An assessment of critical carbon services and water resources in South Africa's terrestrial protected area network

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List of abbreviations

CBD	Convention on Biological Diversity
DEA	Department of Environmental Affairs
DEFF	Department of Environment, Forestry and Fisheries
EbA	Ecosystem-based Adaptation
EbM	Ecosystem-based Mitigation
Eco-DRR	Eco-Disaster Risk Reduction
GDP	Gross Domestic Product
GGDP	Global Gross Domestic Product
GW	Ground Water
IAP	Invasive Alien Plant
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
MARS	Multivariate Adaptive Regression Splines
NbS	Nature-based Solutions
PA	Protected Area
SANBI	South African National Biodiversity Institute
SANLC	South African National Land-Cover
SANParks	South African National Parks
SAPAD	South African Protected Area Database
SDG	Sustainable Development Goals
STOCA	Strategic Total Organic Carbon Area
SW	Surface Water
SWSA	Strategic Water Source Area
TBOC	Total Biomass Organic Carbon
TOC	Total Organic Carbon
TSOC	Total Soil Organic Carbon
UN	United Nations
UNEP	United Nations Environmental Programme – World Conservation Monitoring Centre
WDPA	World Database of Protected Areas
WEF	World Economic Forum
WfW	Working for Water

Abstract

Conservation planning can more greatly emphasise the importance of considering ecosystem services alongside biodiversity features to improve the planet's climate change resilience. Protected Areas (PAs) are a form of area-based conservation that successfully protects biodiversity and may conserve ecosystem services important for societal climate change resilience. This study assesses the performance of South Africa's protected area network in protecting strategic carbon and water services, which are important for climate change resilience. My first question investigated how well the country's PAs perform regarding the area coverage of carbon stocks and Strategic Water Source Areas (SWSA). My second question investigated whether the country's PAs have effectively protected the carbon stocks inside their borders. I hypothesised that the carbon stock values would be higher in PAs, given that PAs have successfully prevented the loss of natural land cover inside their borders. I also compared the effectiveness of PAs in protecting carbon stocks in terms of their management authority, province and land cover classes.

I used existing datasets of PAs, environmental variables, SWSAs and carbon stocks for this study. Using the total organic carbon (TOC) and South Africa's Natural Land Cover, I calculated natural Strategic Total Organic Carbon Areas (STOCA). Then I used the STOCAs and SWSAs to assess the PA coverage of these two strategic ecosystem service areas and their overlapping areas. For the second question, I investigated the carbon stock values inside and outside PAs while controlling for environmental variables. I also investigated the effect of natural land cover, provincial designations and management authorities. Results indicate that South Africa's PAs cover 9.8% of the country's mainland but protect 14.8% of SWSAs, 21.7% of STOCAs and 28.5% of the SWSA & STOCA areas. The PAs have greater TOC, Total Soil Organic Carbon (TSOC) and Total Biomass Organic Carbon (TBOC) values inside their borders than outside. Natural areas inside PAs are higher in TOC, TSOC and TBOC values than outside natural or transformed areas.

These results provide evidence that South Africa's PAs are effectively protecting their carbon stocks. Therefore, there is evidence that PAs are important for climate change mitigation and may be important for Nature-based Solutions (NbS) in increasing climate change resilience. Eastern Cape, KwaZulu-Natal, Limpopo, and Western Cape PAs should be studied to improve other PAs' management. Although the PA network is strategically placed to protect

the country's ecosystem service areas, the extent of this protection is short of international PA targets. There are many more strategic ecosystem service areas available for protection. Considering the effectiveness of Eastern Cape and KwaZulu-Natal PAs and the availability of strategic ecosystem service areas for protection, policy-makers and conservation managers should consider these provinces for PA expansion. Limpopo should also be considered for PA expansion, given the high carbon stock values outside PAs. This study shows the importance of South Africa's protected area network for climate change resilience and provides information on where its necessary expansion can best be planned for. It also offers a potential set of metrics and targets for monitoring in the future.

Introduction

Global awareness of the links between nature and society and the grave consequences of its disruption is growing (Crutzen & Stoermer 2000; Millennium Ecosystem Assessment 2005; Rockström et al. 2009; Díaz et al. 2018; WEF 2020; WWF 2020). Climate change is projected to become the most severe driver of global change in the coming decades, with temperature increases and extreme rainfall events being key disrupters (IPCC 2018). The global economy is underpinned by nature, and society has become aware that investments in conservation and climate change action are strategically important (Dasgupta 2020). Furthermore, given various socio-economic challenges (i.e., limited water availability) and drivers of environmental damage, we need strategies that have multiple simultaneous benefits (Cohen-Stacham et al. 2016; Liu et al. 2018; WWF 2020).

One such strategy is the use of Nature-based Solutions (NbS), which can benefit both human well-being and biodiversity through the restoration, protection, and sustainable management of ecosystems (Cohen-Stacham et al. 2016). In so doing, it can address some of the societal problems resulting from climate change. Out of the range of approaches used to protect nature, area-based conservation via protected areas (PAs) has been largely successful in protecting species and biodiversity features (Coetzee et al. 2014; Watson et al. 2014). However, while PAs safeguard broader biodiversity features, they are limited in their extent and representation of specific ecosystems or their services.

With informed management and increased coverage, PAs may adequately represent biodiversity and ecosystem services and foster increased climate change resilience (Griscom et al. 2017; IPBES 2019). Remote sensing and associated technologies have enabled the identification and analysis of broad patterns across landscapes, allowing assessment of PA effectiveness for protecting these ecosystem services. This study assessed the area coverage of two ecosystem services essential for climate change resilience, carbon storage and water provision, across South Africa's protected area network. It also assessed the effectiveness of the protected area network in protecting the country's carbon storage.

1.1. Global change and changing climates

Humans have had a large impact on nature's integrity through the many unsustainable actions we have taken to support the demand for resources from a growing human population and the developing global economy (Crutzen & Stoermer 2000; Crutzen 2002; IPBES 2019; WWF 2020). These direct drivers of biodiversity loss include habitat loss and degradation (mainly from agricultural practices including animal husbandry and cropping), climate change, pollution, invasive species, and the overexploitation of species (Salafsky et al. 2008; IPBES 2019). The WWF Living Planet Report (WWF 2020) shows that between 1970 and 2016, there has been a 68% decline in the population sizes of 4,392 mammal, bird, fish, reptile, and amphibian species across the world. With one million species threatened with extinction, our actions may lead to a future mass extinction event (Ceballos et al. 2015; WWF 2020).

Climate change affects all species and ecosystems across terrestrial, freshwater and marine realms (Scheffers et al. 2016; IPBES 2019; IPCC 2019). Increases in greenhouse gases (e.g. 415 ppm CO_2 in 2021 versus 280 pre-industrial revolution) have altered atmospheric functionionality, which has resulted in changes in the climate, such as increases in average global temperature, the intensification of the global water cycle and the increased frequency of extreme weather events (IPCC 2019). Consequently, biodiversity is at a heightened extinction risk, with 7.9% of species predicted to join the Bramble Cay melomys (*Melomys rubicola*), the first mammal to become extinct due to climate change (Urban 2015; Fulton 2017).

Should society follow the RCP 8.5 (or business-as-usual) trajectory, climate change may threaten one-sixth of the Earth’s species (16%) with extinction. Impacts on different environments, and the multitude of species or individuals within them, will further affect all levels of the biological hierarchy (Noss 1990; King 2009). Consequently, impacts on individuals or populations of a species will be translated into gene-specific or community-wide impacts, such as the loss of genetic diversity or disruption of ecosystem functions across entire habitats (Scheffers et al. 2016; IPBES 2019).

1.2. Ecosystem services or Nature's contribution to people

Global society is supported by the countless contributions of the Earth's ecosystems (Millennium Ecosystem Assessment 2005; Díaz et al. 2018; WWF 2020). These contributions are termed nature's contributions to people or ecosystem services. These may be material contributions such as fish caught from a river or nonmaterial contributions such as the experience of walking through a forest. A third category includes regulating contributions, which are the modifications or regulation of environmental conditions by functional and well-structured, biodiverse ecosystems, such as carbon dioxide sequestration from the atmosphere by plants.

These contributions physically sustain life on Earth and have formed the basis of our global economy (Díaz et al. 2018; Dasgupta 2020). Between 1970 and 2016, the global gross domestic product (GGDP) quadrupled due to the use of the planet's resources and nature's material contributions (WWF 2020). During this period, the extraction of living materials tripled, and the global stock of natural capital decreased by 40%. Presently, society is exceeding the Earth's ecosystems' ability to regenerate by 56%. In 2011, tt was estimated that, at the global scale, ecosystem services (not just material contributions) were worth $125 trillion/year (Costanza et al. 2014). Our economy is bounded by nature (Rockström et al. 2009), meaning we are putting society at risk by degrading our ecosystems and jeopardising ecosystem services (Dasgupta 2020).

It is not just ethical to address global change threats, but it is also a strategic investment to protect nature's diverse contributions for improved human well-being (Costanza et al. 2014; Díaz et al. 2018; IPBES 2019; Dasgupta 2020; WWF 2020). Calls on governments for action have resulted in policies such as the Aichi Biodiversity targets and Sustainable Development Goals to address environmental and societal issues (CBD 2011; UN 2015). The 17 SDGs call for socio-economic development *and* enhanced environmental protection across countries by 2030. In 2020, the World Economic Forum (WEF) listed environmental threats (extreme weather, climate action failure, biodiversity loss, natural disasters, and other human-made disasters) as the top risks to the global economy (WEF 2020). Using integrated strategies, we can address multiple threats (e.g., climate change and biodiversity loss) and multiple SDGs (or economic goals) simultaneously (Liu et al. 2018; IPBES 2019; Leclère et al. 2020; Secretariat of the Convention on Biological Diversity 2020).

1.3. An integrated strategy using Nature-based Solutions

Confronting the planet's threats will require using an integrative approach and evidence-based strategies to systematically address multiple problems simultaneously rather than individually (Gillson et al. 2013; Cohen-Stacham et al. 2016; Liu et al. 2018). For example, Leclère et al. (2020) have shown that preventing the loss of biodiversity (from predominantly habitat use and degradation) may only be possible through an "integrated action portfolio" where increased conservation, sustainable production and sustainable consumption are interventions that are implemented together. Furthermore, society should not promote a solution when it exacerbates another problem, such as planting forests for climate change mitigation in place of naturally occurring vegetation (Bond 2016). No single action, such as a change to the supply of resources on increased conservation action, will, onitsown, solve the societal issues we are facing (Secretariat of the Convention on Biological Diversity 2020). While we target these indirect drivers of loss through adjustments to how we produce, consume and trade, we also need to target the direct drivers and threats in combination with increased conservation action (Secretariat of the Convention on Biological Diversity 2020).

