28] In contrast, a systematic review carried out in 2021 concluded that, while dyslipidaemia is often associated with type 2 diabetes mellitus, it is not associated with diabetic foot conditions.[14] While conflicting reports exist about the relationship between dyslipidaemia and DFU risk, patients presenting with dyslipidaemia are 2.23 times more likely to develop peripheral neuropathy, a significant factor in the pathophysiology of DFUs.[4,29]

Upon review of the patient files, it was noted whether the patient had received a diagnosis of peripheral neuropathy as well as what treatment was prescribed, if any. The incidence of peripheral neuropathy, as documented in the patients' files, was 46%. From the results obtained, an additional 29% of patients presented with signs and symptoms of peripheral neuropathy, but remained undiagnosed and untreated. Thus, the more likely incidence of peripheral neuropathy in the study population may be closer to 75%. This finding is corroborated by a study undertaken in Sudan, where it was reported that the incidence of peripheral neuropathy associated with DFU was 82.1%.[30] In India, it was reported that 95.8% of DFU patients presented with peripheral neuropathy.[31]

An additional concern is that patients' health conditions are not effectively reported in their files and that patient record keeping is not effectively implemented and monitored. This is problematic in that medical practitioners may miss critical information about previous diagnoses, treatments and prescriptions when assessing and providing new treatment plans for patients.[32] A study undertaken in public healthcare centres in South Africa, which aimed to identify healthcare provider related determinants of diabetes and hypertension management, found that co-morbid conditions, as well as special investigations concerning the progression of disease, were infrequently noted.[33] The lack of complete patient health records often results in poorer quality patient care, and further adversely effects clinical research.[34]

In order to reduce the need for antimicrobial use, and thus reduce the burden of disease and antimicrobial resistance, education on the prevention of diabetic foot ulcers is paramount.[35,36] Preventative measures in this study were examined in order to determine whether the best treatment practices are employed in the South African public healthcare sector. It was established that 48.9% of patients did not make use of any preventative measures. Of patients who did make use of preventative measures, the most commonly used form of pressure off-loading was crutches (26.7%). A removable walker, which is one of the most effective preventative measures, was used by only 20% of patients.[36,37] Specialised footwear, including footwear marketed in commercial stores for diabetic patients, was only observed in 6.7% of patients.

In the South African context, the Standard Treatment Guidelines call for the education of patients regarding foot care; however, according to a study undertaken in a regional hospital in Durban (KwaZulu-Natal, South Africa), 90% of diabetic patients had not received any education of diabetic foot disease.[38,39] In addition to this, it was found that only 22.2% of DFU patients reported that they had personally examined their feet, and moreover, that these patients examined their feet only after developing a problem.[38] This further indicates a lack of understanding arising from a dearth of education pertaining to the importance of foot care in the diabetic patient. A similar study in Malaysia reported that 58% of patients did not have sufficient knowledge regarding foot care, and 61.8% of patients had poor foot care practices.[40] A study undertaken in India found that general foot care practice was poor, with many patients found to walk barefoot. Furthermore, 67.7% of patients did not check their footwear for foreign objects before putting them on and 54.8% of patients did not participate in regular foot care activities such as cutting their toenails.[41] A more recent study undertaken in Brazil found that 65.5% of participants had little knowledge regarding preventative measure use.[42] In the South African healthcare context, patients initially present to a primary healthcare clinic. Healthcare professionals at primary healthcare clinics are responsible for the screening of diseases and referral to higher levels of health care should the need arise.[43] It has been suggested that diabetic foot assessments and preventative measure implementation may be overlooked on account of the healthcare professionals stationed at these clinics being overworked and understaffed.[43]

When comparing use of preventative measures to ulcer severity, as a general trend, when ulcer severity increases, the likelihood of previous lower extremity amputation, as a result of a DFU, increases. This is concerning because patients who had undergone previous lower extremity amputation as a result of previous foot ulceration are presenting with DFUs with higher grades of severity. This infers that consequent patient education, or a lack thereof, as well as previous DFU experience of the patient, does not aid in the prevention of DFU reoccurrence and additional amputation. These findings were corroborated by a study undertaken in 14 European healthcare centres where a high ulcer reoccurrence rate was documented, despite regular follow-ups and continued patient education.[44] The importance of effective patient education is thus emphasised, with various reviews highlighting its crucial role in preventing DFUs and reducing their social and economic burden to society.[45,46]

In this study, the majority of patients presented with grade 1 DFUs (33.3%) and grade 2 DFUs (33.3%). Grade 3 ulcers were seen in 17.6% of patients while grade 4 ulcers were seen in 13.7% of patients. Only one patient presented with a grade 5 ulcer. A study undertaken in Nigeria observed the most common ulcer severity as grade 4 (36.9%), followed by grade 3 (26.2%) and grade 2 (17%).[47] Another study undertaken in India found the most common ulcer severity as grade 4 (34%), followed by grade 2 (22%) and grade 1 (18%).[48] A possible explanation as to why fewer ulcers of higher severity were observed in this study is because patients were often admitted at casualty and transferred directly to surgical wards without any further consultation from other healthcare professionals like podiatrists. From there, many patients underwent amputations, and as such were excluded from the study. This possibility is concerning, as patients would not be given the opportunity to undergo less aggressive methods of treatment and be subjected to a poorer quality of life due to the loss of a limb. A study evaluating the management of DFUs found that half of DFU amputations can be prevented with proper treatment.[49]

Polypharmacy is most commonly defined as the use of five or more medications in a day.[16] Patients presenting with type 2 diabetes, in particular older patients, are at risk for polypharmacy due to the nature of treating both macrovascular and microvascular complications of diabetes.[16] It has been found that diabetic patients are twice as likely to experience a drug-drug interaction when compared to patients without diabetes due to the presence of multiple co-morbid conditions in the diabetic populations; it is therefore important to monitor patients' prescriptions.[16] A review looking at the prevalence of polypharmacy in older diabetic patients found that 64% of patients were prescribed more than four medications a day.[50] In the current study, we found that 55.5% of the sample population were prescribed more than five medications on a chronic basis. This review also highlighted that polypharmacy may reduce optimal glycaemic control as well as increase the risk of hospitalisation.[50]

The average number of medications used by patients presenting with both grade 1 and 2 DFUs in this study was six. The highest average number of medications used (7) was seen in those with DFUs of Wagner grade 3 severity. In this study, the average number of drug-drug interactions was 4.7. It has been found that the presence of both polypharmacy and

subsequent potential drug interactions may alter glycaemic targets and result in a deterioration in renal function.[50] This not only poorly affects the overall health of the patient, but impaired renal function is also associated with delayed ulcer healing, amputation and mortality.[50] It is therefore important to effectively manage patients who take multiple medications. This can be accomplished by reviewing the patient's full medication history every time a new drug is considered, improving and increasing clinical pharmacy services, improving communication between healthcare practitioners, and, finally, by implementing effective patient history reporting and record-keeping.

Therefore, in conclusion, addressing the concerns relating to diabetes and DFU management identified in this study are crucial. Large-scale studies should be conducted to review the entire South African context for the magnitude of DFU incidence and management concerns, including adherence to treatment plans and the influence of DFU progression. These studies could help to address the development and implementation of more comprehensive patient education programmes to ensure that individuals with DFUs are well informed about the importance of complying with lifestyle changes and prescribed medications. In addition, these studies would aid in establishing robust monitoring and follow-up systems, which are required when tracking patient progress in adhering to treatment plans and reducing DFU burden.

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Competing interests

We have no competing interests to declare.

Authors' contributions

S.v.V.: Conception or design; acquisition, analysis, or interpretation of data; drafting the work or revising; and final approval of the manuscript. M.J.T.: Acquisition, analysis, or interpretation of data; drafting the work or revising; and final approval of the manuscript. S.L-d.R: Conception or design; acquisition, analysis, or interpretation of data; drafting the work or revising; and final approval of the manuscript.

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Sanguinarine highly sensitises breast cancer cells to doxorubicin-induced apoptosis

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Breast cancer is the most commonly diagnosed cancer and the second most common cause of cancer death in women. The anthracycline, doxorubicin, is a well-known and highly effective treatment for breast cancer patients; however, many patients present with resistance to chemotherapeutic drugs, which ultimately results in treatment failure and contributes to high mortality rates. It is well established that the mitogen-activated protein kinase phosphatase 1 (MKP-1) mediates the response to chemotherapy, where upregulated MKP-1 is associated with chemoresistance. We investigated whether MKP-1 inhibition or silencing can sensitise triple-negative MDA-MB-231 breast cancer cells to doxorubicin therapy. We found that MKP-1 inhibition and silencing sensitises breast cancer cells to doxorubicin-induced apoptosis. Additionally, the inhibition of MKP-1 in combination with doxorubicin treatment promotes autophagy induction, while doxorubicin and not MKP-1 modulation increased lysosomal acidic compartments. As such, this study demonstrated that MKP-1 inhibition has a potential therapeutic benefit for breast cancer patients by increasing the efficacy of conventional chemotherapy. Therefore, MKP-1 inhibition should be developed as a clinically relevant adjuvant therapy, which could provide a novel avenue for therapeutic intervention in combination with chemotherapy in breast cancer patients.

Significance:

- MKP-1 inhibition with sanguinarine and silencing sensitises breast cancer cells to doxorubicin-induced apoptosis.
- The inhibition of MKP-1 with sanguinarine in combination with doxorubicin treatment promotes autophagy induction.
- MKP-1 inhibition can have a potential therapeutic benefit for breast cancer patients by increasing the efficacy of conventional chemotherapy.

Introduction

Currently, 90% of chemotherapy failures are related to drug resistance.[1] Resistance to cytotoxic chemotherapeutic agents may often be random and unpredictable and becomes apparent only at clinical assessment.[2] One such chemotherapeutic agent is the anthracycline, doxorubicin (Dox), which is often used as a first-line therapy for the treatment of breast cancer.[3-5] However, its clinical effects are limited due to its dose-dependent side effects such as cardiotoxicity, gastrointestinal problems, acute vomiting, liver damage and nephropathy.[6,7] Therefore, adjuvant therapies are required that can improve the effectiveness of Dox while conferring a protective effect on normal cells.

The mitogen-activated protein kinase phosphatase 1 (MKP-1) is a member of the MKP family that consists of 11 dual-specificity phosphatases that negatively regulate MAPK. Upon activation, MKP-1 dephosphorylates and deactivates MAPKs, ERK, JNK, and p38, by dephosphorylating specific Thr/Tyr residues.[8] As such, MKP-1 plays an important role in tumorigenesis[9] and negates the cytotoxicity of anticancer drugs in various models of cancer[10-16]. It has been reported that the knockdown of MKP-1 sensitises cancer cells through the upregulation of MAPK activity.[14] The MAPK family mediates cell death through the mitochondrial pathway during conditions of cellular stress, for example, treatment with chemotherapeutic drugs, which is characterised by increased reactive oxygen species (ROS) production in the case of doxorubicin. Here, elevated ROS levels primarily activate the JNK and p38 pathways, resulting in mitochondrial-mediated apoptosis. Furthermore, MKP-1 also regulates the cell cycle and apoptosis through the modulation of mitochondrial function, oxidative stress and autophagy.[17,18] As such, targeting MKP-1 has the potential to effectively sensitise breast cancer cells to Dox treatment.

Autophagy is a cellular degradation process characterised by the sequestration of cytoplasm, long-lived proteins and cellular organelles in double-membrane vesicles called autophagosomes, which are delivered to and subsequently degraded in lysosomes. However, its role in chemoresistance is complex, and often cell type and context dependent.[19-21]

Sanguinarine is a bioactive quaternary benzophenanthridine alkaloid plant extract from *Sanguinaria canadensis* (blood root), *Poppy fumaria, Bocconia frutescens* and *Macleaya cordata* and is a structural homologue of chelerythrine.[22-26] Sanguinarine extracts have long been used in herbal medicine and have antimicrobial, antioxidant, anti-inflammatory and pro-apoptotic activity, and Sanguinarine can downregulate MKP-1 expression.[23,26-29] Sanguinarine has been reported to decrease anti-apoptotic proteins, such as Bcl-2, and increase levels of pro-apoptotic Bax in pancreatic carcinoma cells, while decreasing the expression of tumour-promoting NFκβ in cervical cancer cells, indicating a promising possibility for breast cancer treatment.[28,29] Therefore, the aim of this study was to investigate whether the modulation of MKP-1 improves the potential of Dox to induce apoptosis and autophagy in cancer cells in vitro.

Materials and methods

Cell culture

The triple-negative human mammary adenocarcinoma cell line, MDA-MB-231, obtained from American Type Culture Collection (Rockville, MD, USA), was used in this study. The MDA-MB-231 cells were cultured in Glutamax-Dulbecco's Modified Eagle's Medium (DMEM; Celtic Molecular Diagnostics, Cape Town, South Africa) supplemented with 10% foetal bovine serum (FBS) (Sigma Chemical Co., St Louis, MO, USA) and penicillin streptomycin (PenStrep; Sigma Chemical Co., St Louis, MO, USA). The cells were maintained in a humidified incubator set at 5% CO_2 at 37 °C and were routinely sub-cultured upon reaching 70–80% confluency.

Experimental protocol

Doxorubicin (D1515, Sigma Chemical Co., St Louis, MO, USA) was diluted to 5 μM in Glutamax-DMEM in ready to use aliquots; sanguinarine (Sang; Sigma Chemical Co., St Louis, MO, USA) was first diluted in methanol to a concentration of 0.01 M followed by dilution to 0.5 μM in growth medium; and dexamethasone (Dex; Sigma Chemical Co., St Louis, MO, USA) was dissolved to 0.1 M in distilled water and subsequently in growth medium to a final concentration of 100 nM; methanol was used as the vehicle. The concentration of Dox was determined with dose- and time-responses, which is presented in Supplementary figure 1. The following experimental groups were used in this study: (1) control, (2) Dex, (3) Dex and Dox, (4) Dox, (5) Sang, (6) Sang and Dox, (7) MKP-1 siRNA, (8) MKP-1 siRNA and Dox, (9) negative control (stealth RNAi) and (10) vehicle. The Sang groups were treated for 24 h, after which the Dox and Dex groups, including the combination treatment groups, were added and left to incubate for an additional 24 h.

MKP-1 siRNA Transfection

Silencing of MKP-1 gene expression was performed using reverse transfection. A volume of 20 pmol of MKP-1 siRNA duplex was used per culture well. And 20 pmol of MKP-1 siRNA duplexes (DUSP1VHS40581 and DUSP1VHS40583; Invitrogen™, USA, MKP-1 siRNA #159527B10, #159527B11) was diluted into transfection medium (Glutamax-DMEM containing no antibiotics or serum), after which Lipofectamine™ RNAiMAX (13778075; Invitrogen™, USA) was added and gently mixed. The RNAi duplex-Lipofectamine RNAiMAX complexes were allowed to incubate for 40 min and then made up to a final volume using DMEM (no antibiotics). MDA-MB-231 cells were plated directly into culture plates containing the RNAi duplex-Lipofectamine RNAiMAX complexes. Stealth™ RNAi (STEALTH RNAI NEG CTL MED GC, 12935300; Invitrogen™, USA) was used as a negative control. The cells were left to incubate for 48 h, after which Dox was added for a duration of 24 h.

Cell viability with trypan blue

The trypan blue exclusion technique[30] was used to determine the viability of MDA-MB-231 cells. Following completion of the treatment protocol, the cell monolayer was rinsed with warm sterile phosphate-buffered saline (PBS). Cells were trypsinised and centrifuged for 3 min at 1500 rpm. The supernatant was decanted, and the pellets were resuspended in sterile PBS. The cell suspension was mixed in a ratio of 1:1 with 0.4% trypan blue and loaded into a haemocytometer for counting. The total number of cells was counted, and the number of blue cells was used as an indication of cell death. The results were expressed as the percentage (%) of viable cells.

Caspase 3/7 Glo assay

The Caspase-3/7 activity was measured in MDA-MB-231 cells using the Caspase-Glo® 3/7 assay (Promega, Madison, WI, USA). The Caspase-Glo® 3/7 reagent was prepared and equilibrated at room temperature and mixed with the lyophilised substrate before the reconstituted working buffer reagent was stored at –20 °C. The working buffer reagent and the culture plate were equilibrated to room temperature prior to use. Following the addition of the working buffer solution, the culture plate was incubated at 22 °C for 1 h without exposure to light. The content of each well was transferred to a white-walled 96-well plate, and the luminescence was measured using a luminometer.

Morphological analysis with Hoechst33342 and LysoTracker

For morphological determination of cell death, MDA-MB-231 cells were stained with Hoechst 33342 (10 mg/mL). Hoechst 33342 was made up in the growth medium and was left to incubate for 5 min. Thereafter, LysoTracker™ Red (Invitrogen™, USA) was added to each well and was left to incubate for an additional 5 min. Images were acquired directly after the incubation period through an Olympus Cell® system attached to an IX-81 inverted fluorescence microscope equipped with an F-view-II cooled CCD camera (Soft Imaging Systems). By using a Xenon-Arc burner (Olympus Biosystems GMBH) as a light source, images were excited with the 360 nm DAPI and 572 nm excitation filter. Emission was collected using a UBG triple band pass emission filter cube. Images were processed and background subtracted using the Cell® software. A minimum of three images were taken in randomly chosen fields, where at least three independent experiments per treatment group were conducted. Morphological changes such as condensed nuclear chromatin and apoptotic bodies were quantified using the Cell® system.

Flow cytometry

LysoTracker™ Red (Invitrogen™, USA) was used to analyse the lysosomal acidic compartment in MDA-MB-231 cells. Following treatment, the cell monolayer was rinsed with warm sterile PBS. Cells were trypsinised and centrifuged for 3 min at 1500 rpm. Each pellet was re-suspended in 0.5 mL of the LysoTracker™ Red (Invitrogen™, USA) working solution (final concentration of 100 nmol/L made up in growth medium) and was left to incubate for 15 min at 37 °C. Following incubation, the cells were gently re-suspended before being filtered through a 50-μm nylon mesh into FACS tubes and analysed immediately on the flow cytometer. Analyses were performed on a FACSAria I flow cytometer (Becton Dickinson Biosciences, San Jose, CA) equipped with a 488 nm Coherent Sapphire solid state laser (13–20 mW), 633 nm JDS Uniphase HeNe air-cooled laser (10–20 mW) and 407 nm Point Source Violet solid state laser (10–25 mW). For each sample, population information from a minimum of 10 000 events was acquired using FACSDiva Version 6.1 software. Data were expressed in arbitrary values as a percentage relative to the untreated control.

Western blot analysis

After treatment, the cells were placed on ice, whereafter cell monolayers were rinsed with 1 mL cold PBS. Modified radio-immuno precipitation (RIPA) buffer (50 mM Tris-HCL, 1 mM EDTA, 1 mM phenylmethylsulfonyl fluoride (PMSF), 1 mM benzamidine, 4 μg/mL SBTI-1, 1 μg/mL leupeptin, 1% NP40, and 0.25% Na-deoxycholate; pH 7.4) was added to each well and was left to incubate on ice for 5 min. The cell suspension was transferred to pre-chilled Eppendorf tubes. Protein concentration was quantified using the Bradford protein method.[31] Following protein determination, lysates were diluted in Laemmli's sample buffer, boiled for 5 min and then centrifuged for 5 s. The prepared cell lysates were separated on 10% polyacrylamide gels by sodium dodecyl sulfate polyacrylamide gel electrophoresis at 200 V (Mini Protean System, Bio-Rad, Hercules). Following sodium dodecyl sulfate polyacrylamide gel electrophoresis, proteins were transferred to polyvinylidene fluoride (PVDF) membranes (Immoblin-P, Millipore) using a semi-dry electro-transfer system (Bio-Rad, USA). Membranes were blocked in 5% (w/v) fat-free milk in 0.1% Tris Buffered Saline-Tween20 (TBS-T) for 1 h at room temperature with gentle agitation. Membranes were then incubated overnight at 4 °C in the appropriate primary antibodies, including caspase 3 (Cell Signalling, MA, USA), cleaved PARP (Cell Signalling, MA, USA), LC3 (Cell Signalling, MA, USA), p62 (Cell Signalling, MA, USA) and MKP-1 (Santa Cruz Biotechnology, CA, USA), while β-actin (Cell Signalling, MA, USA) was used as a loading control. The membranes were incubated in anti-rabbit horseradish peroxidase-conjugated secondary antibody (1:10 000), Amersham Biosciences, UK, and Dako Cytomation, Denmark) for 1 h at room temperature the following day. The membranes were developed with the ECL detection Kit (Bio Vision Inc.) and imaged using the CL-Xposure (Thermo Scientific)

X-ray film. Exposed bands were quantified by densitometry using the UN-SCAN-IT© densitometry software (Silk Scientific Corporation, Utah, USA). Bands were expressed as optical density readings relative to the untreated control present on the same blot.