Nature-based Solutions (NbS) provide an integrated strategy that considers the SDGs and is primarily for the benefit of people but can also address conservation concerns (Cohen-Stacham et al. 2016; Griscom et al. 2017). NbS reflects an umbrella concept that arose in the late 2000s as a product of ecosystem service thinking. The NbS concept is promoted by the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005; Cohen-Stacham et al. 2016) and incorporates strategic actions that address societal challenges, such as climate change. These are actions to restore, protect and sustainably manage modified and natural ecosystems to achieve biodiversity and human well-being benefits (Cohen-Stacham et al. 2016). This concept recognises that we can work with nature rather than using technology alone, although the two can complement each other. For example, coral reef protection and replanting mangroves dampen damaging ocean surges, thereby offering a degree of protection to certain coastal communities and infrastructure (Guannel et al. 2016). In tackling climate change, NbS consists of ecosystem-based approaches, including Ecosystem-based Adaptation (EbA), Ecosystem-based Mitigation (EbM) and Eco-Disaster Risk Reduction (Eco-DRR). These use or augment ecosystem services to reduce negative climate change impacts on people (Cohen-Stacham et al. 2016).

Protecting ecosystems and the services they provide may help people adapt to and mitigate climate change and its impacts. For example, in the climate-vulnerable Namakwa District of South Africa, the use of low-cost technology to stabilise soil has resulted in reduced water run-off, increased water infiltration and increased vegetation cover (Muller et al. 2019). The increased retention of water and improved vegetation cover supports the protection of rangeland, thereby providing greater resilience to climate change of both the rangeland and the people who depend on it for their livelihoods.

Restoring degraded ecosystems and protecting natural ecosystems also help to mitigate climate change threats through increased carbon sequestration (Cohen-Stacham et al. 2016; Griscom et al. 2017; Seddon et al. 2019). A global focus on forests for EbM is important given that land-use change, including deforestation for agriculture, contributed 12% of global CO_2 emissions between 2007 and 2016. While the exact figures are debated, global tree restoration would help to sequester carbon dioxide and counter emissions (Bastin et al. 2019). Additionally, increased conservation of all biomes and the management of agricultural land uses could contribute 37% of the CO_2 mitigation needed for a 66% chance of preventing global warming from increasing to 2°C and above (Griscom et al. 2017). While better land management of all land-use types and the restoration of degraded areas are essential, improved conservation actions to protect our existing ecosystems and their capacity to continue to provide such services are urgently needed.

1.4. The role of protected areas

Protected areas provide a critical tool for protecting ecosystems and contributing to the climate change resilience of species (Coetzee et al. 2014; Watson et al. 2014) but are also net contributors to the global economy (Balmford et al. 2015). PAs may be government-designated or private and fall under the area-based conservation umbrella (Maxwell et al. 2020). Community conservancies and other effective area-based conservation measures (OECMs), such as the protection of water catchments, play a similar role.

Protected areas have generally formed through an *ad hoc* process considering economic, political or biological reasons specific to the particular context of their time and place (Joppa & Pfaff 2009, 2010). Consequently, PAs are not as representative of biodiversity and ecosystem service needs as they could be. In addition to issues of representativeness, some

PAs have funding or governance problems leading to less effective protection inside some PAs (Watson et al. 2014; Geldmann et al. 2015). Despite such cases, evidence indicates that PAs have been effective in maintaining forest cover, natural land cover and biodiversity intactness compared to similar areas outside (Ament & Cumming 2016; Bowker et al. 2017; Shumba et al. 2020). Additionally, PA planning has been incorporating more features to be as effective as possible. A study on PA expansion into river conservation (Nel et al. 2009) provides an assessment and guide for incorporating catchment management zones into PAs so that they may be more effective in protecting freshwater biodiversity and resources. Further improvements can always be made to PA conservation planning, such as by enlarging, connecting, and better managing PAs, and including a focus on protecting shifting species ranges or habitats.

In recognising the biodiversity crisis, targets were set to expand PAs to prevent species extinctions, but these targets are not (or are barely) being met (CBD 2011; Secretariat of the Convention on Biological Diversity 2020). Aichi Target 11 stated that 17% of the global terrestrial and freshwater area would be protected by 2020. The PA estate expanded from 10% in 2000 to at least 15% before 2020. However, it failed to reach the 17% target even with OECMS (UNEP-WCMC and IUCN 2021). Global PA protection is at 15.7% as of December 2021 (UNEP-WCMC and IUCN 2021) as compared to 14.1% in 2010 (Maxwell et al. 2020). Hannah et al. (2020) show that conserving 30% of the global area through area-based conservation would reduce the extinction risk of species by a half. This expansion would contribute to achieving conservation goals, reducing extinction risk and enhancing climate change resilience. This is also being adopted as a target for 2030 (CBD 2021). Biodiversity targets and species vulnerability assessments are done to identify where protected area expansion will best account for biodiversity goals and vulnerable species (Margules & Pressey 2000; Chape et al. 2005; Gillson et al. 2013).

Protected areas should also consider the protection needs of ecosystem services, particularly those important for regulating ecosystem functioning. Aichi targets 14 and 15 (regarding the restoration and protection of ecosystem services) have not been met, meaning that ecosystem services important for people and for climate change resilience are in decline (Secretariat of the Convention on Biological Diversity 2020). Some ecosystem services may be best protected through changes to land management practices, such as moving away from intensive monoculture agriculture to maximise food-generating ecosystem services in the face of harsher climatic conditions. Other services, such as those provided by Strategic Water Source Areas (SWSA), can be protected by managing land in a way that does not pollute surface or ground water (Le Maitre et al. 2018).

All plants sequester carbon, but with global changes to land cover, PAs may be an important method of maximising carbon sequestration. Conservation planners use a range of metrics in systematic planning to deliver evidence-based protection (Margules & Pressey 2000). South Africa's National Parks (SANParks) is mandated to conserve the country's biodiversity and cultural heritage, promote responsible and sustainable tourism and ensure socio-economic development (SANParks 2022). Expanding and enhancing PAs to better cover and protect climate change adaptation and mitigation services (SWSAs and carbon sequestration) serves as a form of NbS (Griscom et al. 2017; IPBES 2019). Therefore, the SANParks mission for biodiversity and cultural heritage conservation aligns with the methods of NbS though SANParks does not explicitly include ecosystem services as one of its main goals. CapeNature is the PA management authority for the Western Cape. It has a broader commitment toward the conservation of the province's natural environment, which encompasses biodiversity and ecosystem services, such as those relating to SWSAs (CapeNature 2022). Overall, PA authorities are mandated to conserve biodiversity, landscapes and heritage. These directly or indirectly relate to the conservation of ecosystem services that are important for biodiversity and people. These services be considered among other criteria for conservation planners.

The size of PAs, or the area they cover, is not necessarily enough to assess the performance of PAs given external and global change pressures (Chape et al. 2005). Studies should assess the effectiveness of PAs in protecting ecosystem services just as studies assess the PA performance in protecting land cover and ecological integrity. Forest cover has been successfully maintained in tropical African PAs (Bowker et al. 2017) and it is understood that PAs in South Africa are protecting vegetation cover (Ament & Cumming 2016; Shumba et al. 2020). In some cases, there are spill-over effects from PAs, where there can be either increases or decreases in natural vegetation cover in a buffer area around the PAs (Ament & Cumming 2016). The decreased vegetation cover or negative spill-over effects may occur when PAs push people out of the area and attract people to the edges through increased tourism. The increased vegetation cover or positive spill-over effects may occur due to incentives for maintaining the vegetation cover adjacent to PAs. Ament & Cumming (2016) found that a 10 km buffer zone accounts for any of these spill-over effects due to the PAs (Ament & Cumming 2016).Although there is evidence that PAs in South Africa are protecting vegetation cover, these results have not been interpreted in terms of carbon storage, carbon sequestration or climate change mitigation.

An area's carbon stocks consist of aboveground (vegetation biomass) and belowground (soil) organic carbon. Higher vegetation cover inside PAs may indicate increased vegetation biomass, translating to a greater quantity of carbon stocks inside PAs. There are higher values of carbon stocks inside PAs in the Mediterranean region than in their buffers, indicating that PAs can be effective in protecting the ecosystem services they cover (Lecina-Diaz et al. 2019). This study is one of few that directly investigates the effectiveness of PAs in protecting carbon stocks. Studies have also shown that natural land cover and higher functional biodiversity correlate with higher aboveground carbon values (Sintayehu et al. 2020). Maxwell et al. (2020), found that the globally protected coverage of aboveground carbon biomass is at 23.7%, while coverage of global soil-carbon stocks is at 14.6%. Carbon stocks may be protected but require greater coverage. The world needs to protect larger areas to maintain higher carbon stocks and prevent degradation of soils, which could result in a larger release of CO_2 (Smith 2008; Wiesmeier et al. 2016)

The role of South Africa's PAs in protecting strategic water source areas (SWSAs) is somewhat explored in this study (Nel et al. 2017; Le Maitre et al. 2018). SWSAs are areas responsible for supplying a disproportionately large amount of surface water runoff relative to their size, having high groundwater recharge or both. SWSAs are considered as 'ecological infrastructure' (Nel et al. 2017) that serve as critical foundations for ecosystem service flows and built infrastructure on which people greatly depend. The protection of the Catskills water source area in the USA resulted in a clean supply of water to New York City and a high return of investment compared to using a filtration plant (Chichilnisky & Heal 1998). This shows the immense value to society in increasing the protection of SWSAs for climate change resilience.

Both Nel et al. (2017) and Le Maitre et al. (2018) state the need for protecting SWSAs. The protection of groundwater and surface water needs to be approached in an integrated way as surface water depends on groundwater recharge. Protection of groundwater requires addressing land use and land management practices and protecting the soils to maintain aquifer recharge and prevent pollution. While some groundwater areas have settlements on them, others do not. There have been ongoing efforts worldwide (Chichilnisky & Heal 1998) and in South Africa (Nel et al. 2009; Nel et al. 2017) to incorporate freshwater ecosystems in conservation planning and PA expansion.

In South Africa, the protection of water source areas has been recognised as important since the 1800s and early 1900s due to drought (Le Maitre et al. 2018). South Africa's climate and rainfall are highly variable, and its uneven distribution of water resources and past droughts highlight the importance of increased protection of the country's water source areas. Recent efforts have addressed the protection of these freshwater ecosystems and their ecosystem services. Catchments were argued for inclusion in PA expansion strategies (Nel et al. 2009), after which surface water SWSAs were motivated for, defined and calculated (Nel et al. 2017).

More recently, groundwater has been included in the SWSAs (Le Maitre et al. 2018). Surface water SWSAs contribute to 50% of the run-off across South Africa, Lesotho and Swaziland and support 50% of South Africa's population despite comprising only 8% of the countries' land area (Nel et al. 2017). Additionally, only 13% of these surface water SWSAs are protected despite an extensive network of state-owned and private PAs in South Africa. When considering recent groundwater SWSAs and transboundary SWSAs (into Lesotho, 11% of SWSAs are considered protected (Le Maitre et al 2018). The expansion of PAs consider SWSAs amongst a range of metrics for more holistic conservation planning for their benefits toward biodiversity and people.

South African scientists have authored studies assessing carbon stocks (DEA 2015; DEFF 2020), SWSAs and potential for EbA (Desmet & Knowles 2019) across the country, showing the country's commitment to increasing climate change resilience and adopting NbS (DEA & SANBI 2017). South Africa is a biodiverse country that has been mainstreaming environmental protection for many years (Richardson & van Wilgen 2004; DEA & SANBI 2017; DEA 2019). Established in 1995, the Working for Water (WfW) programme has managed invasive alien species to protect South Africa's water resources while also protecting the country's biodiversity. The adoption of EbA guidelines (DEA & SANBI 2017) and policies on climate change (DEA 2012) showcases the country's commitment to addressing climate change. South Africa is an important contributor to the world's biological heritage and contains three of the 36 global biodiversity hotspots (Critical Ecosystem Partnership Fund 2022). Area-based conservation is needed to protect the biodiversity of the region. However, area-based conservation may also have the potential to protect areas important for climate change resilience resulting in Nature-based Solutions (NbS).

The country's carbon stocks reports (DEA 2015; DEFF 2020) assessed carbon stock across the country and have contributed valuable datasets that help in the understanding of carbon stocks and potential areas for climate change mitigation importance. However, the studies do not consider the role of PAs in protecting these carbon stocks. Desmet and Knowles (2020) conducted an assessment identifying areas for EbA spatial priorities across South Africa. Their study considered various ecosystem service metrics such as SWSAs, soil carbon, biodiversity resilience and rangeland integrity. This assessment aids in identifying important areas to conserve for climate change adaptation. This study considers PAs as a part of the biodiversity resilience but does not assess the role of PAs in protecting the areas they designate as important for climate change adaptation.

Ament & Cumming (2016) and Shumba et al. (2020) show that the country's national parks and Private Land Conservation Areas (PLCAs) offer protection of natural land cover and biodiversity intactness, but the studies do not assess ecosystem services within the context of Nature-based Solutions (NbS) and not within the overall protected area (PA) estate across the country. Nel et al. (2017) suggest that expanding South Africa's PA coverage of SWSAs would secure a larger quantity of water resources and contribute to Ecosystem-based Adaptation (EbA). Given existing PA, SWSA and carbon stock information for South Africa, one can investigate South Africa's protection of ecosystem services important for climate change resilience. Important outstanding questions remain how effectively PAs protect South Africa's water resources and carbon stocks and which areas would be most effective candidates for PA expansion.

1.5. Study rationale

I consider two methods of assessing the performance of South Africa's protected area network in protecting strategic carbon and water services - area of coverage and effectiveness of protection. The area refers to the PA coverage of an area strategic for a service (e.g., SWSAs) and effectiveness refers to the quality of the protection offered. In the case of carbon stocks, management quality may be indicated by comparing the quantity of carbon stocks inside and outside of PAs. SWSAs are not quantitative values even if they rely on some quantitative information and will only be assessed based on the performance in the area of coverage. Although the metrics may not be flawless, they are still useful for policy and management purposes (Chape et al. 2005; Rodríguez-Rodríguez et al. 2011; Shumba et al. 2020). They can inform where PAs should expand and whether management strategies need to be adjusted to better protect the resources inside PAs.

In this study, I assess the performance of South Africa's protected area network in protecting its carbon services and water resources. My first question investigates how well South Africa's PA network is performing in protecting carbon stocks and SWSAs through area of coverage. This is guided by studies evaluating PA networks' coverage of ecosystem services (Lecina-Diaz et al. 2019; Maxwell et al. 2020) and biodiversity features (Rodríguez-Rodríguez et al. 2011). Assessing PA coverage also provides an opportunity for monitoring PA targets and future conservation planning (Margules & Pressey 2000; Chape et al. 2005). My second question asks how effectively our protected areas have been protecting these carbon stocks. This question examines the quantity of carbon stocks rather than the area coverage of carbon stocks and is guided by studies on the effectiveness of parks in protecting natural land cover and biodiversity (Coetzee et al. 2014; Ament & Cumming 2016; Bowker et al. 2017; Shumba et al. 2020). I hypothesise that carbon stocks will be higher in the protected area network given the protection of vegetation cover by protected areas (Ament & Cumming 2016; Bowker et al. 2017; Shumba et al. 2020). This would indicate that PAs are effective in protecting ecosystem services critical for climate change mitigation and resilience. I further investigate PA coverage and effectiveness according to broad classifications of management authorities and provincial divisions for a more in-depth assessment of the protection of these ecosystem services.

Methods

2.1. Study Area

This study assessed government/state-owned and private protected areas (PA) across the terrestrial mainland of South Africa. I used protected areas listed in the South African Protected Area Database's (SAPAD) fourth quarter of 2020. PAs were then checked according to the World Database of Protected Areas (WDPA) designations for a list of the most up-to-date Protected Areas (PAs) according to both sources (UNEP-WCMC and IUCN 2021). Databases of PAs allow for the spatial assessments of PA effectiveness (Chape et al. 2005). I chose to assess the protected areas only (and not conservation areas) due to the fenced borders and more strictly regulated protection found with formally designated protected areas. In some cases, there are PAs without fences (e.g. Table Mountain National Park) that were included because of their formal protection, authority type (e.g. SANParks) and their inclusion on SAPAD. The information includes the name, year established, governance type (state-owned or private), management authority, and spatial boundaries.

The governance type and management authority categories enable the assessment of protected area (PA) contribution to service provision according to the managing authority and whether the PA is government/state or individual landowners (private). I categorised the management authorities into South African National Parks (SANParks), Private protected areas (Private) and the remaining state-owned management authorities (Other). SANParks operates at the national scale, while the other two categories consist of a network of management authorities operating at the provincial and localized scales.

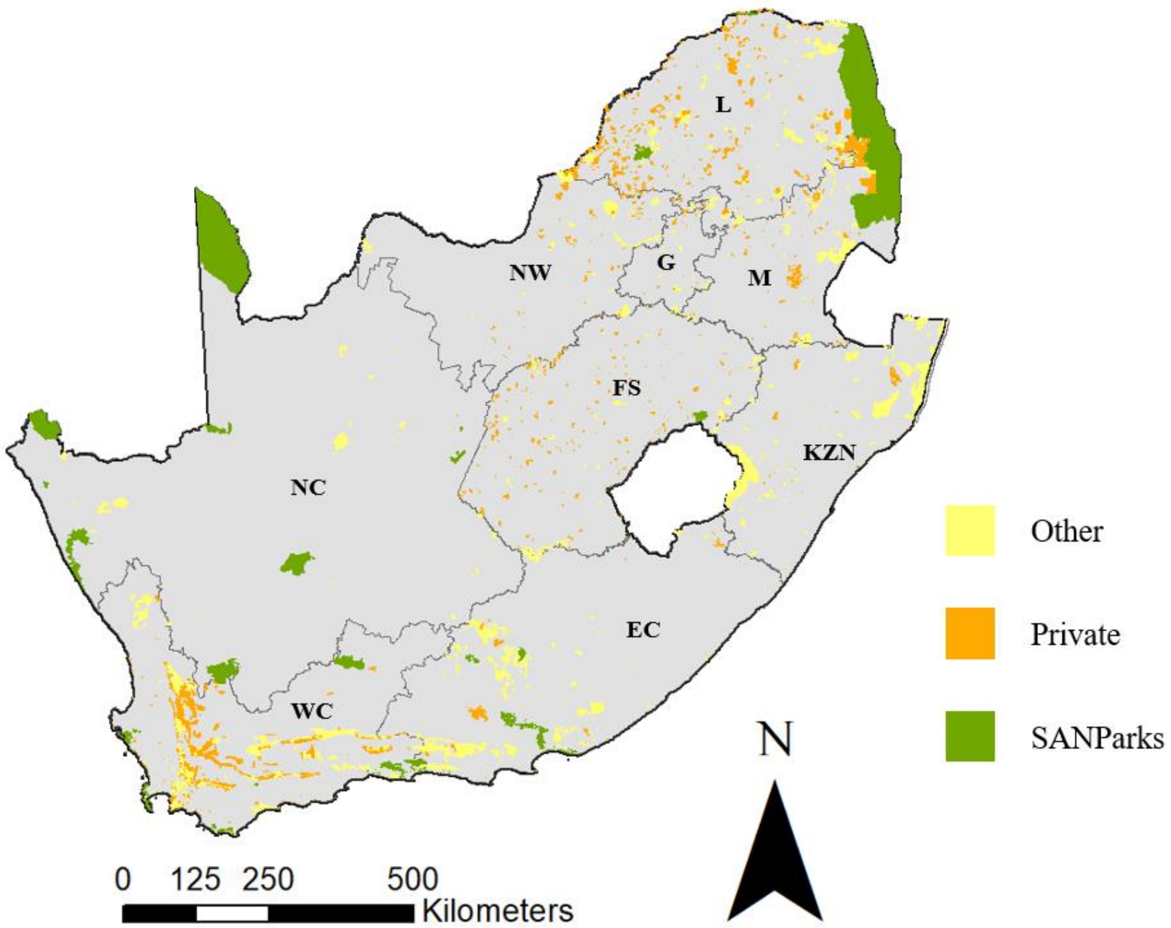

Figure 1. South Africa's Protected Area (PA) network. PAs are categorised into South African National Parks (SANParks), Private PAs (Private) and the remaining state-owned PAs (Other). The country is divided into nine provinces, including Limpopo (L), North West (NW), Gauteng (G), Mpumalanga (M), the Northern Cape (NC), Free State (FS), KwaZulu-Natal (KZN), Western Cape (WC) and Eastern Cape (EC). See Table A1 for more information on these PA authority classifications.