Statistical analysis

All values are expressed as a percentage of the control. The results are presented as mean ± standard error of the mean (SEM) for an $n = 3$. Comparisons between different groups were made by one-way analysis of variance (ANOVA), followed by the Bonferroni post-hoc test. Statistical analyses were performed using GraphPad Prism version 5.01 (Graphpad Software, Inc, CA, USA), and a value of $p < 0.05$ was considered statistically significant.

Results

MKP-1 expression modulated by dexamethasone, sanguinarine and siRNA

Treatment with the MKP-1 inducer, Dex (100 nM), for 24 h significantly increased MKP-1 expression in MDA-MB-231 cells ($p < 0.01$; Figure 1). In contrast, treatment with the MKP-1 inhibitor, Sang (0.5 μM), for 48 h ($p < 0.001$) and treatment with the MKP-1 silencer, MKP-1 siRNA (20 pmol), for 24 h downregulated MKP-1 expression in vitro ($p < 0.05$). Additionally, the expression of MKP-1 was also downregulated following co-treatment with Sang and Dox ($p < 0.001$), but not with Dox alone.

MKP-1 inhibition and silencing in combination with Dox decreases cell viability

Dox treatment significantly decreased cell viability of MDA-MB-231 cells when compared to the control group ($p < 0.001$; Figure 2A). While treatment with the activator of MKP-1, Dex, alone had no effect on cell viability, the combination of Dex with Dox resulted in a significant increase in cell viability when compared to Dox treatment alone ($p < 0.001$; Figure 2A). In contrast, treatment with the MKP-1 inhibitor, Sang, alone did not have a significant effect on cell viability (Figure 2B); however, the combination of Dox and Sang resulted in a significant decrease in cell viability ($p < 0.001$) when compared to Dox treatment alone. Similarly, treatment with MKP-1 siRNA alone resulted in no significant change in cell viability when compared to the control (Figure 2C); however, a significant decrease in cell viability was observed when comparing the combination treatment of MKP-1 siRNA and Dox with Dox treatment alone ($p < 0.01$; Figure 2C). Therefore, the inhibition of MKP-1 in conjunction with Dox treatment induced a greater reduction of viable cells than Dox alone.

MKP-1 inhibition during doxorubicin treatment promotes caspase 3/7 cleavage

As expected, Dox treatment resulted in a significant increase in caspase 3/7 activity, indicating the execution of apoptotic cell death ($p < 0.001$; Figure 3A, B and C). Both Dex and Sang as well as MKP-1 siRNA treatment alone had no effect on caspase 3/7 activity, as observed by the cell viability data (Figure 3B). However, under conditions of MKP-1 inhibition with Sang in combination with Dox, there was a significant increase in caspase 3/7 activity compared to Dox alone ($p < 0.001$; Figure 3B), also indicating that MKP-1 inhibition in conjunction with Dox treatment resulted in apoptotic cell death, which is in line with the cell viability results. However, neither MKP-1 siRNA nor the combination of siRNA with Dox had any significant effect on caspase 3/7 (Figure 3C).

Total caspase 3 and PARP cleavage display differential effects under conditions of MKP-1 induction, inhibition and silencing

The expression of total caspase 3 following Dox treatment was significantly decreased ($p < 0.001$), while PARP cleavage was increased ($p < 0.001$), which supports the Caspase-Glo® 3/7 and viability

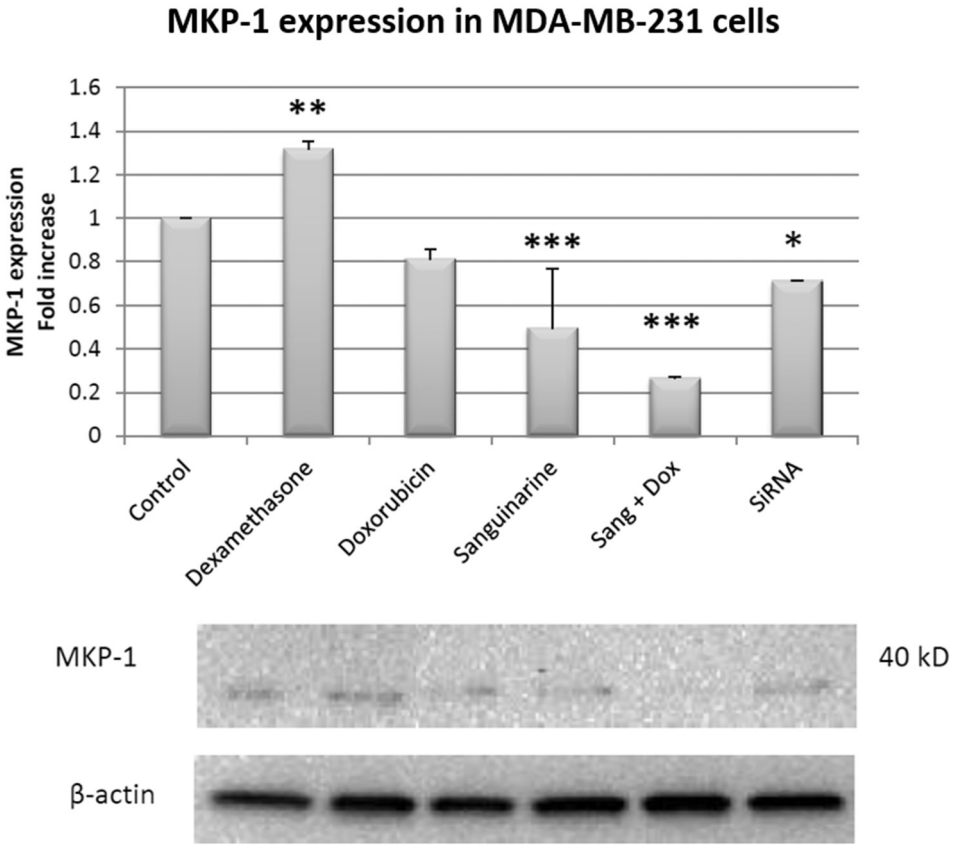

Figure 1: The expression of MKP-1 following treatment with the MKP-1 activator, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and Dox. Data are expressed as mean ± SEM ($n = 3$). *$p < 0.05$ versus control, **$p < 0.01$ versus control, ***$p < 0.001$ versus control.

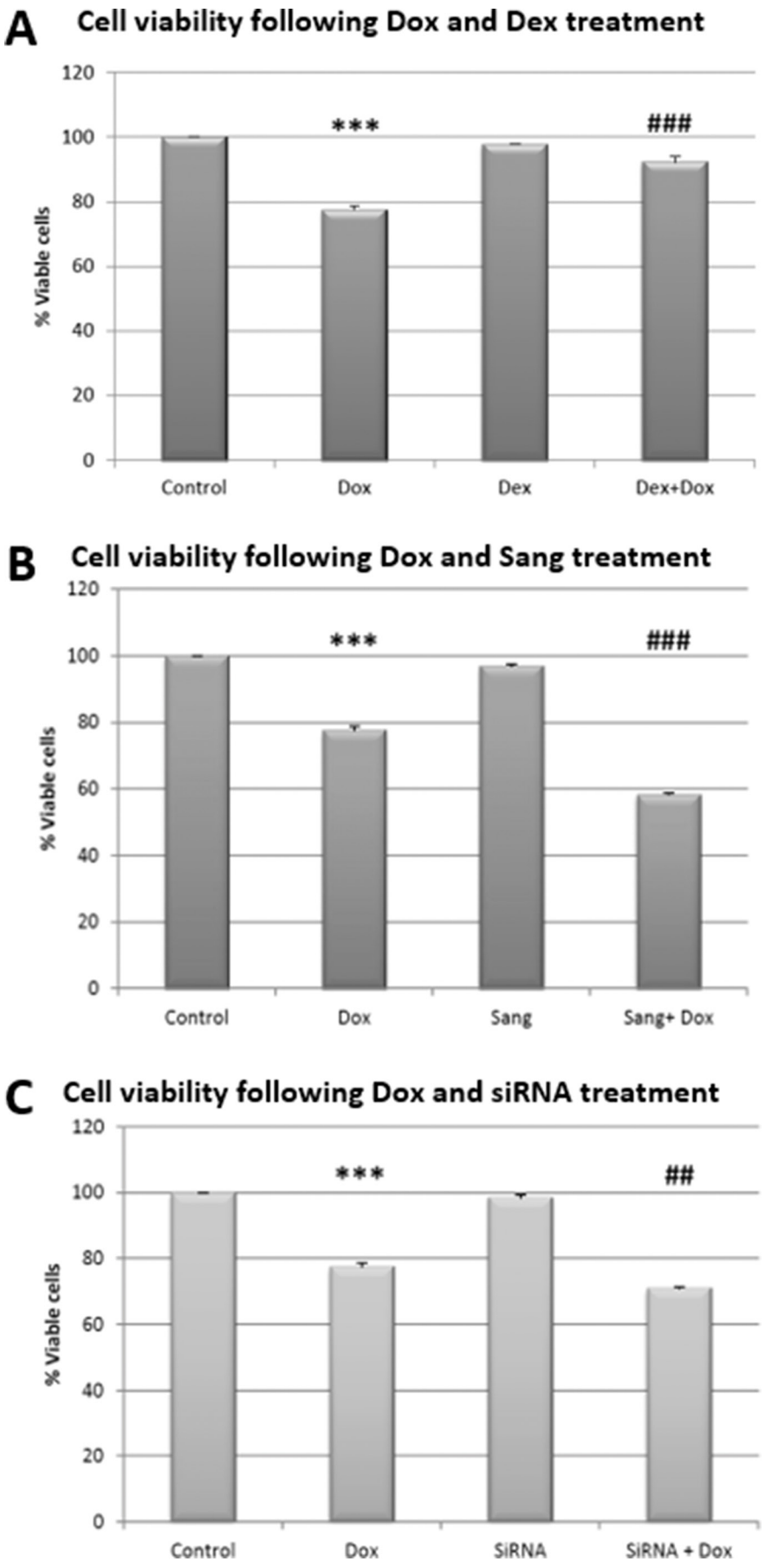

Figure 2: The cell viability of MDA-MB-231 cells following treatment with the MKP-1 inducer, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and Dox. (A) Cell viability following Dox and Dex treatment. (B) Cell viability following Dox and Sang treatment. (C) Cell viability following Dox and siRNA treatment. Data are expressed as mean ± SEM ($n = 3$). ***$p < 0.001$ versus control, ##$p < 0.01$ versus Dox, ###$p < 0.001$ versus Dox.

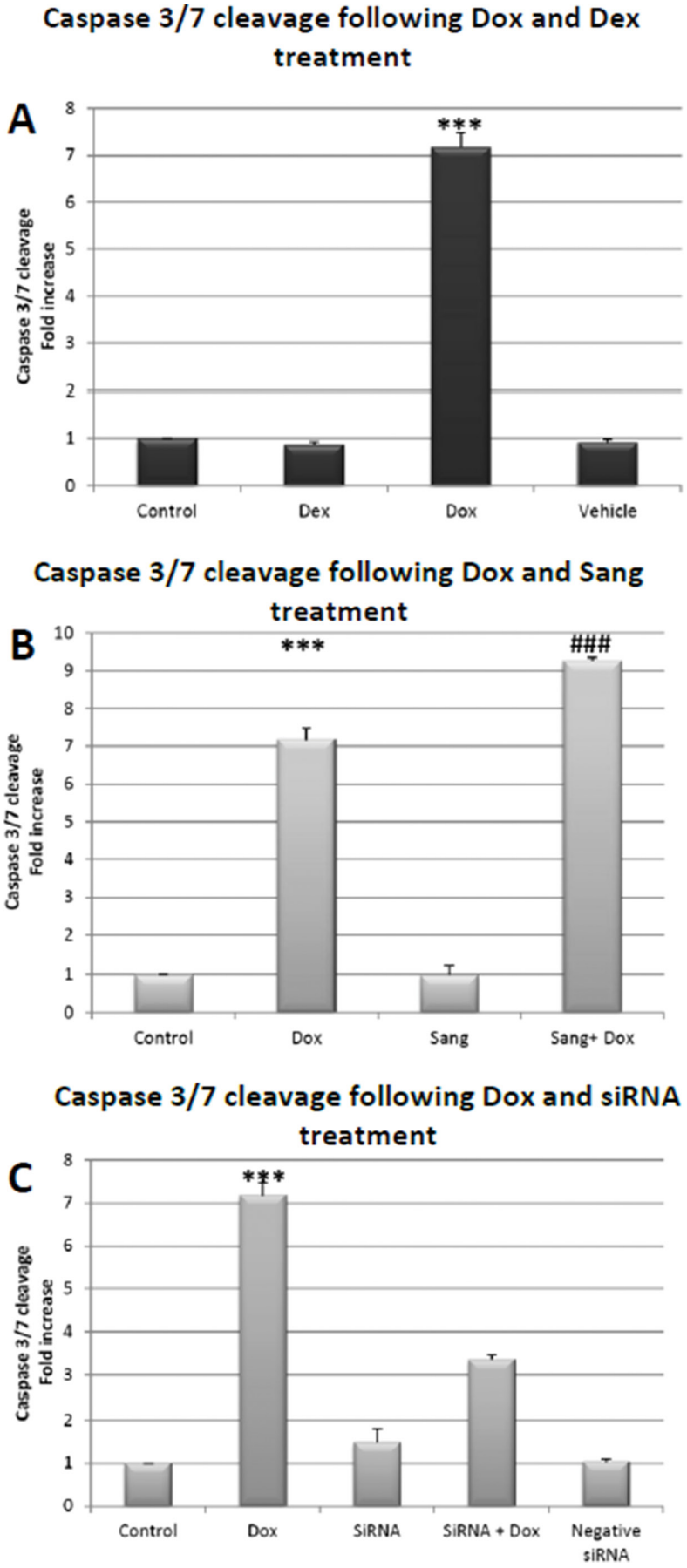

Figure 3: Caspase-3/7 activity as a measure of apoptosis in MDA-MB-231 cells following treatment with the MKP-1 inducer, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and Dox. (A) Caspase-3/7 activity following Dox and Dex treatment. (B) Caspase-3/7 activity following Dox and Sang treatment. (C) Caspase-3/7 activity following Dox and siRNA treatment. Data are expressed as mean ± SEM ($n = 3$). ***$p < 0.001$ versus control, ###$p < 0.001$ versus Dox.

assays. The activator of MKP-1, Dex, significantly increased caspase 3 expression when compared to the control ($p < 0.01$) without PARP cleavage. In contrast, the combination of Dox and Dex treatment resulted in the decreased expression of caspase 3 ($p < 0.01$) and increased cleavage of PARP ($p < 0.001$). Therefore, Dex confers protection against apoptosis, where the addition of Dox abolishes this effect. The inhibitor of MKP-1, Sang, resulted in no significant change in caspase 3 expression or PARP cleavage when compared to the control. However, the co-treatment of Sang and Dox resulted in a significant decrease in caspase 3 expression ($p < 0.001$) and PARP cleavage ($p < 0.01$) when compared to the Dox group, which is supported by our findings for the Caspase-Glo® 3/7 and viability assays. The expression of caspase 3 was significantly increased following treatment with MKP-1 siRNA when compared to the control ($p < 0.05$) with no change in PARP cleavage;

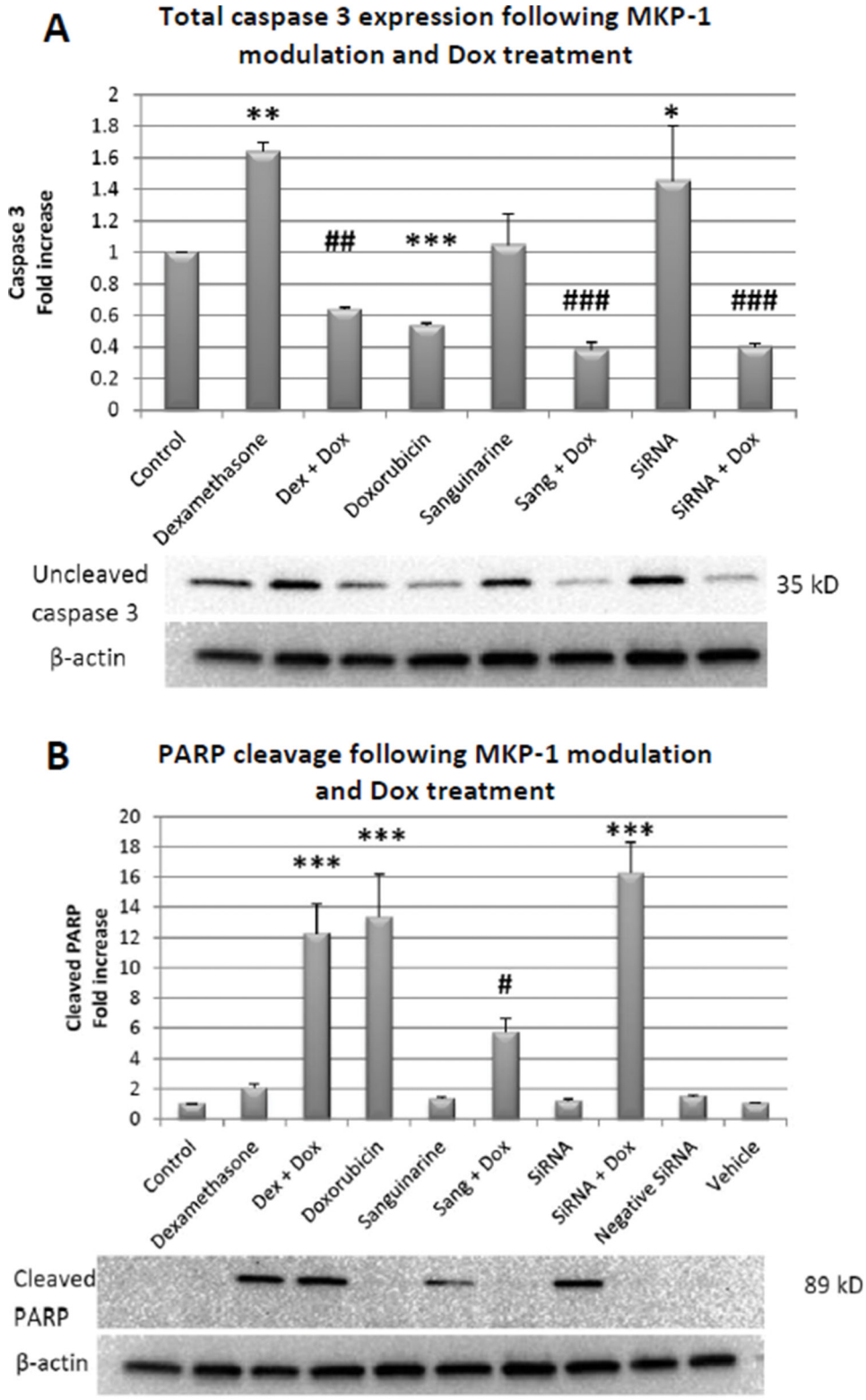

Figure 4: The expression of caspase 3 and the cleavage of PARP as a measure of apoptosis in MDA-MB-231 cells following treatment with the MKP-1 inducer, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and with Dox. (A) The expression of total caspase 3. (B) The cleavage of PARP. Data are expressed as mean ± SEM ($n = 3$). *$p < 0.05$ versus control, **$p < 0.01$ versus control, ***$p < 0.001$ versus control, #$p < 0.05$ versus Dox, ##$p < 0.01$ versus Dox, ###$p < 0.001$ versus Dox.