2.2. Land Cover variables assessed

This project relied on pre-existing datasets accessible online. I used carbon stock data in units of t/ha calculated by the CSIR for 2018 (CSIR Smart Places 2020a, 2020b). I used two carbon measures: total soil organic carbon (TSOC) and total organic carbon (TOC). The TSOC was calculated using the ISRIC Africa SoilGrids data, while the TOC was calculated using TSOC and the carbon from the biomass of woody, herbaceous and litter vegetation elements. Both datasets were at a 1 km squared resolution. I calculated the difference between the TOC and TSOC data to get a dataset on the biomass, which I designated Total

Biomass Organic Carbon (TBOC). TSOC is a good indicator of past land use actions as well, whereas TBOC is more indicative of current practices. Additionally, these data used the 2018 South African National Land-Cover (SANLC) map (DEFF 2019) obtained from the Department of Environment, Forestry and Fisheries (DEFF) to account for the different effects of land use on carbon stocks. I also used the SANLC to identify the country's human-altered areas (Figure A1). I used South Africa’s biome data (SANBI 2018) as an environmental variable to control for its effects.

To assess the coverage of South Africa’s water resources, I used surface and groundwater strategic water source area (SWSA) data from the Biodiversity GIS website (Water Research Commission 2017). The surface water (SW) SWSAs are areas that provide a disproportionately large amount of water runoff, given their size. Groundwater (GW) SWSAs are areas that have high groundwater availability and are an essential national resource. The SWSA data also included areas that were both groundwater and surface water SWSAs (GW & SW).

2.3. Objective 1 – Assess Protected Area coverage of SWSAs and carbon stocks

I assessed the percentage of ecosystem services (carbon stocks and water resources) covered by South Africa’s protected area network. I did this using layers of the protected area information (DEFF 2021; UNEP-WCMC and IUCN 2021), SWSA data (Water Research Commission 2017) and carbon stock data (TOC, TSOC and TBOC) (CSIR Smart Places 2020a, 2020b) in the ArcMap 10.7.1 program (ESRI 2019).

To assess carbon resources, I created categories of carbon stocks according to the quantity of carbon per unit of area (t/ha). I used the SANLC layer to remove human-altered (“Transformed”) land, including land uses such as mines, cities, and agricultural (cultivated) land. I used the remaining area to clip the TOC, TSOC and TBOC layers. By doing this, the remaining carbon stock areas should be natural. Therefore, such areas would align with Nature-based Solutions (NbS). From these layers, I calculated the specific areas in South Africa responsible for the top 50% of the TOC, TSOC and TBOC layers. I have designated these areas as strategic carbon areas such as was done for SWSAs. The size of the resulting TBOC layer was very small, while the resulting TSOC layer barely differed from the TOC layer. TOC mainly consists of TSOC, so it makes sense that strategic areas for carbon would look very similar (DEFF 2020). For this reason, only TOC was assessed in terms of area coverage resulting in Strategic Total Organic Carbon Areas (STOCA).

Using the PA and ecosystem service layers, I intersected these layers showing how much of the different strategic ecosystem service areas were protected. I first intersected the SWSA polygons with the PA polygons then the STOCA polygons with the PA polygons. Following this, I intersected the resulting layers (protected SWSAs & protected STOCA) to create layers representing the protected area coverage of areas that are both SWSAs and STOCAs. These strategic areas are the most strategic to protect as they cover areas important for water and for carbon stocks.

I calculated the percentage of the ecosystem service area protected by the protected area network by importing this layer from ArcGIS using Microsoft Excel and R version 4.0.3 (R Core Team 2020). I calculated the percentages of areas protected according to the area of the provinces (Table 1,2; Figure 2) and PA management authorities (Table 2,3). Identifying the percentages according to provinces and management authorities may be more useful for identifying PA performance against an administration framework.

2.4. Objective 2 – Assess carbon stock values in protected and unprotected areas

2.4.1. Sampling approach

I conducted the sampling using ArcGIS 10.7.1 (ESRI 2019). I followed the approach used in Shumba et al. (2020), which assessed the effectiveness of private land conservation areas in maintaining land cover and biodiversity intactness in South Africa. This approach also follows Bowker et al. (2016), which examined the effectiveness of African National parks in maintaining forest cover. I generated 500 random points (or the maximum number possible in the case of smaller parks) spaced 100 m apart in each PA in South Africa. For this section, I only included PAs established before 2018, which is the year in which the carbon stock values were calculated. I also generated 1,000,000 random control points spaced 100 m apart in the area outside of the 10 km buffer zones around the PAs.

I extracted environmental information for each point. These data included: distance to roads (m) (World Bank & SANRAL 2007); distance to towns (m) (Natural Earth 2018); elevation

(m) (NASA JPL 2013); slope (calculated from elevation); mean annual precipitation (mm) (Fick & Hijmans 2017); and biome designation (SANBI 2018). Additionally, I extracted PA information (name, year established, and size), carbon stock data (TOC, TSOC and TBOC) and SANLC information for the points. The spatial information was projected in the World Geodetic System (WGS) 1984 UTM Zone 35 projection in ArcMap.

2.4.2. Data Analysis

I conducted the analysis in R version 4.0.3 (R Core Team 2020). Given that this study assessed the effectiveness of PAs in protecting carbon stocks, I designated protection as the treatment variable and TOC, TSOC and TBOC (T/ha) as the response variables. I considered protection a categorical variable with points inside PAs labelled as "Protected" and points generated outside PAs labelled as "Unprotected".

I included the PA management authority and SANLC type as explanatory variables to investigate their interaction with the effect of PAs. Some "Cultivated" areas are high in carbon (DEA 2015) but are not natural. Increased carbon sequestration is vital for climate change mitigation, but nature-based solutions (NbS) emphasise the restoration and protection of biodiversity. It is beneficial to consider whether human-altered areas or natural areas would have more carbon. Therefore, I classified an area as "Transformed" if it was designated as "Cultivated", 'Built-up", "Mines & Quarries" or "Planted Forest". In contrast, I classified all other areas as "Natural". All areas designated as "Waterbodies" were excluded from this analysis.

Under and below ground, carbon stock values are influenced by land-use patterns (such as changes in natural land cover). Therefore, I followed other studies (Bowker et al. 2017; Shumba et al. 2020) in including the environmental information (elevation, biome, etc.) as variables in the model to control their effects. Shumba et al. (2020) and Bowker et al. (2016) used the MatchIt package (Ho et al. 2006) in R to pair the treatment and control points as another way of controlling for the effects of the environmental variables. However, I chose not to follow this procedure because the diagnostic plots for a model fit with matched data (Figure A2) were worse (non-linear, non-normal and less homoscedastic) than diagnostic plots for the equivalent model with unmatched data (Figure A3)..

I used linear regression models to assess how the explanatory variables (treatment and environmental variables) influenced the carbon stocks (TOC, TSOC and TBOC). A number of transformations (e.g. log transformation) were attempted, but none adequately resolved the skewness of the data. Therefore, I used a square-root transformation on the carbon stocks to normalise the skewed distribution of the data but at the cost of interpretability. As a result, the output estimates of the linear models must be interpreted on the square root scale.

The pairwise relationships between the response variables and covariates were not linear. For this reason, I built the linear models using Multivariate Adaptive Regression Splines (MARS) using the Earth package in R (Stephen Milborrow. Derived from mda:mars by Trevor Hastie and Rob Tibshirani. Uses Alan Miller's Fortran utilities with Thomas Lumley's leaps wrapper. 2021). This creates a piecewise linear model that captures the non-linear relationship of the data. MARS identifies 'knots', which are points in the data where the regression splines change. These knots are included in the models alongside the explanatory variables.

I ran one set of models to assess solely the effect of the treatment or PA status ("Protected" versus "Unprotected") on the carbon stock values and three sets of models to investigate how further variables (SANLC, PA management authorities and biomes) may change the effect on carbon stocks. The first set of models included a model for TOC, a model for TSOC and a model for TBOC with the treatment and the environmental variables as the explanatory variables. In the first of the other models, I assessed the influence of SANLC ("Transformed" versus "Natural") as an interactive term. After investigating the influence of SANLC, I ran a set of models to assess the influence of provinces as an interactive term. In the final set of models, I reclassified "Protected" points according to their management authorities to investigate how they differed from "Unprotected" areas. The assessment of PA performance interactions with provincial categories and PA management authorities is for administrative and management purposes. The estimates from the linear models are square-rooted carbon stock values (t/ha) that are relative to a baseline determined by the model – e.g., the "Unprotected" treatment (areas outside of PAs). Given that the estimates are relative to a baseline value, they can only be interpreted as relative values, and absolute values could not be used. These relative values determine the differences between "Protected" and "Unprotected" areas.

Results

3.1. Objective 1 – Assess Protected Area coverage of SWSAs and carbon stocks

3.1.1. Overview

Protected Areas (PA) cover 9.8% (120,064 km^2) of South Africa's mainland (Table 1). PAs cover 14.8% of Strategic Water Source Areas (SWSA), which is less than the protection of the 21.7% of Strategic Total Organic Carbon Areas (STOCA) (Table 1, Figure 2a). Overall, 8.1% of the groundwater SWSAs, 17.4% of the surface water SWSAs, and 28.9% of the ground and surface water SWSAs are protected. The strategic water source and carbon areas (SWSA & STOCA) have 28.5% of their area protected (Table 2). Furthermore, the country protects 43.6% of the SWSA & STOCA areas, which are both ground and surface water.

3.1.2. Provincial categories

The KwaZulu-Natal, Limpopo, Mpumalanga and Western Cape PAs protect the largest percentage of their provinces and of the SWSAs, STOCAs and combined areas (Table 1; Table 2). Mpumalanga PAs protect the largest percentage of their province (22.6%) while the North West PAs protect the smallest percentage of their province (4.8%). The Western Cape PAs protect the greatest proportion of the province's STOCAs with nearly a half protected (48.3%). Mpumalanga PAs come second to those of the Western Cape (33.0%) followed by Limpopo (26.0%). The Northern Cape and the Eastern Cape are the only provinces where there is 10% or less of their STOCAs that are protected. All provinces (except the Northern Cape) protect proportionately more STOCAs than compared to their representation of their provinces.

Out of all the provinces, the Western Cape PAs protect the largest proportion of the province's SWSAs (38.8%), while the Northern Cape PAs protects the lowest (1.1%). Protected areas in Limpopo and Mpumalanga PAs come in at second and third out of the provinces' protection of their SWSAs (13.8% and 13.5%). However, Limpopo and Mpumalanga PAs join Gauteng and the Northern Cape PAs in protecting a percentage of their SWSAs that's lower than the percentage that they protect of their provinces. This means that they protect proportionately less of SWSAs given their representation of their provinces.

The Eastern Cape, KwaZulu-Natal, Limpopo, Mpumalanga and Western Cape PAs are the only PAs that protect SWSAs that are both ground and surface water. KwaZulu-Natal PAs protect the greatest percentage of their groundwater SWSAs (11.0%) but the Western Cape PAs protect the greatest area of groundwater SWSAs in the country (2042 km^2; Table 1). The Western Cape SWSAs also protect the greatest percentage of their surface water SWSAs (62.9%) and of their ground and surface water SWSAs (71.4%). KwaZulu-Natal PAs protect 15.8% or 5,090 km^2 of their surface water SWSAs, indicating a large area available to be protected in the province.

The Western Cape PAs are the only province PAs where more than 30% of SWSA & STOCA is protected (Table 2). The Western Cape PAs are the only PAs of the provinces to protect a greater percentage of SWSA & STOCA than that of the country (70.5%). KwaZulu-Natal covers the second largest area of SWSA (17.7%), and of the SWSA & STOCA (27.9%). The Western Cape protects 70.5% of the SWSA & STOCA areas and 90.8% of these areas that are both ground and surface water (Table 2). KwaZulu-Natal, Limpopo and Mpumalanga also protect more than 20% of these ground and surface water SWSA & STOCA areas.

The area of South Africa below Lesotho and on the eastern coast is the top portion of the Eastern Cape and the bottom portion of KwaZulu-Natal. This area has little to no PAs despite the area containing much of the SWSAs, STOCAs and combined areas (Figure 2). The same can be observed for the center eastern area of the country (Mpumalanga) apart from the Kruger National Park and some other smaller PAs.

3.1.3. Management authority categories

At the national scale, state-owned PAs other than SANParks (Other) protect the largest portion of the country (4.2%) followed by SANParks (3.4%) and Private PAs (2.1%) (Table 3). Despite the small differences in PA size, Other PAs protect eight times more of the SWSAs than SANParks (22,365 km^2 vs 2,591 km^2) and three times more than Private PAs (22,365 km^2 vs 7,416 km^2). The Other PAs protect nearly three times more of the STOCA (12.9%) areas than SANParks PAs (4.6%) but more than three times than Private PAs (4.2%). SANParks PAs protect a larger area of the STOCAs than Private PAs but Private PAs protect a larger area relative to their total PA network size. Other PAs also protect the largest area of the groundwater, surface water, and combined SWSAs, followed by Private PAs and SANParks PAs. In terms of the combined SWSA & STOCA, SANParks has the lowest percentage of area (1.9%) protected. Private PAs perform better with 5.9% of SWSA & STOCA protected but the Other state-owned PAs perform the best (20.7%) and contribute to 72% of the total SWSA & STOCA area. Other PAs also protect 27.0% of the ground and surface water SWSA & STOCA areas, which is more than 14.2% of Private PAs and 2.5% of SANParks PAs.

Table 1. Percentage (%) and area (km^2) of the South Africa's strategic ecosystem service areas protected in each province and overall for the country. There are also the percentages of the total PA estate that various PA management authorities cover. The strategic ecosystem services assessed include the Strategic Water Source Areas (SWSA) and the Strategic Total Organic Carbon Area (STOCA). The SWSAs are divided into different categories, including groundwater only (GW), surface water only (SW), both groundwater and surface water (GW & SW) overlapping each other, and the total area of SWSAs protected.

	Protected		STOCA Protected		SWSA Protected: GW only		SW only		GW & SW		Total	
Province	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**
Eastern Cape	**7.0**	11,823	**10.0**	8,304	**18.7**	1,631	**5.0**	1,211	**2.3**	171	**7.5**	3,014
Free State	**4.1**	5,266	**11.4**	1,533	**3.3**	202	**10.7**	350			**5.8**	552
Gauteng	**4.7**	847	**14.4**	379	**3.6**	121					**3.6**	121
KwaZulu-Natal	**13.8**	12,883	**22.4**	11,126	**40.7**	1,493	**15.8**	5,090	**15.2**	1,438	**17.7**	8,022
Limpopo	**20.1**	25,267	**26.0**	8,180	**11.2**	1,471	**22.9**	627	**16.2**	553	**13.8**	2,650
Mpumalanga	**22.6**	17,356	**33.0**	9,775	**3.9**	81	**13.8**	2,593	**25.8**	287	**13.5**	2,961
North West	**3.5**	3627	**17.8**	952	**3.6**	522					**3.6**	522
Northern Cape	**4.8**	18,050	**2.9**	563	**1.1**	291					**1.1**	291
Western Cape	**19.1**	24,945	**48.3**	18,779	**11.0**	2,042	**62.9**	5,854	**71.4**	6,344	**38.8**	14,240
Grand Total	**9.8**	120,064	**21.7**	59,591	**8.1**	7,854	**17.4**	15,725	**28.9**	8,793	**14.8**	32,372

Table 2. Percentage (%) and area (km^2) of South Africa's protected area intersecting Strategic Water Source Areas (SWSA) and Strategic Total Organic Carbon Areas (STOCA) according to each province. These areas are both Strategic Water Source Areas (SWSA) and Strategic Total Organic Carbon Areas (STOCA). The SWSAs are divided into different categories, including groundwater only (GW), surface water only (SW), both groundwater and surface water (GW & SW) overlapping each other, and the total area of SWSA protected.

	GW only		**SW only**		**GW & SW**		**Total**	
Province	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**
Eastern Cape	**27.5**	1,403	**7.3**	1,128	**3.6**	170	**10.7**	2,701
Free State	**9.5**	11	**12.4**	294			**12.3**	305
Gauteng	**12.1**	65					**12.1**	65
KwaZulu-Natal	**52.3**	870	**26.6**	4,707	**24.4**	1,227	**27.9**	6,804
Limpopo	**9.7**	392	**34.5**	438	**26.6**	438	**18.2**	1,268
Mpumalanga	**10.7**	58	**23.7**	2,160	**39.3**	269	**24.1**	2,488
North West	**14.4**	157					**14.4**	157
Northern Cape	**1.6**	67					**1.6**	67
Western Cape	**26.9**	1,356	**83.3**	5,377	**90.8**	6,095	**70.5**	12,828
Grand Total	**19.6**	4379	**26.9**	14,104	**43.6**	8,198	**28.5**	26,681

Table 3. Percentage (%) and area (km^2) of South Africa's strategic ecosystem service areas protected by protected area (PA) management authorities. There are also the percentages of the total PA estate that various PA management authorities cover. The strategic ecosystem services assessed include the Strategic Water Source Areas (SWSA) and the Strategic Total Organic Carbon Area (STOCA). The SWSAs are divided into different categories, including groundwater only (GW), surface water only (SW), both groundwater and surface water (GW & SW) overlapping each other, and the total area of SWSA protected. The authorities categorised as "National" include South African National Parks (SANParks), Private protected areas (Private) and the remaining state-owned management authorities (Other).

	Protected		**STOCA Protected**		**SWSA Protected**							
					GW only		**SW only**		**GW & SW**		**Total**	
PA Authority Categories	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**
Other	**4.2**	51,866	**12.9**	35,478	**4.4**	4,230	**14.0**	12,647	**18.0**	5,488	**10.3**	22,365
Private	**2.1**	26,113	**4.2**	11,452	**2.6**	2,522	**2.3**	2,088	**9.2**	2,806	**3.4**	7,416
SANParks	**3.4**	42,085	**4.6**	12,662	**1.1**	1,102	**1.1**	990	**1.6**	499	**1.2**	2,591
Grand Total	**9.8**	120,064	**21.7**	59,591	**8.1**	7,854	**17.4**	15,725	**28.9**	8,793	**14.8**	32,372

Table 4. Percentage (%) and area (km^2) of South Africa's protected intersecting Strategic Water Source Areas (SWSA) and Strategic Total Organic Carbon Areas (STOCA) according to grouped Protected Area Management authorities. The SWSAs are divided into different categories, including groundwater only (GW), surface water only (SW), both groundwater and surface water (GW & SW) overlapping each other, and the total area of SWSA protected. The authorities categorised as "National" include South African National Parks (SANParks), Private protected areas (Private) and the remaining state-owned management authorities (Other).