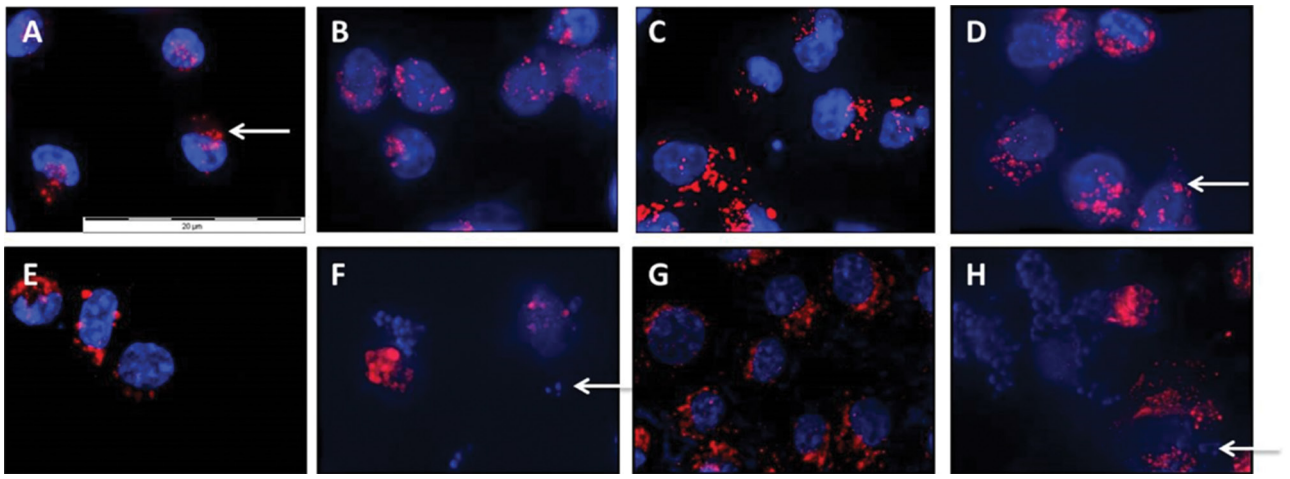

Figure 5: The effect of 24-h Dox treatment in combination with MKP-1 inhibitors and inducers on autophagy and apoptosis in MDA-MB-231 cells. (A) Control, (B) Dox, (C) Dex, (D) Dex and Dox, (E) Sang, (F) Sang and Dox, (G) siRNA and (H) siRNA and Dox. Red fluorescence indicates LysoTracker™ red, while blue fluorescence indicates nuclei (Hoechst 33342). The arrows indicate apoptotic bodies (blue) and autophagic vacuoles (red).

however, co-treatment with the MKP-1 silencer and Dox significantly reduced caspase 3 expression ($p < 0.001$), while increasing PARP cleavage ($p < 0.001$) when compared to Dox (Figure 4A,B). Therefore, MKP-1 inhibition and silencing sensitise breast cancer cells to apoptosis during Dox treatment.

MKP-1 inhibition and silencing during Dox treatment promotes changes in cell morphology

Morphological analysis revealed an increase in the size and number of acidic vesicles in response to both Sang and MKP-1 siRNA (Figure 5B), as well as in cells treated with both Sang and Dox (Figure 5F) or MKP-1 siRNA and Dox (Figure 5H). An increase in cell death markers, such as pyknosis and apoptotic bodies, was observed in the groups treated with Dex and Dox (Figure 5D) or MKP-1 siRNA and Dox (Figure 5H) where the highest degree of cell death was seen in the cells treated with Sang in combination with Dox (Figure 5F).

MKP-1 inhibition promotes autophagy

A significant increase in the conversion of LC3-1 to LC3-II was observed when MKP-1 was inhibited with Sang during Dox treatment when compared to Dox treatment alone ($p < 0.01$; Figure 6A). Furthermore, the expression of the cargo recruiter, p62/SQSTM1, was significantly increased in the Dex ($p < 0.001$) and Sang ($p < 0.01$) treated groups when compared to the control (Figure 6B). Evident in the increased conversion of LC3-1 to LC3-II and the twofold reduction in p62 expression, autophagy was induced.

Lysosomal acidic compartments undergo differential changes under conditions of MKP-1 induction, inhibition and silencing during Dox treatment

Treatment with Dox significantly increased lysosomal acidic compartments compared to the control ($p < 0.05$; Figure 7A). Dex treatment, a known MKP-1 inducer, had no effect on lysosomal acidic compartments compared to the control. However, the combination treatment of Dex and Dox resulted in a significant increase in lysosomal acidic compartments compared to the control ($p < 0.05$), although to the same extent as Dox treatment alone (Figure 7A). Sang treatment alone and in combination with Dox did not result in a significant change in lysosomal acidic compartments (Figure 7B). MKP-1 siRNA resulted in no significant change in lysosomal acidic compartments when compared to the control (Figure 7C). However, a significant ($p < 0.05$) increase in lysosomal acidic compartments was observed with Dox in conjunction with MKP-1 siRNA compared to control.

Discussion

It is well established that MKP-1 is associated with cancer progression and resistance to chemotherapy.[13,14] It has been reported that MKP-1 is overexpressed by more than fivefold in primary samples from breast cancer patients.[32-34] We, therefore, investigated whether doxorubicin treatment and treatment with the MKP-1 inhibitor, sanguinarine, and silencing of MKP-1 using siRNA can inhibit MKP-1 expression in MDA-MB-231 cells (Figure 1). Doxorubicin treatment did not alter the expression levels of MKP-1, which is in contrast to a study performed by Rojo et al.[35] who reported that doxorubicin decreased MKP-1 expression in a time- and dose-dependent manner. However, treatment with the glucocorticoid dexamethasone significantly increased MKP-1 expression in the MDA-MB-231 cells. This is supported by studies that confirmed that dexamethasone treatment is an inducer of MKP-1 expression.[36,37] Additionally, we investigated whether the bioactive plant extract sanguinarine can inhibit MKP-1 expression in breast cancer cells. Treatment with sanguinarine significantly decreased the expression of MKP-1 in triple negative breast cancer cells. This is supported by a study performed by Vogt et al.[26] in which sanguinarine treatment inhibited MKP-1 expression in PANC-1 and HeLa cells. Furthermore, the silencing of MKP-1 with MKP-1 siRNA also significantly decreased the expression of MKP-1 in vitro. This confirmed dexamethasone as an inducer of MKP-1 expression, while sanguinarine and MKP-1 siRNA effectively inhibited MKP-1 expression. We also found that co-treatment with sanguinarine and doxorubicin inhibits the expression of MKP-1, which is supported by existing reports that both doxorubicin and sanguinarine are inhibitors of MKP-1 expression.[10,26,35]

Based on these findings, we investigated the effects of MKP-1 modulation on the viability and apoptosis of breast cancer cells following doxorubicin treatment in vitro. Doxorubicin treatment significantly decreased cell viability of breast cancer cells (Figure 2A–C), which is supported by our findings of the increased activity of caspase 3 and 7 in vitro (Figure 3A). Furthermore, doxorubicin treatment significantly decreased total caspase 3 and increased PARP cleavage (Figure 4A,B). It is therefore concluded that doxorubicin induced apoptosis in vitro in our model. The sensitivity of these cell lines to doxorubicin has also been well established where increased levels of apoptosis are evident following doxorubicin treatment.[38-40] We then investigated whether the modulation of MKP-1 during doxorubicin treatment promotes or inhibits apoptosis induction in breast cancer cells. MKP-1 upregulation by dexamethasone alone did not affect cell viability or induce apoptosis (Figure 2A, 3A and 4), which is supported by previous studies which reported that glucocorticoids protect mammary gland epithelial cells, hepatocytes

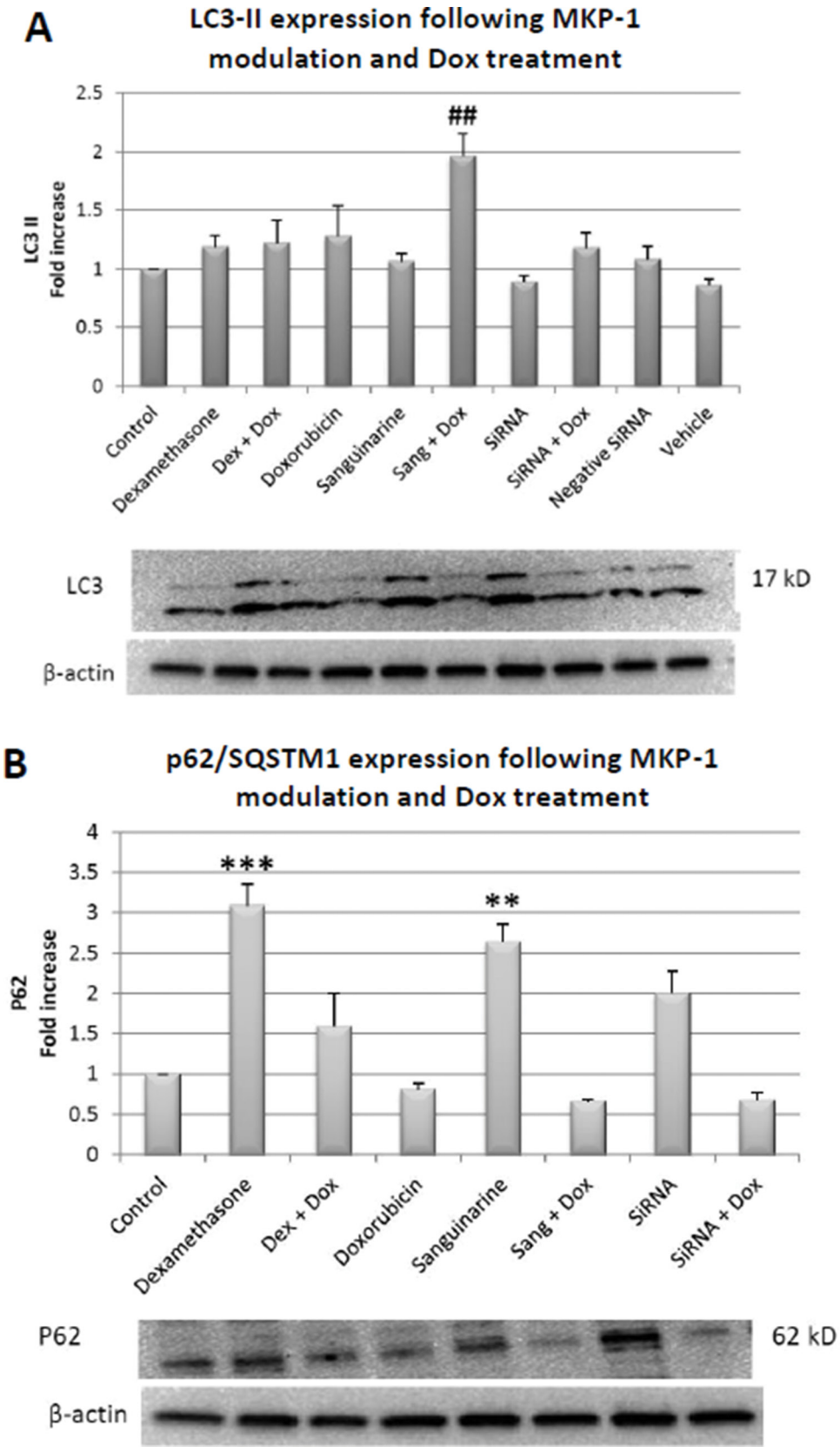

Figure 6: The expression of LC3-II and p62/SQSTM1 as a measure of autophagy in MDA-MB-231 cells following treatment with the MKP-1 inducer, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and with Dox. (A) Treatment with Dox and Dex. (B) Treatment with Dox and Sang. (C) Treatment with Dox and siRNA. Data are expressed as mean ± SEM ($n = 3$). $^{**}p < 0.01$ versus control, $^{***}p < 0.001$ versus control, $\#\#p < 0.01$ versus Dox.

and ovarian follicular cells against cell death signals and apoptosis.[41] This protective effect may be mediated by the upregulation of MKP-1, which can inhibit MAPK-induced apoptosis. However, co-treatment with dexamethasone and doxorubicin promoted cell death, indicating that the upregulation of MKP-1 alone confers a protective effect against apoptosis, but doxorubicin treatment abolishes this effect. Furthermore, the inhibition

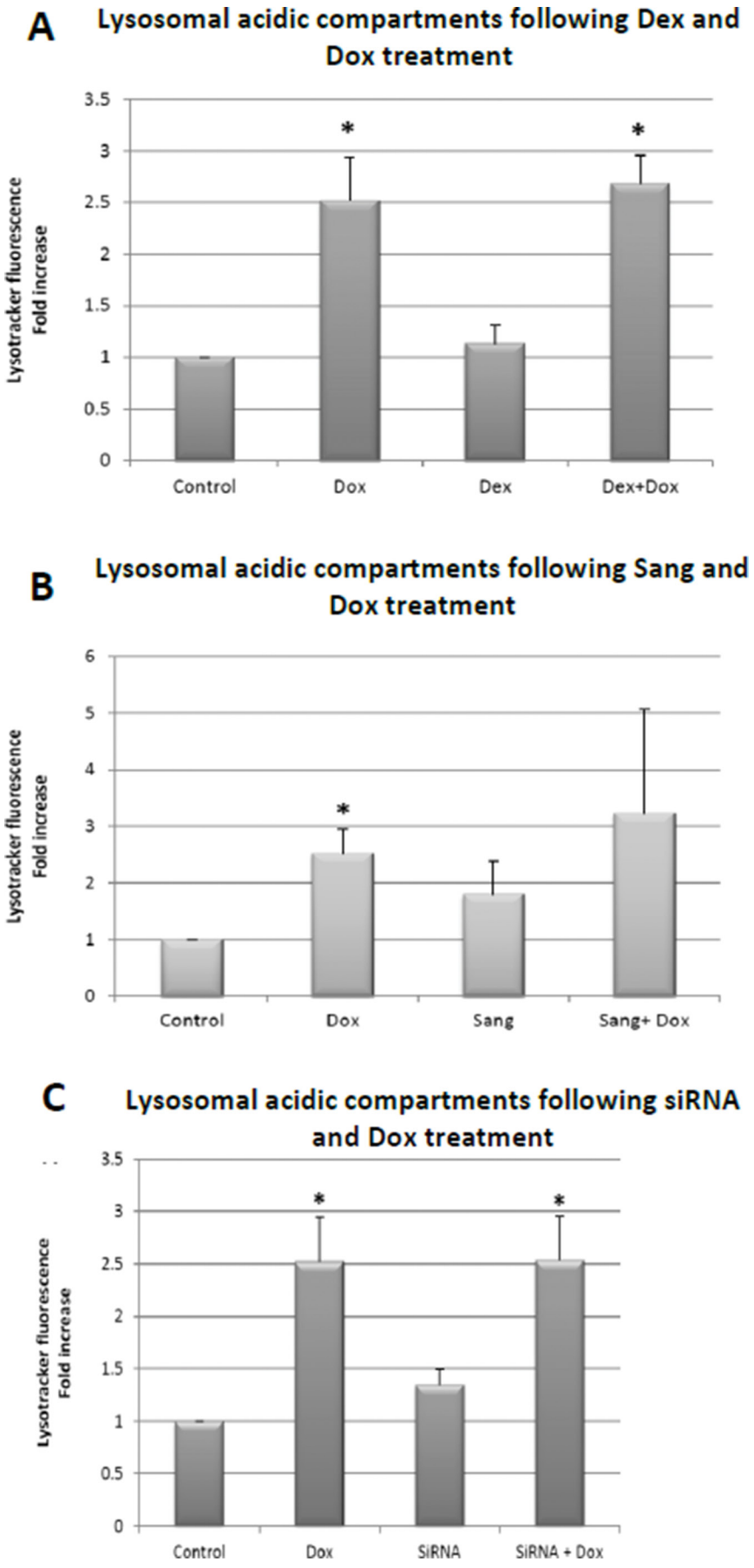

Figure 7: Lysosomal acidic compartments in MDA-MB-231 cells following treatment with the MKP-1 inducer, Dex, the MKP-1 inhibitor, Sang, MKP-1 silencing with siRNA, and with Dox. (A) Treatment with Dox and Dex. (B) Treatment with Dox and Sang. (C) Treatment with Dox and siRNA. Data are expressed as mean ± SEM ($n = 3$). *$p < 0.05$.

of MKP-1 with sanguinarine alone did not affect breast cancer cell apoptosis (Figure 2B, 3B and 4A-B). This suggests that the inhibition of MKP-1 alone is not an effective inducer of apoptosis. However, it has been reported that sanguinarine inhibits cancer cell proliferation with different degrees of sensitivity in different triple negative breast cancer cell lines.[42,43] Co-treatment with sanguinarine and doxorubicin decreased the amount of viable cancer cells and induced apoptosis (Figure 2B, 3B and 4A-B). These results indicate that sanguinarine improves the efficacy of doxorubicin treatment by sensitising breast cancer cells to doxorubicin-induced cell death in vitro. This is supported by studies showing that MKP-1 inhibition induced apoptosis in cervical and renal cell carcinomas[16], as well as in mesangial cells[44]. As with sanguinarine treatment, the silencing of MKP-1 with MKP-1 siRNA alone did not affect apoptosis (Figure 2C, 3C and 4B). However, the co-administration of doxorubicin and siRNA significantly decreased cell viability and induced apoptosis. This supports our findings for sanguinarine and doxorubicin co-treatment. Furthermore, Wang et al.[45] reported that the inhibition of MKP-1 sensitised ovarian cancer cells to cisplatin-induced apoptosis, which is mediated through the activation of the MAPKs. Therefore, the inhibition of MKP-1 during doxorubicin treatment may have important therapeutic value. Various chemotherapeutic agents induce apoptosis through the activation of the MAPKs, namely ERK, JNK and p38. These MAPKs are negatively regulated by MKP-1. MAPKs are involved in apoptosis induction, and their activation by chemotherapies induces cytochrome c release from the mitochondria. This results in the oligomerisation of apoptotic protease activating factor-1 (Apaf-1), recruiting pro-caspase-9 and inducing its autoactivation, which results in the downstream activation of the effector caspase 3.[46] Furthermore, JNK family members are involved in the activation of apoptosis by transcription-dependent processes, including death receptor induction.[47] Therefore, loss or inhibition of MKP-1 reduces its inhibition on members of the MAPK family, which may facilitate apoptosis following doxorubicin treatment. Furthermore, Small and co-authors[10] reported that MKP-1 inhibition enhanced chemosensitivity to doxorubicin through the activation of JNK. To further validate our findings for apoptosis, morphological changes commonly associated with the progression of apoptosis, such as chromatin condensation and the formation of apoptotic bodies, were also investigated (Figure 5A–H). The doxorubicin-treated groups displayed increased morphological characteristics that are associated with cell death, including pyknosis and the formation of apoptotic bodies. Co-treatment with sanguinarine and doxorubicin displayed the highest degree of apoptosis induction when compared to the other treatment groups. This further supports our findings that under conditions of MKP-1 inhibition, MDA-MB-231 cells are sensitised to doxorubicin-induced apoptosis.