PA Authority Categories	**GW only**		**SW only**		**GW & SW**		**Total**	
	%	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**	**%**	**Area (km^2)**
Other	**12.9**	2,888	**21.8**	11,408	**27.0**	5,065	**20.7**	19,360
Private	**4.5**	1,005	**3.6**	1,883	**14.2**	2,662	**5.9**	5,551
SANParks	**2.2**	486	**1.6**	813	**2.5**	472	**1.9**	1,770
Grand Total	**19.6**	4,379	**26.9**	14,104	**43.6**	8,198	**28.5**	26,681

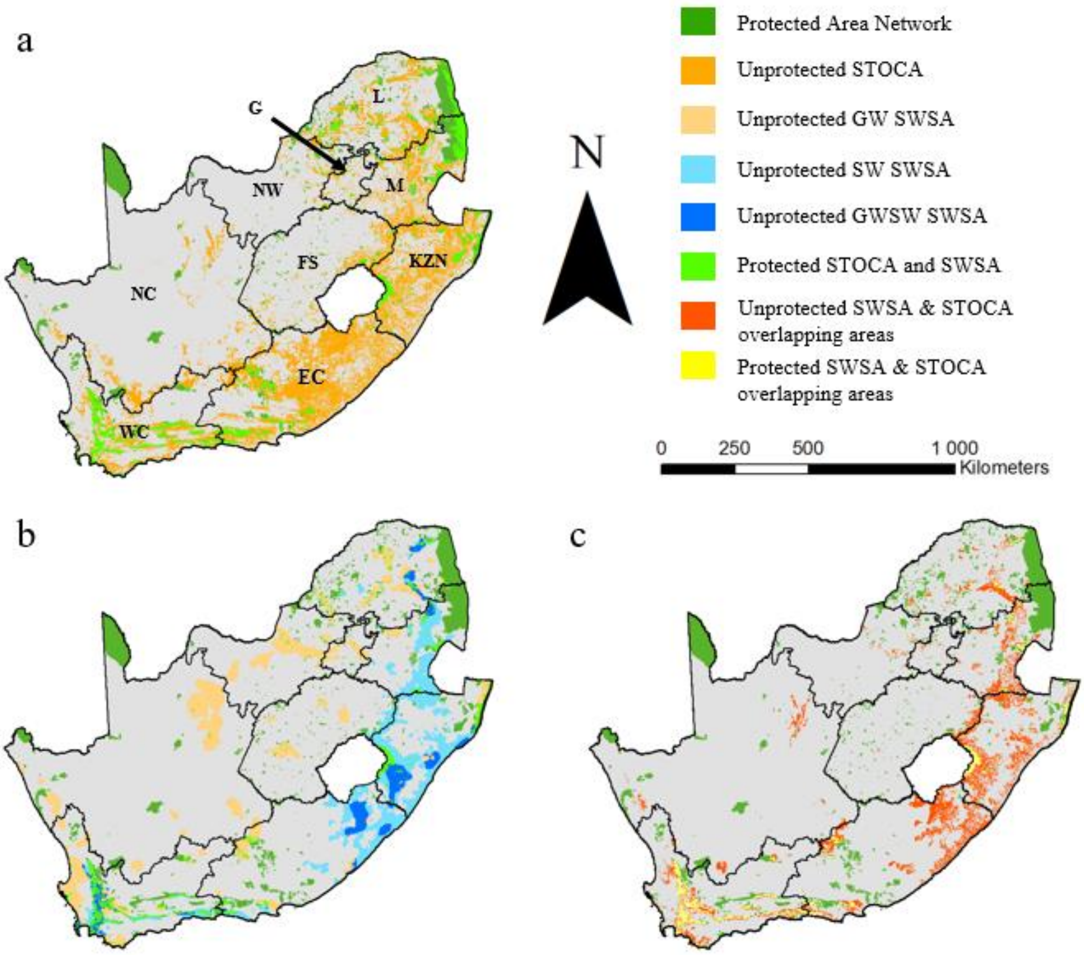

Figure 2. The a) Strategic Total Organic Carbon Area (STOCA), b) Strategic Water Source Areas (SWSA), and c) SWSA & STOCA overlapping areas that are unprotected or protected by the South African Protected Area network. The protected area network is also shown. The SWSAs include groundwater (GW), surface water (SW) and areas containing both (GWSW). The country is divided into its provinces, including Limpopo (L), North West (NW), Gauteng (G), Mpumalanga (M), the Northern Cape (NC), Free State (FS), KwaZulu-Natal (KZN), Western Cape (WC) and Eastern Cape (EC).

3.2. Objective 2 – Assess carbon stock values in protected and unprotected areas

3.2.1. Protected Area overview

There is evidence that South African PA have 0.871 tons of total organic carbon (TOC) per hectare squared more than unprotected areas (SE = 0.004, t = 196.890, p-value < 0.001; Table 5). Additionally, PAs have 0.676 tons of total soil organic carbon (TSOC) per hectare squared (SE = 0.004, t = 158.758, p-value < 0.001) and 0.441 tons more of total biomass organic carbon (TSOC) per hectare squared than unprotected areas (SE = 0.002, t = 183.393, p-value < 0.001; Table 5). All environmental variables (except one category of biome for TSOC) have significant effects on the TOC, TSOC and TBOC (Table 5). These environmental variables were included in the model to control for their effects. After this linear model (Table 5), the estimates of the environmental variables for other models are shown in the Appendices (Table A2, A2, A3) with the summarised tables of the treatment variables shown in their place (Table 6, 7, 8).

Natural protected areas have 0.779 $(t/ha)^{-2}$ of TOC more than human-altered ("Transformed") unprotected areas (Table 6; Figure 3). These areas also have 0.620 $(t/ha)^{-2}$ of TSOC and 0.319 $(t/ha)^{-2}$ of TBOC more than unprotected transformed areas (Table 6). Natural Areas have 0.125 $(t/ha)^{-2}$ of TOC (SE = 0.009, t = -13.583, p-value < 0.001), 0.081 $(t/ha)^{-2}$ of TSOC (SE = 0.009, t = -9.153, p-value < 0.001) and 0.143 $(t/ha)^{-2}$ of TBOC (SE = 0.005, t = -28.934, p-value < 0.001) less than transformed areas (Table 6; Figure 3). Protected natural areas have 0.417 $(t/ha)^{-2}$ of TOC (SE = 0.016, t = 25.341, p-value < 0.001), 0.309 $(t/ha)^{-2}$ of TSOC (SE = 0.016, t = 15.579, p-value < 0.001) and 0.224 $(t/ha)^{-2}$ of TBOC (SE = 0.009, t = 25.442, p-value < 0.001) more than unprotected natural areas.

3.2.2. Provincial categories and Management Authority categories

On average, the protected areas across the provinces have 0.769 $(t/ha)^{-2}$ TOC (SE = 0.014, t = 54.036, p-value < 0.001) more than unprotected areas (Table 7; Figure 4). Limpopo PAs have the highest TOC, TSOC and TBOC values out of all the provinces' PAs. The North West PAs have the lowest TOC and TSOC values, while the Free State has the lowest TBOC values (Table 7; Figure 4). Besides Limpopo PAs, the Eastern Cape, KwaZulu-Natal, Western Cape and Gauteng PAs have high TOC and TSOC values. The Eastern Cape PAs and Gauteng PAs also have higher TBOC values. Of all the unprotected areas of the provinces, KwaZulu-Natal has the highest TOC and TSOC values while the North West has the lowest TOC and Gauteng has the lowest TSOC. Otherwise, the Eastern Cape has unprotected areas' second-highest TOC and TSOC values. Mpumalanga is the only province where TSOC is lower in the PAs than outside of the PAs (Table 7; Figure 4). Limpopo and KwaZulu-Natal unprotected areas are the highest in TBOC. Unprotected areas in KwaZulu-Natal and Western Cape are higher in TBOC than PAs.

All PA management authorities have significantly higher TOC, TSOC and TBOC values than unprotected areas (Table 8; Figure 5). SANParks PAs has the highest of both TOC and TSOC with 1.261 $(t/ha)^{-2}$ more TOC (SE = 0.016, t = 80.625, p-value < 0.001 and 1.180 $(t/ha)^{-2}$ more TSOC (SE = 0.015, t = 77.739, p-value < 0.001) than unprotected areas. Out of SANParks, Private and Other PAs, Private PAs has the lowest TOC and TSOC values. The differences between PAs and unprotected areas were lower for TSOC than for TOC, particularly for Private PAs. For TBOC, SANParks has the lowest value while Private PAs has the highest value with 0.513 $(t/ha)^{-2}$ more TBOC (SE = 0.003, t = 183.994, p-value < 0.001) than unprotected areas (Table 5).

Table 5. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to treatment ("Protected" versus "Unprotected") and multiple environmental variables. The environmental variables include biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). The baseline biome designation is "Albany Thicket". P-values designated as NS are non-significant. The variables in bold refer to the 'knots' where the relationship of the piecewise model changes.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	TreatmentProtected	0.871	0.004	196.890	<0,001
	BiomeAzonalVegetation	-1.031	0.017	-60.964	<0,001
	BiomeDesert	-0.424	0.028	-14.956	<0,001
	BiomeForests	0.832	0.022	37.567	<0,001
	BiomeFynbos	1.105	0.014	80.625	<0,001
	BiomeGrassland	-1.904	0.014	-138.353	<0,001
	BiomeIndianOceanCoastalBelt	-0.284	0.030	-9.362	<0,001
	BiomeNama-Karoo	-0.243	0.013	-18.271	<0,001
	BiomeSavanna	-2.089	0.012	-167.544	<0,001
	BiomeSucculentKaroo	0.641	0.014	44.232	<0,001
	MAP	0.251	0.000	534.230	<0,001
	Slope	0.313	0.001	413.326	<0,001
	Elevation	-0.001	0.000	-61.437	<0,001
	Road_dist	0.000	0.000	-11.541	<0,001
	Places_near	0.000	0.000	21.211	<0,001
	MAP_31	-0.155	0.001	-279.706	<0,001
	MAP_76	-0.127	0.001	-123.211	<0,001
	Slope_9.614593	-0.264	0.001	-239.723	<0,001
	Elevation_1156	0.003	0.000	168.109	<0,001
sqrt(TSOC)	TreatmentProtected	0.676	0.004	158.758	<0,001
	BiomeAzonalVegetation	-0.820	0.016	-50.490	<0,001
	BiomeDesert	-0.298	0.027	-10.988	<0,001
	BiomeForests	0.811	0.021	38.135	<0,001
	BiomeFynbos	1.071	0.013	81.363	<0,001
	BiomeGrassland	-1.686	0.013	-127.920	<0,001
	BiomeIndianOceanCoastalBelt	-0.273	0.029	-9.421	<0,001
	BiomeNama-Karoo	-0.009	0.013	-0.712	NS
	BiomeSavanna	-2.081	0.012	-174.042	<0,001
	BiomeSucculentKaroo	0.707	0.014	50.945	<0,001
	MAP	0.210	0.000	506.103	<0,001
	Slope	0.285	0.001	392.711	<0,001
	Elevation	0.000	0.000	-21.877	<0,001
	Road_dist	0.000	0.000	-3.256	0.001
	Places_near	0.000	0.000	14.333	<0,001
	MAP_80	-0.137	0.001	-111.690	<0,001
	MAP_33	-0.113	0.000	-226.530	<0,001
	Slope_9.657719	-0.240	0.001	-227.014	<0,001
	Elevation_1197	0.003	0.000	164.366	<0,001
sqrt(TBOC)	TreatmentProtected	0.441	0.002	183.393	<0,001
	BiomeAzonal Vegetation	-0.718	0.009	-79.432	<0,001
	BiomeDesert	-0.876	0.015	-58.464	<0,001
	BiomeForests	0.395	0.012	33.373	<0,001
	BiomeFynbos	0.493	0.007	67.028	<0,001
	BiomeGrassland	-0.949	0.007	-129.534	<0,001
	BiomeIndian Ocean Coastal Belt	0.106	0.016	6.556	<0,001
	BiomeNama-Karoo	-0.616	0.007	-86.420	<0,001
	BiomeSavanna	-0.488	0.007	-73.123	<0,001
	BiomeSucculent Karoo	-0.083	0.008	-10.831	<0,001
	Map	0.112	0.000	577.578	<0,001
	Slope	0.144	0.000	361.444	<0,001
	Elevation	-0.001	0.000	-159.239	<0,001
	Road_dist	0.000	0.000	-25.029	<0,001
	Places_near	0.000	0.000	35.655	<0,001
	MAP_39	-0.113	0.000	-253.270	<0,001
	MAP_91	0.095	0.001	78.186	<0,001
	MAP_50	-0.032	0.000	-74.401	<0,001
	Slope_9.844008	-0.129	0.001	-219.985	<0,001
	Elevation_1145	0.001	0.000	84.074	<0,001

Table 6. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the interaction between treatment ("Protected" versus "Unprotected") and land-cover state ("Transformed" versus "Natural). Multiple environmental variables were used as covariates in the models and their outputs are shown in Table A2. P-values designated as NS are non-significant.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	TreatmentProtected:SANLCNatural	0.487	0.017	28.648	<0,001
	TreatmentProtected	0.417	0.016	25.341	<0,001
	SANLCNatural	-0.125	0.009	-13.583	<0,001
sqrt(TSOC)	TreatmentProtected:SANLCNatural	0.392	0.016	24.020	<0,001
	TreatmentProtected	0.309	0.016	19.579	<0,001
	SANLCNatural	-0.081	0.009	-9.153	<0,001
sqrt(TBOC)	TreatmentProtected:SANLCNatural	0.237	0.009	25.989	<0.001
	TreatmentProtected	0.224	0.009	25.442	<0.001
	SANLCNatural	-0.143	0.005	-28.934	<0.001

Table 7. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the interaction between the treatment ("Protected" versus "Unprotected" status) and South Africa's provincial designation. Multiple environmental variables were used as covariates in the models and their outputs are shown in Table A3. The provinces include the Eastern Cape (the baseline category), Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West, Northern Cape and Western Cape.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	TreatmentProtected:ProvinceFreeState	-0.189	0.018	-10.310	<0,001
	TreatmentProtected:ProvinceGauteng	1.286	0.035	36.873	<0,001
	TreatmentProtected:ProvinceKwaZuluNatal	-0.368	0.019	-19.155	<0,001
	TreatmentProtected:ProvinceLimpopo	0.452	0.018	25.170	<0,001
	TreatmentProtected:ProvinceMpumalanga	-0.728	0.021	-35.200	<0,001
	TreatmentProtected:ProvinceNorthWest	0.190	0.020	9.472	<0,001
	TreatmentProtected:ProvinceNorthernCape	0.046	0.025	1.808	NS
	TreatmentProtected:ProvinceWesternCape	-0.202	0.018	-11.033	<0,001
	TreatmentProtected	0.769	0.014	54.036	<0,001
	ProvinceFreeState	-1.202	0.010	-121.597	<0,001
	ProvinceGauteng	-1.564	0.024	-63.930	<0,001
	ProvinceKwaZulu-Natal	0.315	0.011	28.324	<0,001
	ProvinceLimpopo	-0.037	0.012	-3.137	0.002
	ProvinceMpumalanga	-0.553	0.013	-43.347	<0,001
	ProvinceNorthWest	-1.682	0.010	-173.364	<0,001
	ProvinceNorthernCape	-0.553	0.009	-63.100	<0,001
	ProvinceWesternCape	-0.142	0.011	-12.926	<0,001
sqrt(TSOC)	TreatmentProtected:ProvinceFreeState	-0.011	0.018	-0.625	NS
	TreatmentProtected:ProvinceGauteng	1.396	0.034	41.336	<0,001
	TreatmentProtected:ProvinceKwaZuluNatal	-0.237	0.019	-12.785	<0,001
	TreatmentProtected:ProvinceLimpopo	0.641	0.017	36.808	<0,001
	TreatmentProtected:ProvinceMpumalanga	-0.685	0.020	-34.200	<0,001
	TreatmentProtected:ProvinceNorthWest	0.120	0.019	6.195	<0,001
	TreatmentProtected:ProvinceNorthernCape	0.259	0.024	10.607	<0,001
	TreatmentProtected:ProvinceWesternCape	0.086	0.018	4.859	<0,001
	TreatmentProtected	0.605	0.014	43.922	<0,001
	ProvinceFreeState	-1.075	0.010	-112.780	<0,001
	ProvinceGauteng	-1.619	0.024	-68.284	<0,001
	ProvinceKwaZulu-Natal	0.321	0.011	29.717	<0,001
	ProvinceLimpopo	-0.492	0.011	-43.171	<0,001
	ProvinceMpumalanga	-0.495	0.012	-40.012	<0,001
	ProvinceNorthWest	-1.582	0.009	-169.031	<0,001
	ProvinceNorthernCape	-0.489	0.008	-57.737	<0,001
	ProvinceWesternCape	-0.215	0.010	-20.580	<0,001
sqrt(TBOC)	TreatmentProtected:ProvinceFree.State	-0.401	0.010	-41.535	<0.001
	TreatmentProtected:ProvinceGauteng	-0.066	0.018	-3.576	<0.001
	TreatmentProtected:ProvinceKwaZulu.Natal	-0.602	0.010	-59.565	<0.001
	TreatmentProtected:ProvinceLimpopo	-0.258	0.009	-27.290	<0.001
	TreatmentProtected:ProvinceMpumalanga	-0.174	0.011	-15.925	<0.001
	TreatmentProtected:ProvinceNorth.West	0.268	0.011	25.443	<0.001
	TreatmentProtected:ProvinceNorthern.Cape	-0.273	0.013	-20.519	<0.001
	TreatmentProtected:ProvinceWestern.Cape	-0.513	0.010	-53.063	<0.001
	TreatmentProtected	0.471	0.008	62.773	<0.001
	ProvinceFree State	-0.444	0.005	-86.333	<0.001
	ProvinceGauteng	-0.012	0.013	-0.940	NS
	ProvinceKwaZulu-Natal	0.120	0.006	20.435	<0.001
	ProvinceLimpopo	0.959	0.006	155.059	<0.001
	ProvinceMpumalanga	-0.216	0.007	-32.178	<0.001
	ProvinceNorth West	-0.611	0.005	-119.830	<0.001
	ProvinceNorthern Cape	-0.398	0.005	-84.770	<0.001
	ProvinceWestern Cape	-0.108	0.006	-18.788	<0.001

Table 8. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the treatment (protected area status). Multiple environmental variables were used as covariates in the models, and their outputs are shown in Table A4. "Unprotected" is the control treatment or baseline and the different categories of the treatment or protected area status include South African National Parks (SANParks), Private protected areas (Private) and the remaining state-owned management authorities (Other). SANParks operates nationally while Private and Other PAs offer at finer scales such as the provincial level. P-values designated as NS are non-significant.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	Man_treatmentOther	0.830	0.007	125.088	<0.001
	Man_treatmentPrivate	0.774	0.005	151.298	<0.001
	Man_treatmentSANParks	1.261	0.016	80.625	<0.001
sqrt(TSOC)	Man_treatmentOther	0.715	0.006	111.743	<0.001
	Man_treatmentPrivate	0.591	0.005	121.061	<0.001
	Man_treatmentSANParks	1.180	0.015	77.739	<0.001
sqrt(TBOC)	Man_treatmentOther	0.327	0.004	92.147	<0.001
	Man_treatmentPrivate	0.513	0.003	183.994	<0.001
	Man_treatmentSANParks	0.253	0.008	29.975	<0.001