Autophagy has been shown to play a dual role in doxorubicin-induced cell death.[48] We therefore assessed whether the modulation of MKP-1 and doxorubicin treatment can regulate autophagy. The co-administration of sanguinarine and doxorubicin induced autophagy in vitro (Figure 6A,B). This may be a synergistic effect between sanguinarine and doxorubicin, as treatment with sanguinarine or doxorubicin alone was not sufficient to induce autophagy. In line with this, sanguinarine has been reported to induce ROS-dependent autophagy and apoptosis in hepatocellular carcinoma cells.[49] This may be mediated through the resulting upregulation of MAPK activity following MKP-1 inhibition. The MAPK family are known regulators of autophagy, either inducing or inhibiting autophagy. It has been reported that ERK activation can induce autophagy by promoting the dissociation of Beclin-1 and Bcl-2, through the direct activation of the Gα-interacting protein (GAIP) and through the activation of ATF4, resulting in the increased transcription of the ATG proteins.[50-52] Furthermore, p38 activation can also induce autophagy through the activation of the ULK complex and LAMP2A translocation to the lysosomal membrane.[53,54] Lastly, JNK activation promotes autophagy through the dissociation of Beclin-1 and Bcl-2, the direct activation of Atg5 and Atg7, and by inducing Sestrin2 transcription, which activates AMPK.[55] Furthermore, at low doses, doxorubicin elicits an autophagic response in breast cancer cells.[56] Additionally, increased levels of ATG2A mRNA have been observed following doxorubicin treatment[57], suggesting increased autophagy activation at the transcriptional level. Conversely, activation of autophagy in cultured cardiomyocytes following 1 μM doxorubicin treatment mediated its cardiotoxic effect.[58] Here, it was shown that autophagy inhibition resulted in decreased cell death,

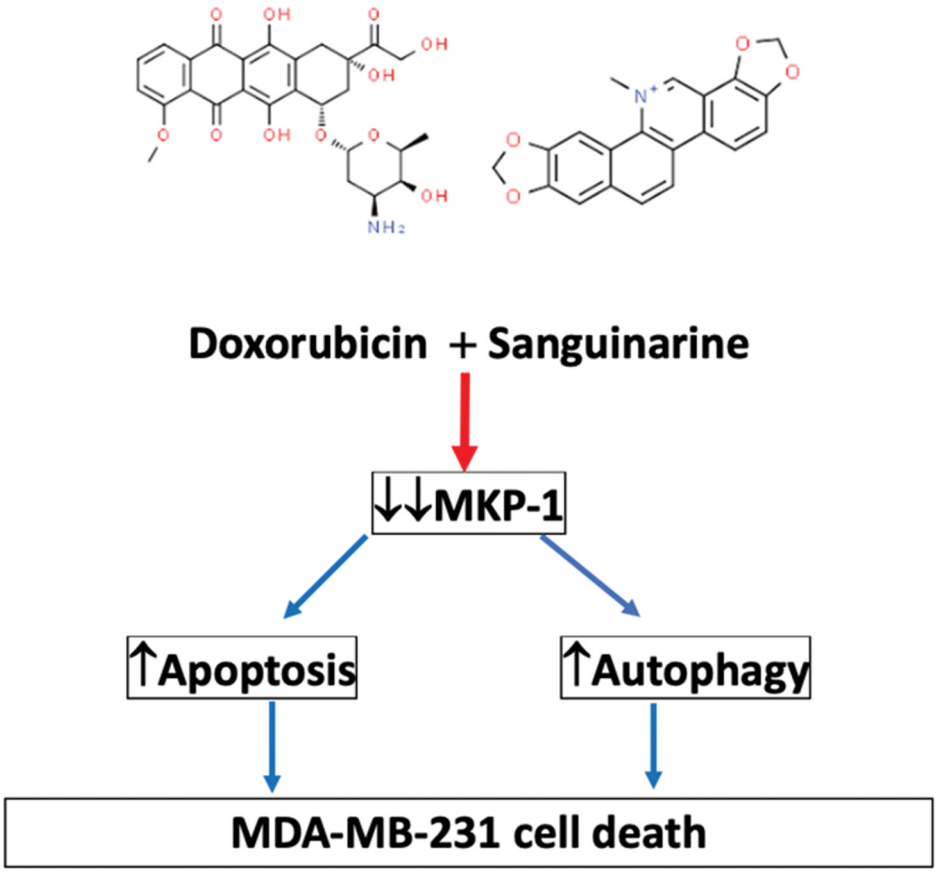

Figure 8: Proposed mechanism of action of doxorubicin and sanguinarine co-treatment in breast cancer cells.

and it was postulated that autophagy directly contributed to doxorubicin-induced toxicity. Apoptosis and autophagy are finely regulated, and MKP-1 inhibition with sanguinarine may promote doxorubicin-induced apoptosis and autophagy as an anti-neoplastic mechanism. However, only doxorubicin, irrespective of MKP-1 modulation, induced an increase in lysosomal acidity (Figure 7A–C). This finding is in line with a study performed by Thomas et al.[59] who showed that doxorubicin increased lysosomal acidity in MDA-MB-231 cells. Our results are also supported by the findings of other authors which show that doxorubicin induces an autophagic response in cancer cells.[60] Figure 8 summarises the main findings of this study and the proposed mechanism of action of doxorubicin and sanguinarine in breast cancer cells.

Conclusions

We have reported a role for MKP-1 modulation during doxorubicin treatment in vitro. It is clear that both apoptosis and autophagy remain central in tumourigenesis. In conclusion, the findings of this study clearly indicate the significant role of MKP-1 in cancer treatment and the importance of modulating MKP-1 in a targeted way in cancer patients receiving chemotherapy.

Future perspectives

The role of MKP-1 in autophagy induction should be further explored to elucidate how the upregulation of autophagy can contribute to apoptosis. Future studies should assess autophagic flux over time and include autophagy inhibitors to quantify autophagosomal accumulation.

Acknowledgements

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Competing interests

We have no competing interests to declare.

Authors' contributions

M.d.P.: Writing – original draft, writing – review and editing. C.F.: Writing – review and editing. H.I.: Methodology, data collection, validation, sample and data analysis, data curation. A-M.E.: Conceptualisation, resources, writing – review and editing, supervision, funding acquisition, project leadership.

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Development of unsupported IrO_2 nano-catalysts for polymer electrolyte membrane water electrolyser applications

IrO_2 is a current state-of-the-art catalyst for polymer electrolyte membrane water electrolyser (PEMWE) applications due to its high stability during the oxygen evolution reaction (OER). However, its activity needs to be significantly improved to justify the use of such a high-cost material. In this study, the activity of the IrO_2 catalyst was improved by optimising and comparing two synthesis methods: the modified Adams fusion method (MAFM) and the molten salt method (MSM). Optimum OER performances of the IrO_2 catalysts synthesised with the two synthesis methods were obtained at different temperatures. For the MAFM, a synthesis temperature of 350 °C produced the IrO_2 catalyst with an overpotential of 279 mV and the highest OER stability of ~82 h at 10 mAcm^{-2}. However, for the MSM, the lowest overpotential of 271 mV was observed for IrO_2 synthesised at 350 °C, while the highest stability of ~75 h was obtained for the IrO_2 synthesised at 500 °C.

Significance:

IrO_2 is still currently a state-of-the-art catalyst in PEMWE due to its high stability in the highly acidic and oxidising conditions of the OER. High-performance IrO_2 catalysts were successfully produced via the MAFM and MSM. Both the MAFM and MSM are simple and easily scalable for high-volume production of metal oxide catalysts. This study showed that the physical/structural properties of the IrO_2 catalysts can be tailored through synthesis methods and synthesis conditions to improve their OER performance.

Introduction

The polymer electrolyte membrane water electrolyser (PEMWE) is an important technology to produce hydrogen (H_2) from renewable energy sources, i.e. green H_2, due to its adaptability to the intermittent energy profiles of renewable energy sources like solar and wind power. However, the high costs associated with PEMWE components have remained a major challenge for the commercialisation of the technology. The high cost of the catalyst is of particular importance as it accounts for about 25% of the total catalyst-coated membrane cost. Furthermore, the catalyst-coated membrane shares about 24% of the total PEMWE stack cost.[1] The oxygen evolution reaction (OER) is a four-electron process dominated by sluggish electrode kinetics, leading to high overpotentials.[2] Therefore, the anodic catalyst in the PEMWE needs to be especially active and stable under the acidic OER environment to reduce the high overpotential. Expensive precious metals and their respective oxides are still known to be the most active and stable towards the OER although alternative non-precious metal materials are being investigated.[3] While high activities are obtained from non-precious metal catalysts, major challenges such as long-term stability need to be addressed before employing these materials as electrodes for large-scale, practical applications.[4] Metal oxides based on Ir and Ru are considered state-of-the-art catalysts for the OER because of their high activity and stability.[2] The IrO_2 catalyst has low overpotential, maintains high stability in acidic media, is corrosion resistant, and has a high selectivity towards oxygen evolution.[5] Wáng et al.[6] summarised the ex-situ OER performances of various materials that incorporated either Ir or Ru into its matrix. A second-best performance was obtained with $Ir_{0.06}Co_{2.94}O_4$ on an Au electrode exhibiting an overpotential of 250 mV and a stability of 200 h at 10 mVcm^{-2}. However, it should be noted that the best performance obtained on a glassy carbon electrode (GCE) (out of 24 studies) was for *a*/*c*-RuO_2, which exhibited a 205 mV overpotential and a stability of 60 h at 10 mVcm^{-2}.[7] The best performance for a monometallic Ir catalyst on a GCE was for mesoporous Ir nanosheets exhibiting an overpotential of 240 mV and a stability of 8 h at 10 mA/cm^2. These findings might suggest that the working electrode type has a significant impact on the measured OER performances.

In this study, the IrO_2 catalysts were developed via two methods: a modified Adams fusion method (MAFM) and a molten salt method (MSM). Although IrO_2 is a commonly used catalyst in the PEMWE, its OER activity needs to be significantly improved to justify the use of such an expensive material. The OER performance of the catalyst depends critically on its morphology, shape and crystal structure.[2,8] Besides optimising the physical properties of IrO_2, the synthesis methods need to be cost-effective, easily scalable, green and clean.[8] Since the introduction of the Adams fusion method in 1923 by Roger Adams and Ralph Shriner[9], the method has been modified and adapted to synthesise various metal oxides including single, binary and ternary metal oxides, supported and unsupported metal oxides as well as adding chemical modifiers to improve the physical properties of the catalysts.[4,10-14] Researchers have used various metals, reagent salts and synthesis temperatures to synthesise various metal oxides.[15] During the MAFM, the temperature used causes the $NaNO_3$ to melt and react with the Ir precursor. The synthesis temperature is always set to at least above the melting point of $NaNO_3$ i.e., above 308 °C. The MSM is also a simple, cost-effective, easily scalable and eco-friendly method for the synthesis of metal oxide catalysts.[8] During the MSM, the metal chloride precursor decomposes on the NaCl/KCl salt bed. The NaCl/KCl salt bed does not chemically react with the Ir precursor but acts as a support for the thermal decomposition of the Ir precursor in air. The synthesis temperature is mostly kept at 650 °C, which is below the melting point of the NaCl/KCl salt mixture.[12] Previous studies suggested the MAFM IrO_2 catalysts showed improved OER performance compared to MSM IrO_2 catalysts.[10,16] In this study, the MAFM and MSM were optimised by varying the synthesis temperatures, and the results were directly compared. Moreover, the reaction time of the MSM was reduced to 4 h (typically 12 h) and only NaCl was used as the salt bed.[16] The MAFM and MSM were compared by examining the

physical and electrochemical properties of the synthesised IrO_2 catalysts. The IrO_2 catalysts were physically characterised using X-ray diffraction (XRD), high-resolution transmission electron microscopy (HRTEM) and Brunauer–Emmett–Teller (BET) analyses. The IrO_2 catalysts' OER performances were evaluated ex-situ via cyclic voltammetry (CV), linear sweep voltammetry (LSV) and chronopotentiometry (CP).

Methods

Electrocatalyst synthesis

Modified Adams fusion method

An amount of 0.36 g H_2IrCl_6 (SA Precious Metals) was dissolved in 10 mL isopropanol (Sigma) and magnetically stirred for 30 min. Thereafter, 3.6 g of finely ground $NaNO_3$ (Alfa Aesar) sample was added to the solution and stirred for an additional 30 min. Excess solvent was evaporated on a hot plate followed by further drying in an oven set to 90 °C, for 30 min. The dried $H_2IrCl_6/NaNO_3$ mixture was then reacted in a pre-heated furnace for 2 h to produce the IrO_2 sample. The furnace temperatures selected for IrO_2 synthesis were 350 °C, 500 °C and 650 °C. The obtained IrO_2 sample was cooled, rinsed and filtered three times with 500 mL of ultrapure water (Milli Q) to remove the unreacted $NaNO_3$ salt. A 0.1 M $AgNO_3$ solution was used to ensure no chloride was present in the filtrate of the final 500 mL ultrapure water rinse/filter. After filtration, the IrO_2 sample was dried in an oven for 4 h at 85 °C and then cooled down overnight inside the oven. A commercial IrO_2 (Alfa Aesar) was used for comparison purposes. The samples synthesised using the MAFM are represented as MAFM-350, MAFM-500 and MAFM-650 to denote the different synthesis temperatures. Equations 1 and 2 show the suggested reactions occurring during the MAFM to produce the IrO_2 catalyst.[17]

$$H_2IrCl_6 + 6NaNO_3 \rightarrow 6NaCl + Ir(NO_3)_4 + 2HNO_3 \quad \text{Equation 1}$$

$$Ir(NO_3)_4 \rightarrow IrO_2 + 4NO_3 + O_2 \quad \text{Equation 2}$$

Molten salt method

An amount of 0.4 g of H_2IrCl_6 (SA Precious Metals) and 15 g of NaCl (Laborem Lab Supplies) was grounded together for 15 min with a pestle and mortar. The H_2IrCl_6/NaCl mixture was then transferred to a crucible and reacted in a pre-heated furnace for 4 h. Furnace temperatures selected for IrO_2 synthesis were 350 °C, 500 °C and 650 °C. Filtration, rinsing and drying were the same as for the MAFM. The samples synthesised using the MSM are represented as MSM-350, MSM-500 and MSM-650 to denote the different synthesis temperatures. A commercial IrO_2 (Alfa Aesar) was used for comparison purposes.

Preparation of the working electrode

A Metrohm rotating disc electrode (RDE) setup fitted with a GCE (0.1963 cm^2 working area) was used for the electrochemical analyses. The GCE was cleaned with 0.05 μm alumina paste (Buehler), polished and dried before use. The catalyst inks were prepared by ultrasonically dispersing 8 mg of the IrO_2 catalyst, 50 μL 5 wt% Nafion® solution (Alfa Aesar) and 1950 μL ultrapure water for 20 min. A micropipette was used to drop 30 μL of the IrO_2 catalyst ink onto the GCE. The working electrode was covered with a glass beaker and dried for 24 h at ambient conditions. A calculated catalyst loading of 0.45 mg cm^2 was obtained.

Physical characterisation

XRD was performed with the Bruker AXS D8 Advance diffractometer using Cu K radiation ($\lambda = 1.5406$ Å) operating at 40 kV and 40 mA. The IrO_2 standard (JCP2_150870) was used for peak allocation. HRTEM was obtained using an FEI/Tecnai T20 operating at 200 kV. BET surface area analyses were performed using the Micromeritics 3 Flex surface characterisation analyser.

Electrochemical characterisation

Ex-situ electrochemical analyses were performed in a three-electrode setup at 25 °C and 1 atm. The Autolab potentiostat PGSTAT302N (Metrohm) was used for all electrochemical analyses. A circulating water bath was used to maintain the temperature of the electrochemical cell. The working electrode (described in 2.2), a 3 M Ag/AgCl reference electrode (Metrohm), a Pt metal sheet (1 cm^2 area) counter electrode (Metrohm), which is five times larger than the working electrode and a 0.5 M $H_2SO_{4(aq)}$ electrolyte were used. All cell potentials in this work were reported versus the reversible hydrogen electrode (RHE). Potentials were converted from the 3 M Ag/AgCl electrode to the RHE by adding 210 mV to all measured potentials using the measured Pt open-circuit potential in the electrolyte. The current was reported to current density by converting the surface area of the working electrode to 1 cm^2 by dividing the current measured with the geometric surface area of the GCE. The electrolyte was purged with N_2 for 15 min before performing electrochemical measurements. Electrode activation was performed via CV cycling in the potential window 0 to +1.4 V versus RHE at a potential scan rate of 20 mVs^{-1} for 50 cycles before conducting any electrochemical characterisations. For LSV and CP analyses, the speed of the RDE was set to 1600 rotations per minute (rpm).

Results and discussion

Physical characterisation

The XRD spectra of the IrO_2 synthesised with the MAFM and MSM, compared to the commercial IrO_2, are shown in Figure 1. The IrO_2 peaks were assigned using the JCP2 standard files for IrO_2 (JCP2_150870) and Ir (JCP2_06–0598). In Figure 1a, the sharpening of the peaks with increasing synthesis temperatures (350–650 °C) shows the phase transition from an amorphous to crystalline IrO_2. The increased crystallinity for IrO_2 can be seen by the sharpening of the diffraction peaks, which are known to produce larger crystallite/particle sizes. This is common for the MAFM because $NaNO_3$ is used as the oxidising agent.[18] Sample MAFM-350 was in the amorphous phase, characterised by broad peaks,[19] and is known to consist of smaller particle sizes, ~2.73 nm. The (110) and (101) facets, which are important stable facets for

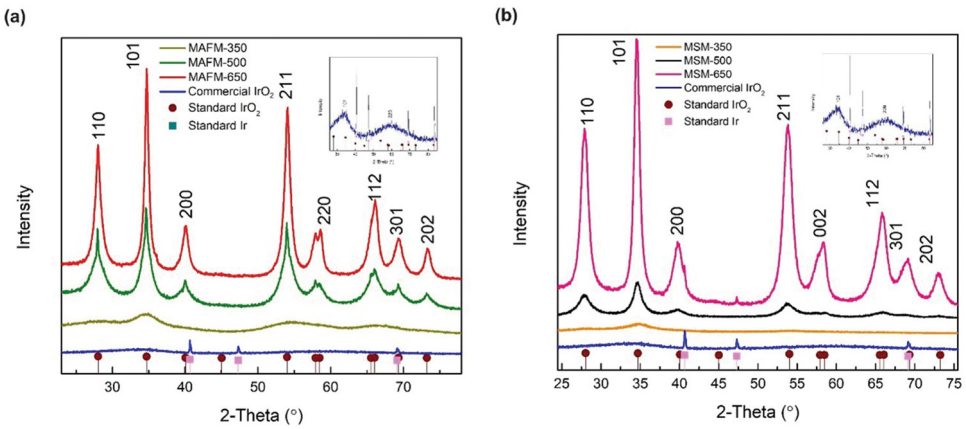

Figure 1: XRD analysis of the commercial IrO_2 and IrO_2 synthesised at temperatures 350 °C, 500 °C and 650 °C with the (a) MAFM and (b) MSM.

IrO_2, were present in samples MAFM-500 and MAFM-650, while only facet (101) was present in MAFM-350. Furthermore, the (211) facet at *Bragg* angle ~69° was present for MAFM-500 and MAFM-650 due to increased crystallisation. The characteristic rutile tetragonal IrO_2 peaks are noticeable for samples synthesised at 500 °C and 650 °C. A similar observation of increased crystallinity with increasing synthesis temperatures, 500–650 °C, was reported by Arico et al.[20] The average crystallite/particle sizes are determined at the (101) facet using the Scherrer formula as shown in Equation 3.[21]

$$d = 0.9\lambda/\beta \cos\theta \qquad \text{Equation 3}$$

where d = average crystallite/particle size, 0.9 = shape factor, λ = x-ray wavelength, β = peak width at half peak height and θ = *Bragg* angle. The (101) facet is preferred since it is a closed-packed Ir atom plane.[22]

MAFM-500 and MAFM-650 have crystallite/particle sizes of ~7.78 nm and ~10.01 nm, respectively. In Figure 1b, a phase transition was also seen for the IrO_2 synthesised with the MSM as the synthesis temperatures increased. MSM-350 was in the amorphous phase that can be seen by the broad diffraction peaks with a crystallite/particle size of ~2.83 nm. MSM-500 and MSM-650 were in the crystalline phase, which can be seen by the sharper diffraction peaks with crystallite/particle sizes of ~7.53 nm and ~8.78 nm, respectively. Furthermore, the MSM-650, and commercial IrO_2 showed an overlap of IrO_2 and Ir at Bragg angle ~40°. At Bragg angle ~47°, metallic Ir was present for MSM-650 and the commercial IrO_2. The presence of metallic Ir in the catalysts may negatively affect the OER performance.[23] The crystallite/particle sizes of IrO_2 synthesised with the MAFM are larger than the IrO_2 crystallite/particle sizes of the MSM. The difference in IrO_2 crystallite sizes of the two synthesis methods may be due to more steps involved in the MAFM, i.e. the precursor diffusion in $NaNO_3$, decomposition of $NaNO_3$, the reaction of the precursor with $NaNO_3$ and the formation of the metal oxide.[18] When compared to the commercial IrO_2, a synthesis temperature of 350 °C for both the MAFM and MSM produced amorphous IrO_2 catalysts with decreased crystallite/particle sizes while a synthesis temperature of 500 °C produced IrO_2 catalysts with similar crystallite/particle sizes. Only at 650 °C were the crystallite/particle sizes of the MAFM and MSM produced IrO_2 catalysts larger than the commercial IrO_2 catalyst.

HRTEM analysis was used to study the morphology of the IrO_2 catalysts synthesised with the MAFM and MSM. Sample MAFM-350 showed well-dispersed uniform spherical particles with sizes ~1.05 nm (Figure 2a). The corresponding selected area electron diffraction (SAED) image in Figure 2a confirmed the amorphous nature of

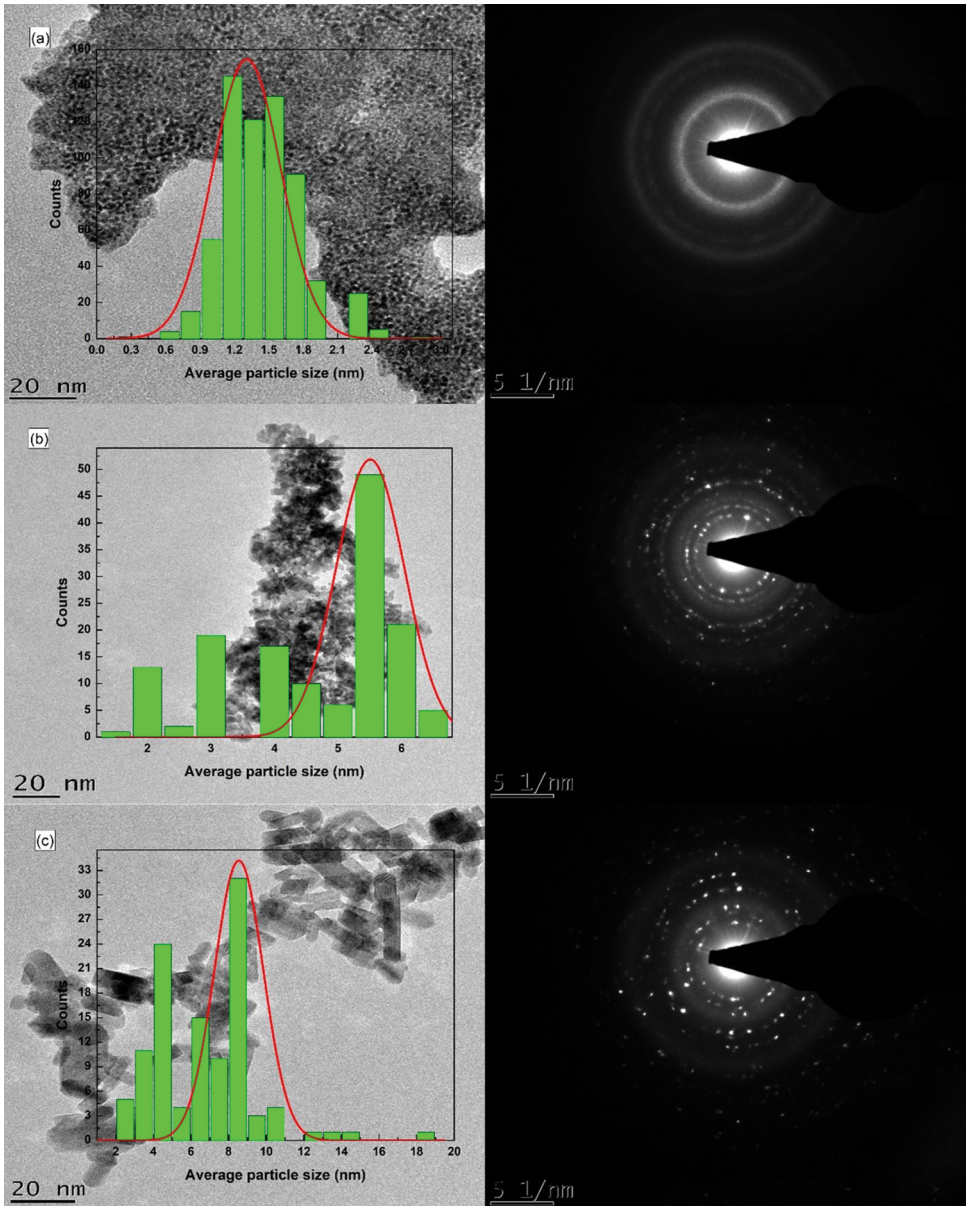

Figure 2: HRTEM and corresponding SAED analyses of the IrO_2 synthesised with the MAFM at temperatures (a) 350 °C, (b) 500 °C and (c) 650 °C.

MAFM-350 with the displayed concentric circles. MAFM-500 (Figure 2b) had cubic-shaped particles, ~5.48 nm, whereas MAFM-650 (Figure 2c) had a combination of cubic and cylindrical-shaped particles, ~ 8.68 nm. The bright dotted rings in the corresponding SAED images of Figure 2b and 2c confirmed the crystalline natures of MAFM-500 and MAFM-650. Subramanian et al.[24] observed similar SAED patterns for IrO_2 catalysts synthesised at higher temperatures. The MSM-350 also had spherical-shaped particles with sizes ~2.31 nm (Figure 3a). The SAED pattern for MSM-350 was like that of MAFM-350, indicating amorphous materials. Figure 3b shows a combination of cubic and cylindrical particles for MSM-500 with sizes of ~6.15 nm. At increased temperatures, Ahmed et al.[16] also obtained cylindrical-shaped IrO_2 particles when using the MSM. The MSM-650 consisted of different particle shapes (spherical, cubic and cylindrical), each with particle diameter sizes of ~8.84 nm (Figure 3c). Similar to MAFM, IrO_2 synthesised via the MSM at temperatures 500 °C and 650 °C showed increased crystallinity as confirmed by the SAED patterns in Figure 3b and 3c, respectively. Puthiyapura et al.[18] suggested that the difference in morphology may be due to the difference in IrO_2 preparation methods. Figure 4 shows the larger spherical-shaped particle sizes, ~8.96 nm, of the commercial IrO_2, which confirmed the particle size estimated with the Scherrer formula. It can be assumed that lower crystallinity and smaller particle sizes may have higher geometric surface areas that increase the OER catalytic activity.[18,22]

The BET surface areas of the IrO_2 catalysts were measured using N_2 adsorption-desorption analysis. The BET surface area is given as the average diameter of the particles by determining the particle-size-dependent area and the charge-deduced area.[25] The BET surface areas of the IrO_2 catalysts are summarised in Table 1. As the synthesis temperature for the MAFM and MSM was increased, the BET surface areas of the IrO_2 catalysts decreased. MAFM-350 had the highest BET surface area of 216.23 m^2/g. The IrO_2 catalysts synthesised via the MAFM had notably higher BET surface areas compared to MSM counterparts. This observation corresponds to the crystallite sizes measured from the HRTEM and the crystallite/particle sizes calculated from XRD. Baik et al.[12] observed a similar increase in IrO_2 catalysts surface area with decreasing MAFM synthesis temperatures, whereas Ahmed et al.[16] observed a similar trend in BET surface areas for their IrO_2 synthesised with the MSM. Furthermore, the commercial IrO_2 had the smallest BET surface area, which may influence the sample's overall OER activity.

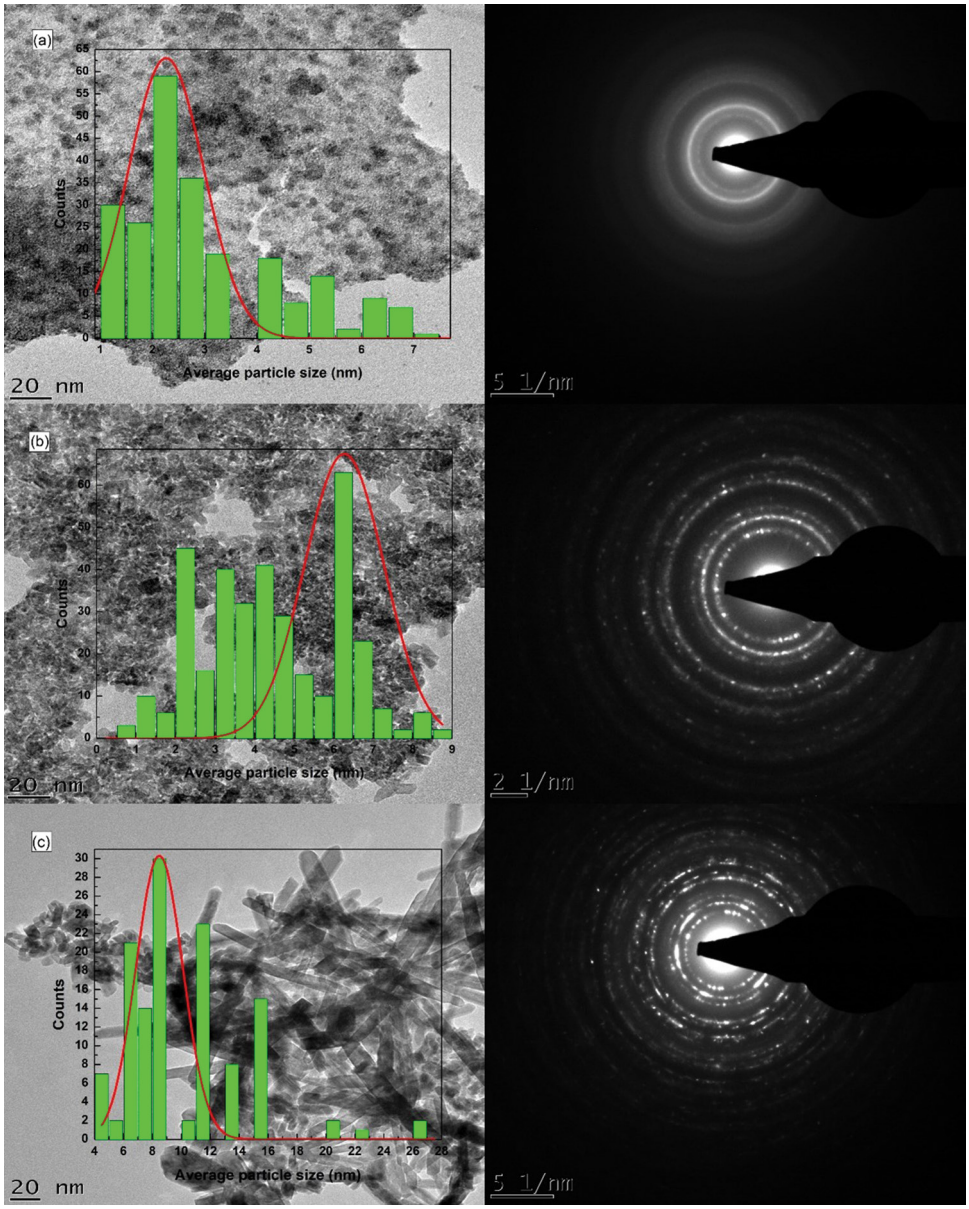

Figure 3: HRTEM and corresponding SAED analyses of the IrO_2 synthesised with the MSM at temperatures (a) 350 °C, (b) 500 °C and (c) 650 °C.

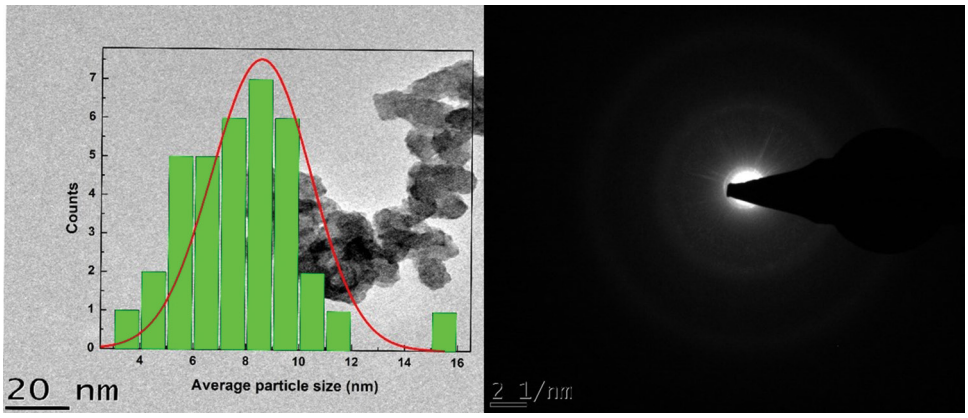

Figure 4: HRTEM and corresponding SAED analyses of the commercial IrO_2.

Table 1: Physical characterisation properties of the commercial, MAFM and MSM IrO_2 catalysts

Sample name	XRD crystallite/ particle sizes (nm)	HRTEM particle sizes (nm)	BET surface area (m^2/g)
MAFM-350	2.73	2.31	216.23
MAFM-500	7.78	3.54	104.84
MAFM-650	10.01	Width: 5.23	53.84
		Length: 11.36	
MSM-350	2.83	4.12	63.89
MSM-500	7.05	4.74	55.62
MSM-650	12.43	Width: 2.73	31.77
		Length: 26.36	
Commercial IrO_2	–	8.69	25.11

Electrochemical characterisation

The cyclic voltammograms were obtained in a potential window of 0 and +1.4 V versus RHE with a potential scan rate of 20 mVs^{-1}. The cyclic voltammograms seem to be influenced by the synthesis temperatures since there is a slight shift in the two redox couples, Ir(III)/Ir(IV) and Ir(IV)/Ir(V), as shown in Table 2. IrO_2 catalysts typically display a lowering in current density and charge as the synthesis temperatures are increased.[7,22,26] Heat treatment is known to dehydrate and crystallise the IrO_2 material, thereby reducing the utilisation of Ir atoms participating in reactions to as low as 1%–2%.(7) In Figure 5a, the Ir(III)/Ir(IV) and Ir(IV)/Ir(V) redox couples for MAFM-350, MAFM-500 and MAFM-650 were observed. Between 0 and +0.65 V versus RHE, no charges were transferred for the MAFM-500 and MAFM-650 due to double-layer charging.[22] In Figure 5b, the Ir(III)/Ir(IV) and Ir(IV)/Ir(V) redox couples for the MSM-350, MSM-500 and MSM-650 were observed, and the peak potentials are also summarised in Table 2. For the anodic potential scan, an additional pre-peak was seen at +0.35 and +0.59 V versus RHE for MAFM-350 and MSM-350, respectively. The peak can also be seen for the commercial IrO_2. The cause of the peaks may be due to the coupled ion-electron transfer, formal potential distribution, relations in the layer or the change in mass transport within the layer as the potential change.[22,27] The pre-peak is also believed to occur due to the oxidation of Ir^{3+} close to the metal/oxide interface and is accompanied by extensive water exchange.[7] IrO_2 synthesised at 500 °C and 650 °C does not exhibit these pre-peaks, ruling out the oxidation/reduction of a sodium layer impurity and also confirming the formation of a dehydrated IrO_2 material due to a lack of the water exchange that takes place during the pre-peak formation. Therefore, the additional peaks are almost certainly due to the presence of active Ir(III) sites at slightly shifted oxidising/reducing potentials. Additionally, the incomplete decomposition of the Ir-metal precursor in the oxide phase may also show the presence of active sites.[28] Upon the cathodic potential scan at 0 V versus RHE, a strong negative 'tail' was seen for MAFM-500, MAFM-650, MSM-500 and MSM-650. This reflects their negative capacitive behaviour (H_{ads}), involving the double-layer and pseudo- capacitances.[22,28] These CV-shaped curves are like those found by Rasten et al.[26], especially for the IrO_2 synthesised at increased synthesis temperatures.

The polarisation curves were obtained using the LSV technique that was performed between +0.8 and +1.8 V versus RHE at a potential scan rate of 2 mVs^{-1}. It is commonly understood that amorphous IrO_2 displays higher OER activity due to complete IrO_2 atom utilisation but suffers stability due to being prone to dissolution. In contrast, crystalline IrO_2 lacks the activity due to low IrO_2 atom utilisation and change in oxide stoichiometry towards the crystalline phase, but displays higher stability.[29] Thus, a strong relationship exists between the structural properties and electrocatalytic performance due to the presence of a mixture of amorphous and crystalline IrO_2.[29] The polarisation curves of the IrO_2 synthesised with the MAFM and MSM are shown in Figure 6a and 6c, respectively. The OER onset potentials of the synthesised IrO_2 were found to be at ~1.5 V versus RHE due to the energy requirement during the H_2O phase transition.[30] MSM-350 had the lowest overpotential of 270 mV compared to 280 mV for MAFM-350. For MAFM, peak OER activity for IrO_2 was observed at 500 °C, which is contrary to findings in the literature, which suggest that the amorphous IrO_2 would be more active. For MSM, the lowest overpotential was observed for MSM-350. At lower current densities (10 $mAcm^{-2}$), the MAFM-350 and MSM-350 had higher OER activities. However, at increased current densities (150 $mAcm^{-2}$), the MAFM-500 and MSM-500 had higher OER activities. There were no results generated at 150 $mAcm^{-2}$ for MAFM-650 due to the IrO_2 degradation caused by the Ir dissolution.[31] The performance difference between MAFM-650 and MSM-650 is quite notable, and the explanation is not clear as MAFM-650 had a higher BET surface and a similar CV to MSM-650. A possible explanation could be due to structural defects occurring during the formation of the Ir^{5+} surface where the OER takes place, which could also explain the higher overpotential at 10 $mAcm^{-2}$. Surface reconstruction occurs during the OER process to expose the real active species while the pristine catalyst could be considered pre-catalysts.[32] Different crystallinity induced by the synthesis temperature typically affects the dissolution rates of IrO_2 with higher stability and lower activities being the result of higher temperatures. Rasten et al.[26] also show improved OER activity of IrO_2 synthesised at decreased temperatures. Most anodically produced IrO_2 electrodes have a corresponding Tafel slope of about 44 mV dec^{-1}.[5,13] Figure 6b and 6d show the Tafel slopes of the IrO_2 catalysts synthesised via the MAFM and MSM, respectively. For both synthesis methods, IrO_2 synthesised at 350 °C exhibited the smallest Tafel slopes, i.e. 62.41 mV dec^{-1} for MAFM-350 and 59.17 mV dec^{-1} for MSM-350, while the Tafel slope magnitude increased with higher synthesis temperatures. IrO_2 catalyst with a smaller Tafel slope generates current more efficiently

Table 2: Anodic/cathodic peak potentials of the Ir(III)/Ir(IV) and Ir(IV)/Ir(V) redox couples of the commercial, MAFM and MSM IrO_2 catalysts

Sample name	Ir(III)/Ir(IV) anodic redox couple (V vs. RHE)	Ir(III)/Ir(IV) cathodic redox couple (V vs. RHE)	Ir(IV)/Ir(V) anodic redox couple (V vs. RHE)	Ir(IV)/Ir(V) cathodic redox couple (V vs. RHE)
MAFM-350	+0.94	+0.43	+1.30	+0.92
MAFM-500	+0.82	+0.76	+1.28	+1.15
MAFM-650	+0.78	+0.77	+1.18	+1.18
MSM-350	+0.97	+0.79	+1.20	+0.98
MSM-500	+0.80	+0.81	+1.23	+1.09
MSM-650	+0.65	+0.82	+1.17	+1.16
Commercial IrO_2	+0.74	+0.75	+1.16	+1.15

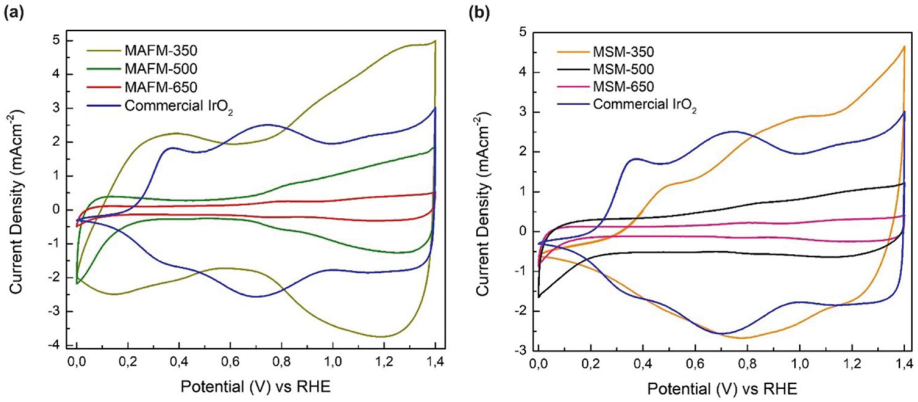

Figure 5: CV analysis at 20 mVs^{-1} in 0.5M H_2SO_4 of the commercial IrO_2 and IrO_2 synthesised with the (a) MAFM and (b) MSM.

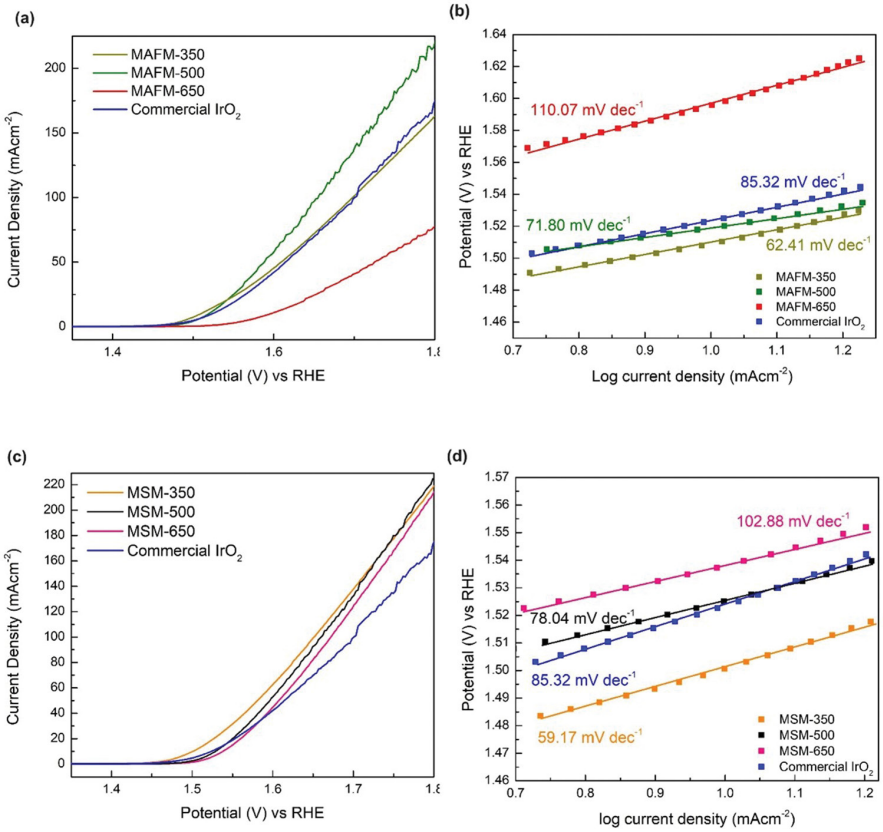

Figure 6: (a) LSV analysis at 2 mVs^{-1} in 0.5M H_2SO_4 of the commercial IrO_2 and MAFM IrO_2 catalysts, (b) Tafel plots of the commercial IrO_2 and MAFM IrO_2 catalysts, (c) LSV analysis at 2 mVs^{-1} in 0.5M H_2SO_4 of the commercial IrO_2 and MSM IrO_2 catalysts and (d) Tafel plots of the commercial IrO_2 and MSM IrO_2 catalysts.

Table 3: Electrochemical properties of the commercial, MAFM and MSM IrO_2 catalysts

Sample name	Overpotential at 10 $mAcm^{-2}$ (mV vs. RHE)	Tafel slopes (mV dec^{-1})	Mass activity at 1.6 V vs. RHE (Ag^{-1})	Potential at 150 $mAcm^{-2}$ (V vs. RHE)	Stability at 10 $mAcm^{-2}$ (hours)
MAFM-350	279	62.41	103	1.79c	82
MAFM-500	292	71.80	137	1.72	44
MAFM-650	359	110.07	28	–	5
MSM-350	271	59.17	140	1.72	23
MSM-500	299	78.04	122	1.71	75
MSM-650	311	102.88	103	1.73	41
Commercial IrO_2	291	85.32	101	1.77	10

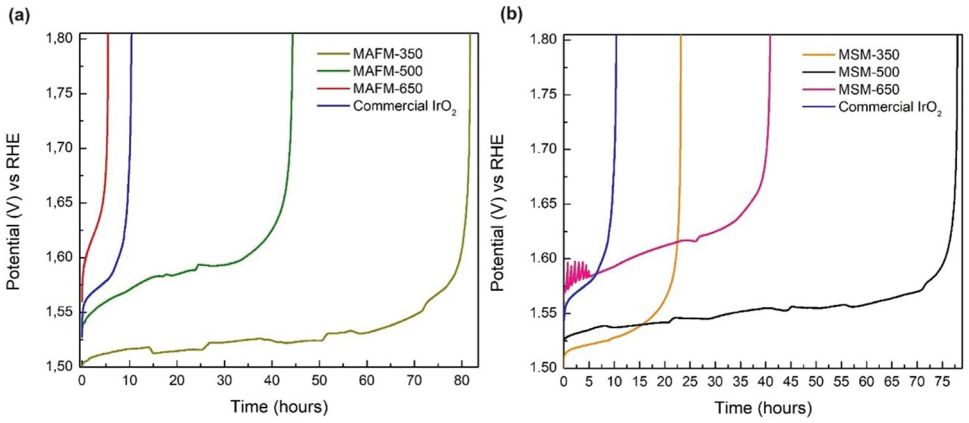

Figure 7: CP analysis at 10 $mAcm^{-2}$ in 0.5M H_2SO_4 of the commercial IrO_2 and IrO_2 synthesised with the (a) MAFM and (b) MSM.

when voltage is applied.[13,14] Siracusano et al.[19] synthesised IrO_2 catalysts with an overall Tafel slopes of 80 mV dec^{-1}. The Tafel slope consisted of an anodic contribution of 59.17 mV dec^{-1} and a cathodic contribution due to the OH adsorbed intermediates. Dang et al. developed a 1-T phase IrO_2 with an overpotential of 235 mV and a Tafel slope of 49 mV dec^{-1}; however, the synthesis method was highly challenging.[33] Table 3 summarises the electrochemical properties of the IrO_2 catalysts. The catalyst mass activities were determined at 1.6 V versus RHE. For the MAFM, MAFM-500 had the highest mass activity (137 Ag^{-1}), whereas for the MSM, MSM-350 had the highest mass activity (140 Ag^{-1}). The commercial IrO_2 catalyst exhibited a mass activity of (101 Ag^{-1}). For the MSM, there was a decreasing activity trend with the increase in synthesis temperature, while for the MAFM, peak activity was observed at a synthesis temperature of 500 °C. Higher mass activities may be attributed to catalyst nanostructures, which allow more exposure to the active sites.[4] The commercial IrO_2 had a lower OER activity when compared to the synthesised IrO_2 from both the MAFM and MSM. The lower OER activities of MAFM-650, MSM-650 and commercial IrO_2 can be attributed to the larger crystallite/particle sizes shown by the XRD and HRTEM analyses.

CP analysis was performed at 10 $mAcm^{-2}$ until the potential reached a value of 1.8 V versus RHE. Performance degradation is normally attributed to dissolution of the IrO_2 catalyst.[34] Figure 7a shows the CP analysis of the IrO_2 synthesised with the MAFM. MAFM-350 had the highest OER stability of ~82 h before reaching the cut-off potential. MAFM-500 and MAFM-650 were stable for ~44 h and ~5 h, respectively. Figure 7b shows the IrO_2 synthesised with the MSM. MSM-500 had the highest OER stability of ~75 h. The stability of MSM-500 was on par with the stability of MAFM-350. MSM-650 was stable for ~41 h compared to ~23 h for MSM-350. The low stability of MSM-350 appears to be the result of the formation of a highly amorphous IrO_2, which lacks the stable facets of IrO_2 needed for stable OER performance. The stability of MSM-350 is more in line with the expected stability of an amorphous IrO_2 catalyst compared to crystalline IrO_2 catalysts. However, MAFM-350 showed stability that exceeded the stability of its more crystalline IrO_2 counterparts, which is contrary to what is commonly expected from amorphous IrO_2 catalysts. The high stability of MAFM-350 could be due to more active sites (deduced from high BET surface area) available for the OER. The detachment of bubble formation on MAFM-350 at an early stage of the analyses may have also contributed to the increased stability.[35] The commercial IrO_2 was stable for ~10 h, outperforming only MAFM-650. A possible explanation for the poor performance of MAFM-650 could be due to structural defects during formation of the Ir^{5+} oxidation state where the OER takes.[35] The low stability of the commercial IrO_2 could be due to both physical and chemical properties such as low surface area and the presence of metallic Ir. Banti et al.[29] also observed a lower BET surface area and OER performance for this commercial IrO_2 catalyst compared to their synthesised IrO_2 catalysts. A summary of the catalysts' stabilities is provided in Table 3.

Conclusion

IrO_2 catalysts suitable for the OER in PEMWE were successfully produced using MAFM and MSM. Both methods can be easily scaled for high-volume metal oxide production. The effects of synthesis method and temperature on the OER performance of the IrO_2 catalysts were studied. It was found that MAFM and MSM influenced the OER performance of the IrO_2 catalysts. However, no specific synthesis method showed both increased OER activity and stability. The effect of temperature on the IrO_2 catalyst performance was different for the two synthesis methods. At 350 °C, the two methods yielded IrO_2 catalysts with contrasting OER performance, i.e. MAFM-350 had significantly better stability but lower activity compared to MSM-350. At 500 °C, MAFM-500 and MSM-500 had similar activities; however, MSM-500 had significantly better stability. At 650 °C, MSM-650 had better activity and stability compared to MAFM-650 with MSM-650 having the poorest overall OER activity of all the IrO_2 catalysts studied. The

commercial IrO_2 exhibited expected performance trends where amorphous IrO_2 has good activity but low stability. The XRD analysis showed a phase transition, from amorphous to crystalline, as the synthesis temperature was increased from 350 °C to 650 °C. IrO_2 catalysts synthesised at 350 °C were spherical shaped and amorphous. Above 500 °C synthesis temperatures, the IrO_2 catalysts synthesised via MAFM had cubic and cylindrical shapes, whereas the IrO_2 catalysts synthesised via MSM consisted of crystallites with different shapes. This study demonstrates that the physical properties of the IrO_2 catalysts can be tailored through the synthesis method and the synthesis conditions, which can result in significant improvements in the OER performance of the IrO_2 catalysts. Improved catalyst OER performance is essential to lower the catalyst loading requirements, which will in turn lower the costs associated with the catalyst component.

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Competing interests

We have no competing interests to declare.

Authors' contributions

S.K.: Data curation, investigation, formal analysis, conceptualisation, methodology, writing – original draft, writing – revisions and editing. C.F.: Visualisation, conceptualisation, methodology, formal analysis, writing – revisions and editing. S.P.: Visualisation, funding acquisition, project administration, supervision.

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Evaluation of pesticide residues and heavy metals in common food tubers from Nigeria

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Pesticide residues and heavy metal content of cassava, yam, cocoyam, potato, water yam and carrot were evaluated by gas chromatography–mass spectrometry and atomic absorption spectroscopy. The detected pesticide residues in the samples were 2,4-dichlorophenoxyacetic acid, glyphosate, hexachlorobenzene (HCB), dichlorobiphenyl, aldrin, endosulfan, profenofos, g-chlordane, carbofuran, biphenyl, heptachlor, lindane and t-Nonachlor. The concentration of HCB ranged between 0.0799 ± 0.06 mg/kg and 0.1596 ± 0.00 mg/kg, which was greater than the permitted maximum limit of 0.5 mg/kg established by the US Environmental Protection Agency. The concentration of aldrin and profenofos detected was lower than the predetermined maximum allowed limits. Endosulfan concentrations in cocoyam (0.2500 mg/kg) and potato (0.3265 mg/kg) were higher than the limits allowed by the Canadian Department of Industrial Research. The heavy metals detected in these samples include cobalt, nickel, lead, manganese, chromium, arsenic and mercury in at least one of the samples evaluated. There was not much difference between the concentration of cobalt in yam (0.036 mg/kg) and the maximum allowed concentration (0.043 mg/kg). Lead was detected in potatoes and carrots but was below detectable concentration in cassava, yam, cocoyam and water yam. Similarly, cocoyam was found to have a significant mercury content (0.658 mg/kg), but mercury content was below detectable concentrations in cassava, yam and water yam.

Significance:

Heavy metal pollutants and pesticide residues can impair human health, and their presence in food can cause various illnesses and health issues. It is important to prevent exposure to these contaminants and ensure that food is safe by identifying and monitoring them. Farmers may provide consumers with more assurance that their products are safe by identifying and monitoring pesticide residues and heavy metal contamination in these food crops. Overall, it is crucial to find and monitor pesticide residues and heavy metal contamination in food to safeguard customer confidence, ensure legal compliance and preserve human health.

Introduction

Pesticides are chemicals that are used to control pests which are harmful to humans, plants and the environment.[1] In parallel, pesticide residues are described as substances that are found in foods for consumption by humans or other animals, and are chemical derivatives considered to be toxic to living organisms.[2] Similar to pesticide residues, the entrance of heavy metals into the food chain is their major route into the human system, which could cause autoimmune disorders and inhibit the functions of some biochemical processes.[3] Heavy metal toxicity has been reported regularly in recent times, with some deaths attributed to it. Other effects of heavy metals on humans include cancers, high blood pressure and gene mutation.[2,4,5] Uncontrolled disposal of household and electronic waste, animal dung and abandoned metallic parts are some of the environmental sources of heavy metals.[6] Environmental pollution is a serious problem in today's modern world, with pesticides and heavy metal pollution being the most prevalent due to their ability to contaminate air and water.[7]

Cassava, yam, cocoyam, potato, water yam and carrot are commonly cultivated in Nigeria due to their multiple usage and nutritional values. These tubers are tropical crops consumed by about 2 billion people and are the major sources of carbohydrates providing energy for the roughly 700 million residents of tropical and subtropical regions.[8] The production of these products and their conversion into goods derived from food is expanding, and farmers profit significantly from their market.[8] Their high post-harvest losses, due to contamination by external and internal hazardous substances (such as mycotoxins, heavy metals and insecticides), reduce economic value and income. These roots/tubers have a crude fat content on the fresh weight of 0.1–0.5% and 1–3% on the dry weight, of which 80% is starch. The carbohydrate content of cassava is larger than that of potatoes.[8] Cassava is a potent source of energy despite being deficient in lipids, minerals and proteins.[9] On the other hand, yam provides energy in the range of 80–120 kcal/100 g.[10] Vitamin A is produced from beta-carotene, and it is present in adequate amounts in potatoes.[11] These tubers' essential amino acid composition is higher than that recommended by the Food and Agriculture Organization (FAO) for daily protein intake and greater than that of soybean protein.[12] These tubers may become polluted during cultivation and food processing and also contain certain endogenous antinutrients.

Currently, there are common applications of several agrochemicals in the cultivation of these crops to ward off pests. All the grown food crops are highly vulnerable to various insect attacks, especially on the farm or in the cultivation area, which has a detrimental impact on both the financial and dietary elements of product quality. Pesticides must be used to control pest infestations, which helps to improve the quality of crops and their production on farms.[13] Consequently, these tubers may get contaminated, and the risks associated with consuming these roots can be divided into two groups: those related to potentially harmful substances present in the crop itself, and those related to processing and product development. However, there are some significant concerns regarding food safety and security. A lot of research still needs to be carried out concerning the level of heavy metal

and pesticide pollution, especially that seen in Nigerian food crops like the tubers that are commonly consumed, such as cassava, yam and cocoyam.[14,15]

The amount of residues from pesticides and heavy metals in tuber-derived food products varies based on the location of the growing area and the system of farming. In Nigeria, pesticide residues detected in some tubers (cassava and yam) were HCB (0.0247), endosulfan (0.0340 and 0.090) and aldrin (0.0000 and 0.0937) mg/kg, respectively.[15] The concentration of isopropylamine in yam was 0.2165 ± 0.00 mg/kg and in cassava was 0.1649 ± 0.00 mg/kg, while the concentration of t-Nonachlor in yam was 0.1093 ± 0.00 mg/kg and in cassava was 0.0006 ± 0.00 mg/kg, as reported by Omeje et al.[15] Adeyeye and Osibanjo[16] detected high concentrations of organochlorine residues in yam (aldrin = ~5.0 μg/kg; dieldrin = ~24.0 μg/kg and p,p´-DDE = ~13.0 μg/kg) and cassava (aldrin = ~6.0 μg/kg; dieldrin = ~31.0 μg/kg and p,p´-DDE = ~21.0 μg/kg) in their study. Heavy metals have been found in tubers like potatoes, yams and cassava in previous studies. The amount of cadmium (Cd) found in yam was reported to be 0.11 mg/kg, and lead (Pb) and nickel (Ni) were also detected.[17] In addition, 0.21 mg/kg of Pb, 42 mg/kg of copper (Cu), 24 mg/kg of zinc (Zn), 18 mg/kg of manganese (Mn) and 12 mg/kg of Ni were reported by Wilberforce and Nwabue[18]. Arsenic (As) concentration in cassava was detected to be 0.017 mg/kg.[15] According to Onianwa et al.[19], the range reported for Ni concentrations in tubers is 0.93–1.79 mg/kg. Akinyele and Shokunbi[20] detected Mn in yams (~4.42 mg/kg), and Orisakwe et al.[21] reported Pb (~0.33 mg/kg), Cd (~0.10 mg/kg) and Ni (~0.30 mg/kg) in cassava.

To enrich the existing body of information, we assessed the presence and concentration of common food pesticide residues and heavy metal contaminants in essential and commonly consumed tuber crops cultivated in Nigeria using gas chromatography–mass spectrometry (GC–MS) and atomic absorption spectroscopy.

Materials and methods

Chemicals and materials

The chemicals and reagents used were of analytical quality and included chloroform, perchloric acid, sodium sulfate, concentrated sulfuric acid (Sigma-Aldrich), n-hexane (Loba Chemie, India) and concentrated nitric acid, anhydrous sodium sulfate, methanol (Sigma-Aldrich) and benzene. The pesticide standards (purity > 95%) were obtained from Restek (Sigma-Aldrich, USA). With concentrations ranging from 50 ng/mL to 200 ng/mL, stock standard solutions of 47 organochlorine pesticides (OCPs), organophosphorus pesticides (OPPs) and other pesticides were made in ethyl acetate and stored at 4 °C in a dark location until analysis. Pesticides are present in spiking solutions in amounts of 10–50 ng/L. The internal standard was aldrin solution (Sigma-Aldrich) in acetone at a concentration of 50 ng/L.

Samples

In April 2022, fresh tubers weighing 500 g each (cassava, yam, cocoyam, potato, water yam and carrot) were purchased from Nsukka open market situated in Enugu State (6°51'24" N and 7°23'45" E) in southeast Nigeria, and transported to the laboratory of the Department of Biochemistry, University of Nigeria, Nsukka. They were processed and stored at 4 °C for further analysis.

Pesticide residue analysis

The pesticide residues were determined with the help of a GC analysis and prepared following the AOAC method[22], with minor modifications. Ten grams (10 g) of the homogenised sample was mixed with 60 g of anhydrous sodium sulfate in an agate mortar to absorb moisture. The homogenate was transferred into a 500 mL beaker, and the extraction was carried out with 300 mL of n–hexane for 24 h. The obtained crude extract was concentrated using a rotary vacuum evaporator at 40 °C to dryness. The sample residue (1 mL) was measured into 50 mL of chloroform transferred to a 100 mL volumetric flask and diluted. Most of the chloroform was evaporated at room temperature before adding 1 mL of the solvent mixture (20% benzene and 55% methanol). The mixture was sealed and heated at 40 °C using a water bath for 10 min. After heating, the organic sample was extracted with n–hexane and water in a proportion of 1:1. The mixture was shaken vigorously for 2 min, and n-hexane phase was transferred onto a small test tube for injection into a Buck 530 Gas Chromatograph (GC) equipped with an on-column, automatic injector, electron capture detector and an HP 88 capillary column (100 mm X 0.25 μm film thickness) (Agilent Technologies, Santa Clara, CA, USA), with injector and detector temperatures of 180 °C and 300 °C, respectively. Overall, the GC enabled the identification of pesticide residues, which were recorded in mg/kg, as the results emerged.

Heavy metal analysis

The heavy metal analysis (Co, Ni, Pb, Mn, Cr, As, Hg and Cd) was performed using a Varian AA240 Atomic Absorption Spectrophotometer (AAS; Varian Inc., Palo Alto, CA, USA) equipped with an acetylene air flame, adapting the protocol described by Quarcoo and Adotey[23], with slight modifications. The pyrolytic-coated graphite tubes of the AAS were equipped with platform instrument settings and furnace programs that helped to ascertain the peak signals. A known concentration of the sample (~2 g) was put into a digestion flask, along with 20 mL of acid mixture (which consisted of 650 mL concentrated HNO_3; 80 mL perchloric acid; 20 mL concentrated H_2SO_4), and subsequently heated until a clear digest was obtained. The digest was diluted with distilled water to the 100 mL mark. The acid level samples as they came along were monitored by a pH meter. The digestate was quantified, assayed for heavy metals using a Varian AA240 Spectrophotometer, and reported in mg/kg. The reference standards (Fluka Analytical, Sigma-Aldrich Chemie GmbH, Switzerland) for the detected element, blanks and their duplicates were digested using conditions consistent with those of the samples.

Statistical analysis

The emergent heavy metal and pesticide residue data were obtained from triplicate determinations of different samples from a given food crop batch. A one-way analysis of variance (ANOVA), using SPSS for Windows (version 16, SPSS Inc., Chicago, IL, USA), was used to establish differences in heavy metals/pesticide residues across the studied food crop samples. Data are expressed as mean ± standard error (SE). A simple *t*-test was used to compare the heavy metals/pesticide residue concentration data and the established/referenced maximum permissible limits (MPLs). The probability level was set at $p < 0.05$ (95% confidence level).

Results

The concentrations of nickel (Ni), chromium (Cr), cobalt (Co), arsenic (As), manganese (Mn), cadmium (Cd), lead (Pb) and mercury (Hg) in the tubers are shown in Table 1.

All the heavy metals evaluated were present in the samples, except for Cd, which was below the detectable concentration in all the samples studied (Table 1). Among the samples, the maximum level of Ni (0.012 ± 0.00 mg/kg) was found in cassava. The concentration of Ni was 0.009 ± 0.00 mg/kg in cocoyam, 0.006 ± 0.00 in yam, 0.007 ± 0.00 in water yam, 0.001 ± 0.00 in carrot and 0.006 ± 0.00 in potato (Table 1).

Co, one of the common heavy metals in the environment, was among those evaluated. The maximum Co concentration of 0.036 ± 0.00 mg/kg was detected in yam. A Co concentration of 0.026 ± 0.00 mg/kg was detected in cocoyam, 0.016 ± 0.00 mg/kg in water yam, 0.011 ± 0.00 mg/kg in cassava, 0.010 ± 0.00 mg/kg in carrot and 0.002 ± 0.00 mg/kg in potato. According to Leyssens et al.[24], Co is an essential constituent of nature, which is released during many anthropogenic activities and is a cofactor of vitamin B_{12}.

Cr was also detected in all the samples. Cr concentrations of 0.093 ± 0.00 mg/kg and 0.083 ± 0.00 mg/kg were found in cocoyam and cassava, respectively. Potato and water yam had Cr concentrations of 0.073 ± 0.00 mg/kg and 0.078 ± 0.00 mg/kg, respectively. The lowest level of Cr was detected in carrots (0.010 ± 0.00 mg/kg). Similarly, cobalt was detected in all the samples, with the highest concentration (0.036 ± 0.00 mg/kg) found in yam. Co was detected in the potato

sample, although at the lowest concentration (0.00 ± 0.00 mg/kg) when compared to those of the other samples.

Similarly, As was found in the samples in various amounts. The amounts found in cassava, yam and cocoyam were 0.045 mg/kg, 0.010 mg/kg and 0.049 mg/kg, respectively. Also, 0.056 ± 0.00 mg/kg, 0.037 ± 0.00 mg/kg and 0.019 ± 0.00 mg/kg As were detected in samples of potato, water yam and carrot, respectively. Potatoes had the highest concentration of As discovered, whereas yam had the lowest concentration (0.010–0.00 mg/kg) (Table 1). The presence of Mn, Cd and Pb was evaluated in the samples. High concentrations of Mn (0.838 ± 0.00 and 0.750 ± 0.00 mg/kg) were detected in water yam and potato. Cassava contained 0.138 ± 0.00 mg/kg of Mn, as shown in Table 1.

Lead was not detected in cassava, yam, cocoyam or water yam. However, higher concentrations of 0.032 mg/kg and 0.028 mg/kg were detected in cassava and carrots, respectively. The World Health Organization (WHO) limit for Mn is not yet established.[15] Mn serves as a cofactor for some enzymes but could cause neurological disorders when above >5 mg/dm^3.[5,25]

The concentrations of Pb were 0.032 ± 0.00 and 0.028 ± 0.00 mg/kg in cassava and carrot, which were below FAO/WHO established MPLs (10 ± 0.00 mg/kg). The concentration of Pb in cassava, yam, cocoyam and water yam was below the detectable range, as shown in Table 1. The concentration of mercury (Hg) was lowest in potato (0.153 ± 0.00 mg/kg) and highest in cocoyam (0.658 ± 0.02 mg/kg), but below the detectable range in cassava, yam and water yam.

Metallic mercury exposure has been reported to cause lung damage.[26] The concentration of Hg in the cocoyam (0.658 ± 0.00 mg/kg) was greater than the 0.5 mg/kg FAO/WHO maximum acceptable limits.[27] However, potatoes showed a Hg concentration below the MPL.[27]

Table 2 shows the concentrations of pesticide residues present in the tubers studied. 2,4-dichlorophenoxyacetic acid, dichlorobiphenyl, HCB, endosulfan, aldrin, profenofos, carbofuran, lindane, g-chlordane, dichlorvos (DDVP), heptachlor, glyphosate, t-Nonachlor and biphenyl were the different pesticide residues detected in the six tubers studied. Aldrin was observed in all the samples studied; the highest amounts were detected in potato (0.1161 ± 0.00 μg/m^3) and cocoyam (0.0779 ± 0.000μg/m^3), followed by carrot (0.0711 ± 0.00μg/m^3), cassava (0.0617 ± 0.00 μg/m^3), water yam (0.0580 ± 0.00 μg/m^3) and then yam (0.0004 ± 0.00 μg/m^3). Similarly, DDVP was found in every sample studied, with the maximum concentration observed in cassava (0.5208 ± 0.00), potato (0.3635 ± 0.05 μg/m^3), followed by carrot (0.3632 ± 0.06), yam (0.1334 ± 0.04) μg/m^3, cocoyam (0.0683 ± 0.00 μg/m^3) and then water yam (0.0562 ± 0.00μg/m^3). Endosulfan (0.2500 ± 0.01 μg/m^3), lindane (0.0914 ± 0.01μg/m^3), g-chlordane (0.0000 ± 0.120 μg/m^3), biphenyl (0.9228 ± 0.00 μg/m^3), 2,4-dichloro phenoxy acetic acid (0.1127 ± 0.00 μg/m^3), HCB (0.1018 ± 0.00 μg/m^3), profenofos (0.2138 ± 0.00 μg/m^3), glyphosate (0.1876 ± 0.00 μg/m^3) and t-Nonachlor (0.1084 ± 0.001 μg/m^3) were detected only in cocoyam. Furthermore, cassava contained 0.0431 ± 0.00 μg/m^3 2,4-dichlorophenoxyacetic acid, 0.1596 ± 0.00 μg/m^3 HCB, 0.1693 ± 0.00 μg/m^3 p'p'-DDD, 0.1476 ± 0.00 μg/m^3 profenofos and 0.0988 ± 0.00 μg/m^3 glyphosate. Also, 0.1285 ± 0.00,

Table 1: Heavy metals and their maximum permissible limits with regulator references

Parameter	Cassava	Yam	Cocoyam	Potato	Water yam	Carrot	MPL	MPL reference
Nickel (mg/kg)	0.012 ± 0.00^A	0.006 ± 0.00^A	0.009 ± 0.00^A	0.006 ± 0.00^A	0.007 ± 0.00^A	0.001 ± 0.00^A	0.10 mg/kg^B	US Environmental Protection Agency[28], Wani et al.[29]
Chromium (mg/kg)	0.083 ± 0.00^A	0.010 ± 0.00^A	0.093 ± 0.00^A	0.073 ± 0.00^A	0.078 ± 0.00^A	0.016 ± 0.00^A	0.10 mg/kg^B	US Environmental Protection Agency[28], Food and Agriculture Organization / World Health Organization[30]
Cobalt (mg/kg)	0.011 ± 0.00^A	0.036 ± 0.00^B	0.026 ± 0.00^A	0.002 ± 0.00^A	0.016 ± 0.00^A	0.010 ± 0.00^A	0.043 mg/kg^B	Institute of Medicine (US) Panel on Micronutrients[31]
Arsenic (mg/kg)	0.045 ± 0.00^A	0.010 ± 0.00^A	0.049 ± 0.00^A	0.056 ± 0.00^A	0.037 ± 0.00^A	0.019 ± 0.00^A	1.4 mg/kg^B	Food and Agriculture Organization / World Health Organization[30], Institute of Medicine (US) Panel on Micronutrients[31]
Manganese (mg/kg)	0.138 ± 0.00^A	0.571 ± 0.00^A	0.172 ± 0.00^A	0.750 ± 0.09^A	0.838 ± 0.11^A	0.516 ± 0.10^A	2.0 mg/kg^B	Onianwa et al.[19], US Environmental Protection Agency[28]
Cadmium (mg/kg)	0.00 ± 0.00^A	0.00 ± 0.00^A	0.00 ± 0.00^A	0.00 ± 0.00^A	0.00 ± 0.00^A	0.00 ± 0.00^A	0.3 mg/kg^B	Food and Agriculture Organization / World Health Organization[30], Institute of Medicine (US) Panel on Micronutrients[31]
Lead (mg/kg)	0.00 ± 0.00^A	0.00 ± 0.00^A	0.00 ± 0.00^A	0.032 ± 0.00^A	0.00 ± 0.00^A	0.028 ± 0.00^A	1.0 mg/kg^A	Food and Agriculture Organization / World Health Organization[30], Institute of Medicine (US) Panel on Micronutrients[31]
Mercury (mg/kg)	0.00 ± 0.00^A	0.00 ± 0.00^A	0.658 ± 0.02^B	0.153 ± 0.00^A	0.00 ± 0.00^A	0.404 ± 0.00^A	0.5 mg/kg^B	US Environmental Protection Agency[28], Institute of Medicine (US) Panel on Micronutrients[31]

The values were triplicate determinations. Values with various superscripts (uppercase [A–D]) are statistically significant ($p < 0.05$) in comparison to the uppermost allowable limits; mean standard error (SE).

Table 2: Pesticide residue concentration (μg/m³) in cassava, yam, cocoyam, potato, water yam and carrot

Parameter	Cassava	Yam	Cocoyam	Potato	Water yam	Carrot	Maximum permissible limit (MPL)	MPL reference
2,4-dichlorophenoxy acetic acid (μg/m³)	0.0431 ± 0.00	0.1285 ± 0.00	0.1127 ± 0.00	BDL	0.0527 ± 0.00	0.0957 ± 0.00		
HCB (μg/m³)	0.1596 ± 0.00	0.0799 ± 0.06	0.1018 ± 0.09	0.1415 ± 0.00	0.0000 ± 0.00	BDL	0.002 mg/m³	Opaluwa et al.[32]
Aldrin (μg/m³)	0.0617 ± 0.00	0.0004 ± 0.00	0.0779 ± 0.00	0.1161 ± 0.00	0.0580 ± 0.00	0.0711 ± 0.00	0.25 mg/m³	Zamora[33]
p'p-DDD (μg/m³)	0.1693 ± 0.00	0.0732 ± 0.00	BDL	BDL	0.0002 ± 0.00	0.1603 ± 0.00		
Profenofos (μg/m³)	0.1476 ± 0.00	0.0000 ± 0.00	0.2138 ± 0.05	0.0817 ± 0.00	BDL	0.0011 ± 0.00	0.25 mg/m³	FAO/WHO[34]
Glyphosate (μg/m³)	0.0988 ± 0.00	0.1098 ± 0.00	0.1876 ± 0.00	0.3130 ± 0.06	BDL	0.1039 ± 0.09		
Dichlorovos (DDVP) (μg/m³)	0.5208 ± 0.00	0.1334 ± 0.04	0.0683 ± 0.00	0.3635 ± 0.05	0.0562 ± 0.00	0.3632 ± 0.06	1.0 mg/m³	International Food Standards/Codex Alimentarius FAO/WHO[35]
Endosulfan (μg/m³)	BDL	BDL	0.2500 ± 0.01	0.3265 ± 0.08	BDL	BDL	0.10 mg/m³	FAO/WHO[34]
Lindane (μg/m³)	BDL	BDL	0.0914 ± 0.01	BDL	BDL	0.0015 ± 0.07	0.50 mg/m³	FAO/WHO[34]
g-chlordane (μg/m³)	BDL	BDL	0.000 ± 0.00	0.0000 ± 0.00	BDL	BDL	0.0020 mg/L	International Food Standards/Codex Alimentarius FAO/WHO[36]
Biphenyl (μg/m³)	BDL	BDL	0.9228 ± 0.20	0.7418 ± 0.00	0.2472 ± 0.00	1.1842 ± 0.44	1.30 mg/m³	FAO/WHO[34]
t-Nonachlor (μg/m³)	BDL	BDL	0.1084 ± 0.06	0.0000 ± 0.00	BDL	BDL	0.040 mg/m³	International Programme on Chemical Safety (IPCS)[37]
Dichlorobiphenyl (μg/m³)	BDL	BDL	BDL	0.1653 ± 0.02	BDL	BDL	0.10 mg/m³	Singh[38]
Carbofuran (μg/m³)	BDL	BDL	BDL	0.2688 ± 0.08	0.1256 ± 0.05	BDL	NA	
Heptachlor (μg/m³)	BDL	BDL	BDL	BDL	BDL	0.0867 ± 0.00	0.050 mg/m³	FAO/WHO[34]

BDL, below detectable limit

0.799 ± 0.00, 0.0732 ± 0.00, 0.0000 ± 0.00 and 0.1098 ± 0.00 μg/m³ were the concentrations of 2,4-dichlorophenoxyacetic acid, HCB, p'p'-DDD, profenofos and glyphosate detected in yam, as shown in Table 2. For potato, 2,4-dichloro and p'p'-DDD were not detected, HCB (0.1415 ± 0.00 μg/m³), profenofos (0.3130 ± 0.00 μg/m³), glyphosate (0.3130 ± 0.00 μg/m³), endosulfan (0.3265 ± 0.08 μg/m³), biphenyl (0.7418 ± 0.00 μg/m³) and dichlorobiphenyl (0.1653 ± 0.02 μg/m³) were detected. Lindane, g-chlordane, t-Nonachlor, carbofuran and heptachlor were also not detected in the sample, as shown in Table 2. Subsequently, 2,4-dichlorophenoxyacetic acid, HCB, p' p'-DDD, profenofos and glyphosate were detected in water yam as 0.0527 ± 0.00, 0.0000 ± 0.00, 0.0002 ± 0.00, 0.0000 ± 0.00 and 0.0000 ± 0.00 μg/m³, respectively. Biphenyl and carbofuran concentrations were 0.2472 ± 0.00 and 0.1256 ± 0.05 μg/m³, respectively. Some pesticide residues found in potatoes include 2,4-dichloro (0.0957 ± 0.00 μg/m³), HCB (0.0000 ± 0.00 μg/m³), p'p'-DDD (0.1603 ± 0.00 μg/m³), profenofos (0.0011 ± 0.00 μg/m³), glyphosate (0.1039 ± 0.00 μg/m³), lindane (0.0015 ± 0.00 μg/m³), biphenyl (1.1842 ± 0.00 μg/m³) and heptachlor (0.0867 ± 0.00 μg/m³). The chemical abstract service (CAS) numbers of some of the pesticide residues tested are listed in Supplementary table 1.

Discussion

Currently, due to the advances in crop production and cultivated food crops, there is an increase in the pollution of heavy metals and chemical residues. Thus, there is a need for continuous evaluation of their presence and concentration to aid in mitigating or preventing any public health issues that could occur as a result.

Several heavy metals, including nickel, lead, cobalt, arsenic, manganese, chromium, cadmium and mercury, were detected in the six samples (cassava, yam, cocoyam, potato, water yam and carrot) using atomic absorption spectroscopy and efficient techniques. The levels of Co in yam did not differ significantly from one another (0.036 ± 0.00 mg/kg) and from the MPL (0.043 mg/kg) established by the US Food and Nutrition Board (2004).

Although Ni was present at varying concentrations in the samples, its concentration was below the MPLs (100 μg/L) as stipulated by the US Environmental Protection Agency and, thus, may not pose any serious health challenges to consumers, such as skin allergies and lung cancer, which are signs of Ni toxicity manifestation. A higher concentration of Ni residue (0.93–0.179 mg/kg) in tubers has been reported by Onianwa et al.[19]. Ni occurs naturally as part of different mineral complexes, with its deficiency in the human system causing retardation of intra-uterine development and reduced iron reabsorption.[20] The highest Co intake in humans occurs through diet. Co has been detected in okra, as reported by Orisakwe et al.[21]

One of the major sources of As in the environment is arsenic-rich fertilisers[36], which are released when applied. Previous researchers have shown high heavy metal accumulation in leafy vegetables.[31] The MPL for Cd is 0.3 mg/kg as set by the FAO/WHO (2006). It has been detected in different food materials such as cassava, yam[15] and cereals. Onianwa

Table 3: The maximum permissible exposure limits (MPLs) of all the pesticide residues based on the US and Canadian country databases

Component	Minimum permissible limits	Institutional body	Reference
Dichlorobiphenyl (also considered among 'polychlorinated biphenyls')	0.1 mg/m^3	US Department of Health and Human Services (DHHS), US National Institute for Occupational Safety and Health	Centers for Disease Control and Prevention[39]
HCB (hexachlorobenzene)	0.002 mg/m^3	United States OSHA PEL	US Department of Labour[40]
Endosulfan	0.1 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
Aldrin	0.25 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
Profenofos	0.25 mg/m^3	US National Institute for Occupational Safety and Health	The National Institute for Occupational Safety and Health (NIOSH)[42]
DDT	0.5 mg/m^3	New Jersey Department of Health and Senior Services	New Jersey Department of Health and Senior Services[43]
Lindane	0.5 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
g-Chlordane	0.5 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
	0.002 mg/L	U.S. Environmental Protection Agency	US Environmental Protection Agency[44]
Dichlorvos (DDVP)	1 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
Heptachlor	0.05 mg/m^3	California Department of Industrial Relations	Permissible Exposure Limits for Chemical Contaminants[41]
t-Nonachlor	0.04 mg/kg	Canadian Health Measures Survey	Canadian Health Measures Survey[45]

et al.[19] reported Cd concentrations of 0.03–0.28 mg/kg in tubers. Also, Commission Regulation (EC) No 1881/2006[46] reported the presence of Cd in rice. Due to its slow excretory rate, high Cd levels threaten human health and could damage the kidneys and liver.[46]

Pb is made available to the environment through lead-containing pipes, combustion of leaded gasoline and the use of lead-based paint.[30] Lead is known to affect the cardiovascular, nervous, skeletal, muscular and immune systems, and causes gastrointestinal symptoms and organ damage when ingested or from prolonged exposure.[30] The maximum exposure permissible limits of some pesticide residues established by international regulators are shown in Table 3.

The concentration of HCB was greater than the MPL (0.002 mg/m^3) reported by OSHA, the US government's workplace safety and health authority. The concentrations of aldrin and profenofos were below the MPL, as reported by FAO/WHO. The pesticide residual amounts in the tests were lower than the permitted exposure level specified by international organisations such as WHO/FAO, the US Environmental Protection Agency and CDIR. However, care should be taken when consuming these food tubers, as prolonged consumption could lead to their bioaccumulation in the body of organisms.

A similar study by Lien et al.[47] reported high concentrations of organochlorine residues in yam. Some pesticide residues are highly persistent in the environment.[47] Oyinloye et al.[48] also detected different concentrations of aldrin, carbofuran, endosulfan and profenofos in *T. occidentalis*. There are many risks associated with pesticide residue exposure, including effects on human health; thus, concentrations of these residues in food samples should be monitored regularly.

Increased d-glutaric acid metabolism and allergic reactions/skin rashes have both been linked to aldrin and lindane.[15] Aldrin, heptachlor, endosulfan and dieldrin were some of the pesticide residues that were detected by Njoku et al.[49] Jayaraj et al.[50] reported some adverse effects of aldrin, heptachlor and lindane, including neurotoxic effects. This could be why the Nigerian government prohibits their use.

Conclusions

Using AAS and GC–MS, we assessed the levels of heavy metals and pesticide residues in regularly grown tuber crops in Nigeria. In all the samples, 13 different pesticide residues were found. In every sample examined, the Cd concentration was below the threshold for detection.

Similarly, Pb and Hg were below the detectable concentration in cassava, yam and cocoyam. Other heavy metals present were lower than the MPLs established by standard organisations. Aldrin and dichlorvos (DDVP) were present in all the samples, with cassava having the highest concentration. Almost all the pesticide residues were detected in cocoyam, potato and carrot. Thus, there should be continuous monitoring of these staple foods to ensure their consumption does not predispose the consumer to heavy metal toxicities, as continuous consumption could potentially threaten people's health.

Competing interests

We have no competing interests to declare.

Authors' contributions

K.O.O.: Conceptualisation and resources, project administration, writing – original draft, supervision. B.O.E.: Formal analysis, investigation, writing – revision and editing, data curation. S.O.O.: Conceptualisation and resources, supervision, writing – revision and editing, validation. All the authors read and approved the final version of the manuscript.

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We the hunted

Classic depictions of human evolutionary ecology cast *Homo* as predator and other hominins, including *Paranthropus robustus*, as prey. Such hypotheses rest on a small number of fossils that exhibit evidence of carnivore predation, including the iconic SK 54 cranium from Swartkrans in South Africa. Here we demonstrate that the SK 54 cranium shares its closest affinities with *H. erectus* sensu lato rather than *P. robustus.* Demonstrating that *Homo* was prey for leopards at Swartkrans weakens the historically significant hypothesis that *Homo* was better able to avoid predation because of being behaviourally and technologically advanced compared to *Paranthropus*. Subsequent ideas about hominin palaeobiology derived from this hypothesis warrant reconsideration.

Significance:

- The small sample of early *Homo* from southern Africa is increased by the allocation of the SK 54 cranium to that genus.
- Evidence from Swartkrans suggests that *Homo* was prey for leopards.
- Hypotheses concerning the biology, behaviour, and technological capabilities of *Homo* and *P. robustus* stemming from Brain's seminal work, *The Hunters or the Hunted?*, should be reassessed.

Introduction

SK 54 is a partial hominin cranium that was recovered from the ~1.9–1.8 Ma palaeocave deposits of Swartkrans Member 1 Hanging Remnant in South Africa in 1949 and subsequently prepared by John T. Robinson.[1-3] This specimen is an iconic hominin fossil that has influenced both the development of the discipline of cave taphonomy and narratives concerning how multiple hominin species shared the landscape of Pleistocene southern Africa.[1] Brain[1,2] described two carnivore puncture marks on its left and right parietal bones (Figure 1) whose location, size, and spacing indicate strongly that they were inflicted by a leopard (famously, the marks conform well to the canines of leopard fossil SK 349 from the same deposit).[4] Leopards are known to be predators rather than scavengers[1,5], and thus this specimen preserves direct evidence of the predation of hominins. Even if future taphonomic analyses conclude that these puncture marks were not caused by a predator, the historical significance of Brain's[4] assessment remains. For this reason, although there are other hominin fossils from Swartkrans that exhibit carnivore modification marks[1,2,6,7], no other specimen has figured as centrally in hypotheses concerning carnivore predation on hominins than SK 54[1,2,6,8-17]. The specimen has previously been attributed to *Paranthropus robustus*[1], and that taxonomy has remained largely unchallenged and current[18-21]. Brain[1] did not explain the reasoning underlying this taxonomic decision, although he did note that the specimen appeared to possess a relatively small brain. Tobias[22] and Clarke[23] noted that SK 54 lacked certain derived circumorbital morphology characteristic of *P. robustus,* but did not assign the specimen to a different species and interpreted the variation as a product of ontogeny. We do, however, note that Braga et al.[24] have recently questioned SK 54's attribution to *P. robustus* based on differences between its circumorbital and postorbital morphology and that of the juvenile *P. robustus* specimen KW 9000/9600 from Kromdraai, and we largely agree with their conclusions. Notwithstanding this recent reassessment, SK 54's attribution to *P. robustus* has underwritten hypotheses that australopiths were prey while early *Homo* were transforming into predators, as elucidated in Brain's[2] classic monograph, *The Hunters or The Hunted?* Here we provide further taxonomic evidence that challenges this narrative.

Materials and methods

Our analysis of SK 54 results principally from morphological observations conducted in South Africa in 2018, 2019 and 2022 on original fossil specimens of *Australopithecus africanus* (Taung 1; Sts 5, Sts 71, Stw 505), *A. sediba* (MH 1), *P. robustus* (DNH 7, DNH 155, DNH 152, SK 46, SK 48 and SK 52) and early *Homo* (Stw 53, SK 847) curated at the Evolutionary Studies Institute of the University of the Witwatersrand, and the Ditsong Museum of Natural History. Because SK 54 is a subadult, we closely compared SK 54 to available subadult specimens of *H. erectus* sensu lato (DNH 134) and a description of *P. robustus* (KW 9000/9600) from southern Africa. We additionally utilised published descriptions and/or casts of subadult specimens attributed to *H. erectus* (Mojokerto 1 and KNM-ER 42700) and *P. aethiopicus* (L338y-6).

Results

SK 54 is a fragmentary neurocranium preserving parts of the occipital, frontal, and left and right parietal bones. The degree of sutural fusion suggests that the specimen may have been a juvenile at the time of death. The specimen is plasticly deformed such that it is not possible to assess overall neurocranial shape, and this deformation precludes meaningful quantitative analysis. One measurement that can be confidently taken on the specimen is cranial vault thickness, which we assess as being minimally 3.3 mm at the posterior aspect of the parietal bone just above the squamosal suture. This measurement compares favourably to that of the subadult *H. erectus* specimen DNH 134 (3.2 mm) and is thinner than that of the subadult *P. robustus* specimen KW 9000 / 9600 at 4.0 mm.[24] Although *H. erectus* specimens are often characterised as having thick vaults, this characteristic is more strongly expressed in Asian rather than early African specimens[25] and in any case the taxonomic valence of this trait is compromised by SK 54's likely young ontogenetic age (see also Antón[26]). Notably, vault thickness in the vicinity of bregma is qualitatively thin in Modjokerto[27], a juvenile specimen conventionally attributed to *H. erectus*[26]. SK 54's

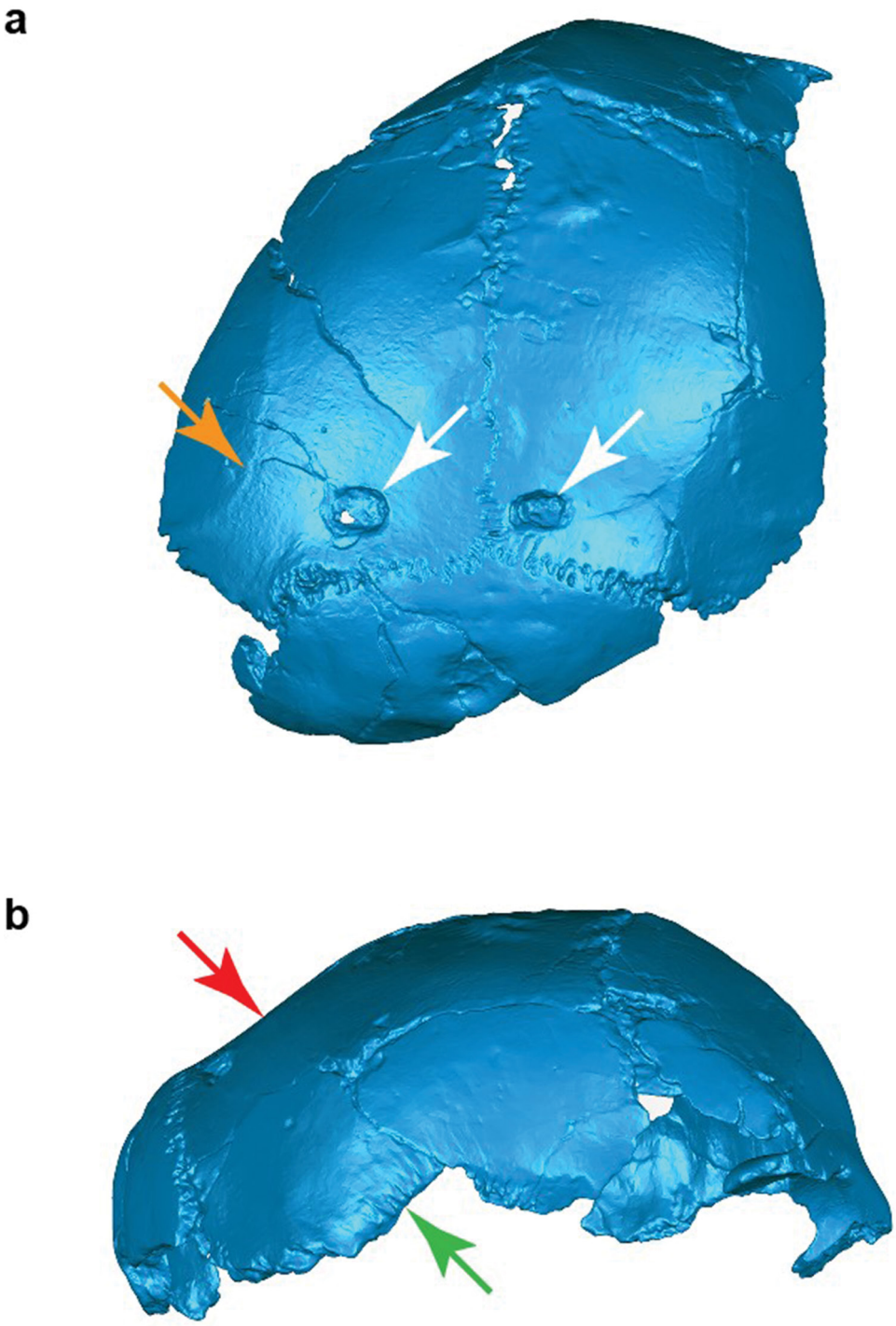

Figure 1: Three-dimensional surface scans of SK 54 shown in (a) superoposterior and (b) lateral views. White arrows indicate puncture marks. Orange arrow indicates the left superior temporal line positioned laterally far from the sagittal suture. Red arrow indicates likely pre-lambdoidal flattening. Green arrow indicates the posterior aspect of the parietal portion of the squamosal suture that is straight and shows minimal overlap with the temporal bone.

neurocranial vault is distorted on both the right and left sides, making a digital reconstruction highly subjective and of little diagnostic value. The individual evidently had a generally small brain, but estimates of its cranial capacity cannot be made with confidence.[28] Nonetheless, aspects of preserved morphology challenge its traditional taxonomic attribution to *Paranthropus* and suggest affinities with *Homo.* The temporal lines are well separated and laterally positioned (Figure 1) – a configuration that is incompatible with adult *P. robustus* specimens that exhibit either a sagittal crest (in putative male specimens) or nearly convergent temporal lines (in female specimens).[29] The KW 9000/9600 fossil from Kromdraai provides the only evidence for temporal line configuration in a subadult *P. robustus*, and the superior temporal line is clearly closer to midline in the vicinity of bregma[24] than the weakly expressed and more laterally positioned temporal lines exhibited by SK 54. Similarly, the juvenile *P. aethiopicus* specimen L338y-6 (whose sutures are as or more open than those of SK 54, implying a coarse similarity in age) exhibits well-developed, strongly convergent temporal lines[30], further suggesting that SK 54 may not be *Paranthropus.* Kimbel et al.[20] have previously argued that SK 54 preserves rugose *striae parietalis* that they suggest are correlated with a high degree of overlap between the temporal squama and parietal at the squamosal suture. They based their inference on the observation by Rak[31] that juvenile *H. sapiens* from a Holocene population

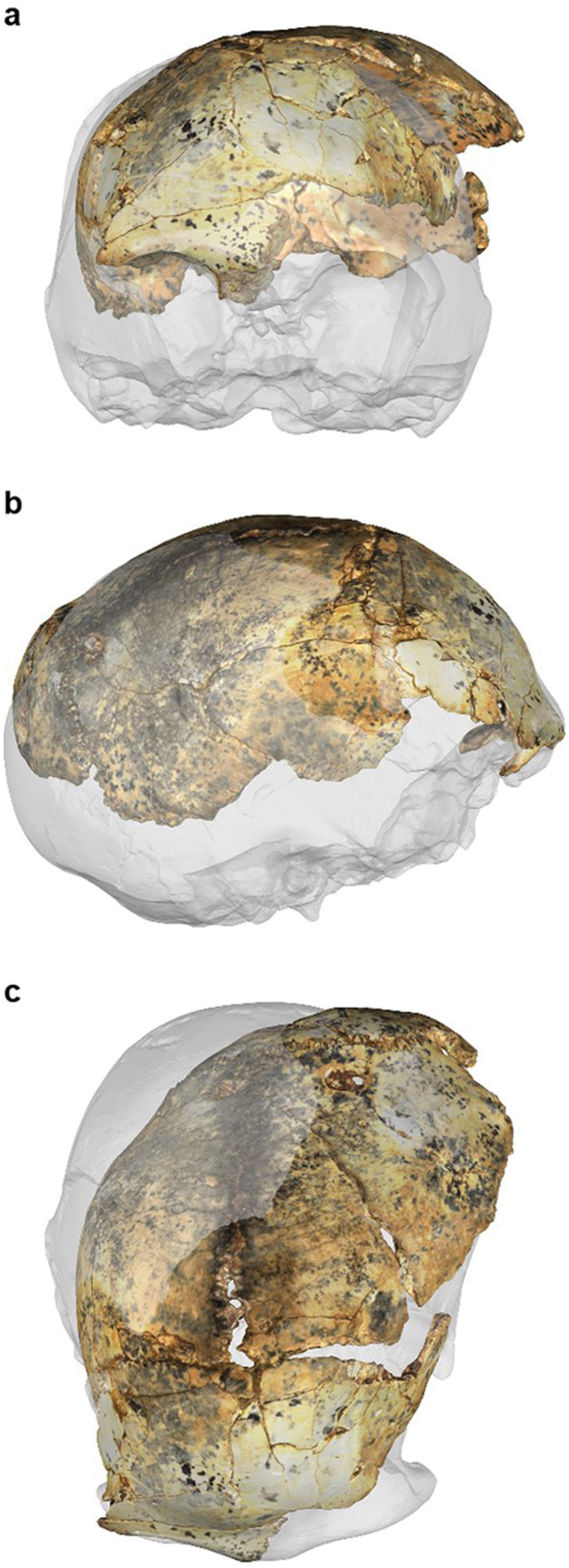

Figure 2: Superimposition of a three dimensional surface scan of SK 54 onto a cast of KNM-ER 42700 (transparent, scaled to 90% of its size) in (a) frontal, (b) right lateral, and (c) superior views. The specimens are aligned at their right orbital margins and circumorbital regions, which are the least distorted portions of SK 54.

exhibited fine rather than rugose striae. However, the length of the *striae parietalis* preserved in SK 54 (Figure 1) are notably less than those of L338y-6 and adult *P. robustus* specimens DNH7, DNH152, and DNH155, and both the length and rugosity of SK 54's striae closely resemble the condition in the juvenile *H. erectus* sensu lato specimen DNH 134. In our assessment, enough of the inferior bevelled edge of the right parietal (Figure 1) is preserved to indicate that the temporal and parietal portions of the squamosal suture would not have overlapped extensively, unlike the extensive overlap seen in both adult and juvenile *Paranthropus*.[30-32] Finally, *contra* Kimbel et al.[20], the very wide separation of the superior temporal lines on the frontal bone argues against the inference that a frontal trigon would have developed in adulthood.

Two discrete traits of SK 54 may suggest affinities with *Homo erectus* sensu lato. The preserved posterior portion of the squamosal suture is straight as it rises anteriorly and superiorly (Figure 1). Rightmire et al.[33] note that, "A low temporal squama with a straight upper border passing downward toward asterion is a consistent marker for [H. erectus]." Moreover, SK 54's parietal bones are flattened anterior to the lambdoidal suture (Figure 1), although there is distortion present in this region. Pre-lambdoidal flattening is a derived characteristic of many *H. erectus* specimens; in their description of the skulls from Dmanisi, Rightmire et al.[33] state that:

> *There are also good indications that the Dmanisi skulls share at least a few (specialized?) characters with populations from the Far East. An example is provided by parasagittal flattening of the posterior vault. Flattening or even depression of the parietal surfaces is pronounced at Dmanisi, and it is common in the [H.] erectus crania from Sangiran in Java.*

The fragmentary and deformed nature of SK 54 precludes a definitive taxonomic allocation but, heuristically, superimposing SK 54 onto *H. erectus* sensu lato specimen KNM-ER 42700[34] demonstrates a striking similarity between the two specimens (Figure 2). We agree with Braga et al.[24] that a provisional assignment of SK 54 to *Homo* seems warranted, and we argue that a tentative species-level allocation to *H. erectus* sensu lato is plausible. This assignment adds to the evidence for *Homo* at Swartkrans Member 1 Hanging Remnant that includes the juvenile cranium SK 27 that Clarke[35] reclassified from *P. robustus* to *Homo*, and the suggested partial skull consisting of individual fossils SK 80, SK 846b, SK 847[36] and sometimes also the mandible fragment SK 45[2] . At 1.9–1.8 Ma[3], these fossils are slightly younger than the 2.04–1.95 Ma DNH 134 cranium from Drimolen Main Quarry that also shows affinities to *Homo erectus*[32].

Discussion

Brain's work on cave taphonomy remains seminal, and his taphonomic assessment linking SK 54 with leopard predation is currently unchallenged. Assuming that those taphonomic conclusions remain valid, our taxonomic reassessment of SK 54 demonstrates that *Homo* was also prey for leopards in the early Pleistocene, and this characterisation could not be further removed from classic depictions of *Homo* the hunter and *Paranthropus* the hunted. Allocating SK 54 to *Homo* tempers the impetus for supposing that early *Homo* and *P. robustus* were differentially predated because of the former's behavioural and technological advancement.

It is impossible to know with certainty how the history of palaeoanthropology might have been different had SK 54 been recognised as *Homo w*hen it was first discovered, but it is reasonable to infer that the impact of such a realisation would have been significant. Only 6 years prior to the publication of Brain's[1] now-classic paper, the description of the newly discovered *H. habilis*[36] included an assessment of the relative tool-making skills and trophic positions of the new species and its contemporary, *Zinjanthropus boisei* (i.e. *P. boisei*):

> *While it is possible that Zinjanthropus and Homo habilis both made stone tools, it is probable that the latter was the more advanced tool maker and that the Zinjanthropus skull represents an intruder (or a victim) on a Homo habilis living site.*[37]

Shortly thereafter, the highly influential *Man the Hunter* conference was held, followed by the publication of its accompanying edited volume[38,39] that described hunting as a fundamentally important human adaptation. Brain's[2,3] interpretation of SK 54, based on an incorrect taxonomy, was therefore compatible with the thinking of the time, but it could have instead been a powerful challenge to conventional wisdom. Ideas, like species, evolve and have descendants, so the evidence presented here should prompt a reassessment of hypotheses concerning the biology, behaviour, and technological capabilities of *Homo* and *Paranthropus* that are derived from earlier ideas positing *Homo* as predator and *Paranthropus* as prey (for example, Lockwood et al.[29]). Our findings complement a recent zooarchaeological analysis showing that the appearance of *H. erectus* is not associated with increased evidence for hominin carnivory.[38]

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Competing interests

We have no competing interests to declare.

Authors' contributions

J.M.M., A.B.L., A.I.R.H., S.E.B., and D.S.S. wrote the paper. J.M.M. and D.S.S. additionally participated in conceptualisation, data collection, sample analysis, and data analysis.

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