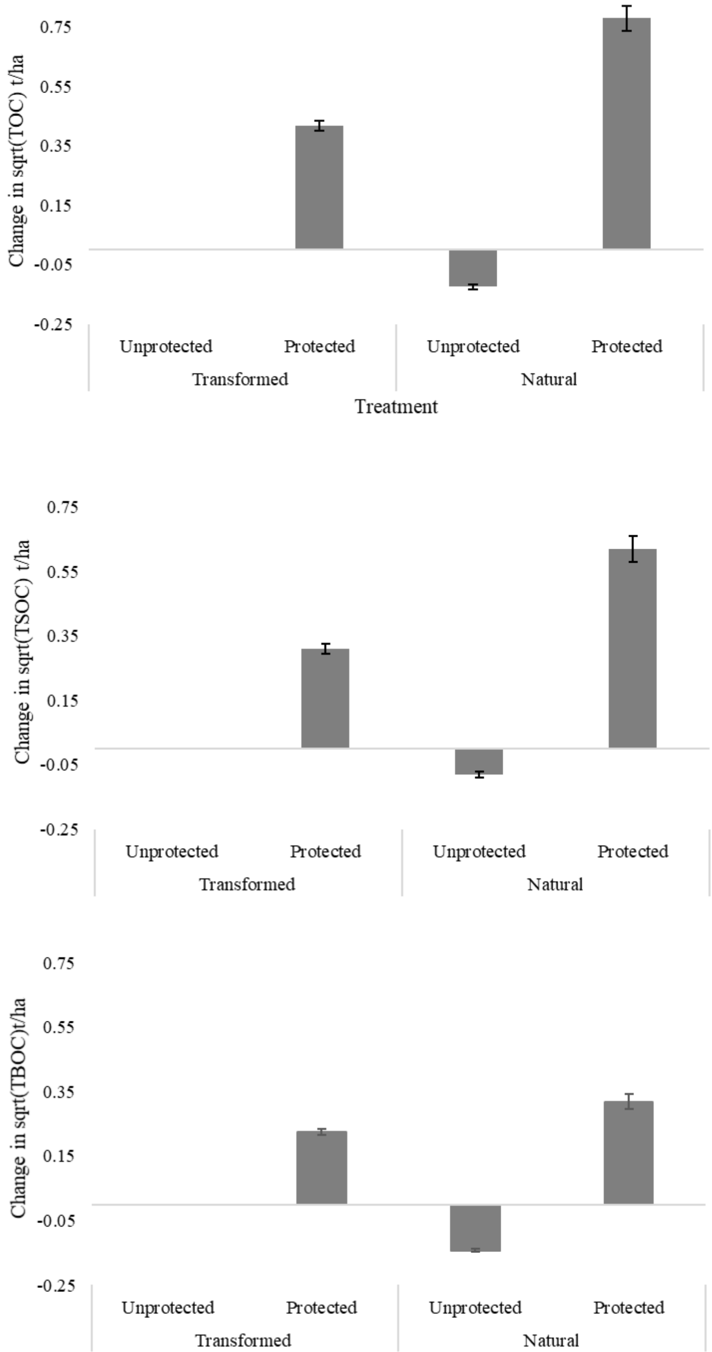

Figure 3. The changes in square root of a) total organic carbon (TOC) (t/ha), b) Total Soil Organic Carbon (TSOC) (t/ha), and c) Total Biomass Organic Carbon (TBOC) (t/ha) values relative to the baseline categorical variable of the model in response to the protected area status / treatment ("Protected" versus "Unprotected") and natural land cover state ("Natural" versus "Transformed"). The left-most variable is the baseline category to which the other variables are compared. The error bars represent standard errors of the estimates. These values are based off the outputs of the linear models shown in Table 6.

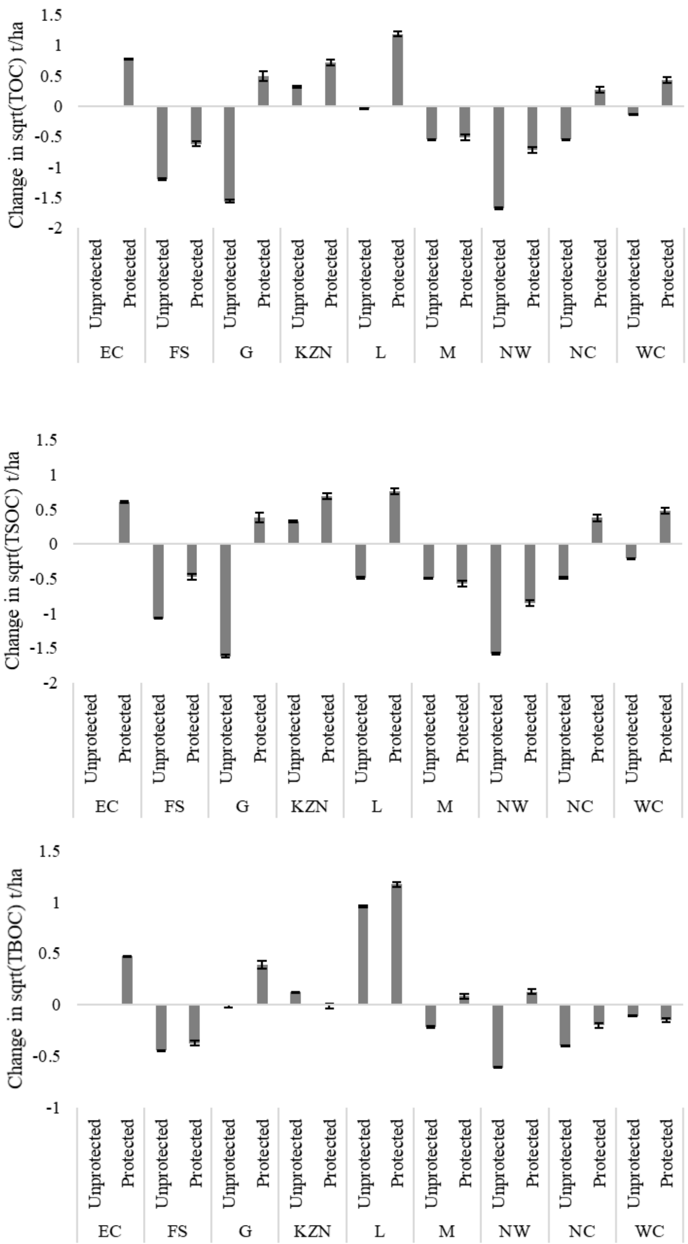

Figure 4. The changes in square root of a) total organic carbon (TOC) (t/ha), b) Total Soil Organic Carbon (TSOC) (t/ha), and c) Total Biomass Organic Carbon (TBOC) (t/ha) values relative to the baseline categorical variable of the model in response to the protected area status / treatment ("Protected" versus "Unprotected") and provincial designations. The provinces of the country include Eastern Cape (EC), Free State (FS), Gauteng (G), KwaZulu-Natal (KZN), Limpopo (L), Mpumalanga (M), the Northern Cape (NC), North West (NW) and the Western Cape (WC). The left-most variable is the baseline category to which the other variables are compared. The error bars represent standard errors of the estimates. These values are based off the outputs of the linear models shown in Table 7.

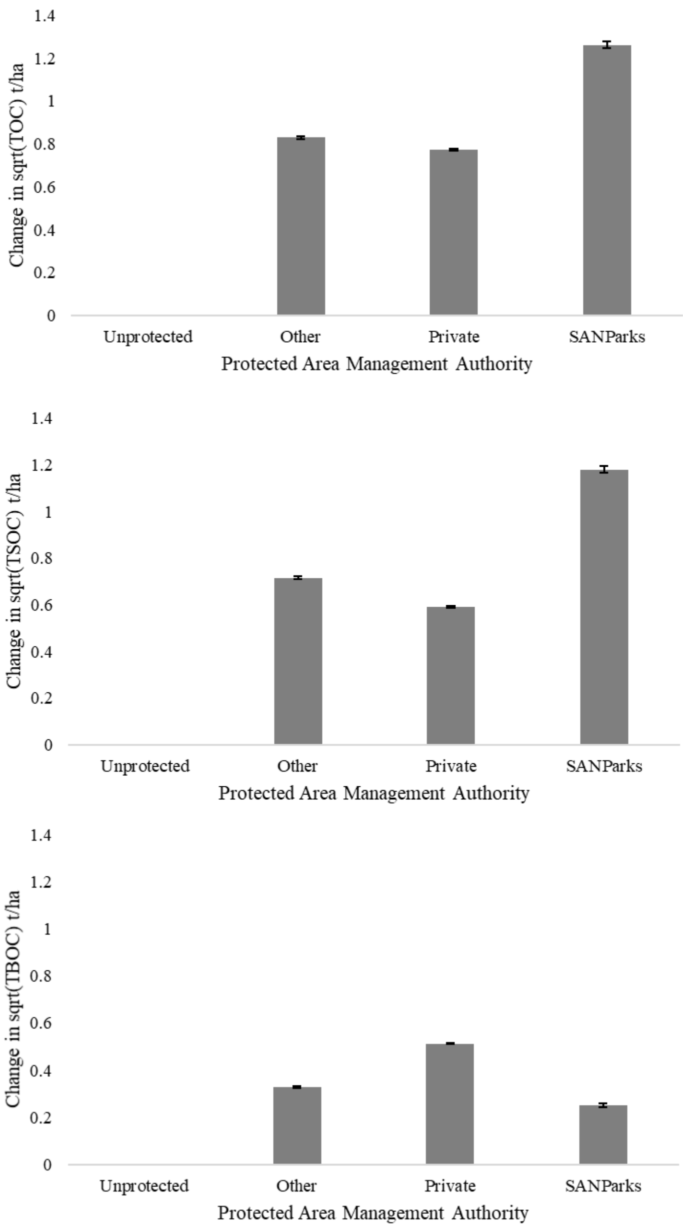

Figure 5. The changes in square root of a) total organic carbon (TOC) (t/ha), b) Total Soil Organic Carbon (TSOC) (t/ha), and c) Total Biomass Organic Carbon (TBOC) (t/ha) values relative to the baseline categorical variable of the model in response to the protected area status / treatment ("Protected" versus "Unprotected") and protected area management authority. The protected area management authorities are grouped into SANParks PAs (National Parks), Private PAs and the remaining state-owned (Other) PAs. The left-most variable is the baseline category to which the other variables are compared. The error bars represent standard errors of the estimates. These values are based off the outputs of the linear models shown in Table 8.

Discussion

The results provide evidence that protected areas (PAs) have larger carbon stock values than areas outside of them. Furthermore, protected natural areas have higher carbon stock values than unprotected transformed and natural areas. The higher carbon values are observed for most provincial PAs and all nationally categorised PAs. These higher values show that PAs and their management techniques are effective in securing climate change resilience in the country. The results also provide more insight into the country's PA coverage of water and carbon services. The PAs cover 9.8% of its surface but proportionately more of the areas strategic for carbon services and water resources. However, there is a need for a more extensive PA network to secure these areas, which are important for climate change resilience. These data can be used for future monitoring and systematic conservation planning.

4.1. National scale patterns

The higher carbon stock values for total organic carbon (TOC), total soil organic carbon (TSOC) and total biomass organic carbon (TBOC) in PAs provides evidence that PAs are effective in protecting carbon stocks, which confirms that PAs are important for climate change resilience. A study by Lecina-Diaz et al. (2019) in the Mediterranean region supports these carbon stock contrasts. It found increased carbon stock values inside PAs compared to their buffer areas. They are also somewhat supported by other studies of PAs in Africa by Ament & Cumming (2016), Bowker et al. (2017) and Shumba et al. (2020), who found that some PAs have been successful in preventing the loss of natural land cover. The transformation of habitats is one of the most significant drivers of biodiversity loss and causes the loss of natural land cover (Salafsky et al. 2008; IPBES 2019). This associated loss in natural vegetation corresponds to a loss in above- and below-ground biomass carbon and soil organic carbon over time (Smith 2008; Sintayehu et al. 2020). Given that PAs effectively prevent land cover loss and its impacts, it follows that the PAs would contain areas of higher carbon stock value.

The higher TSOC values in PAs is significant given that the bulk of carbon in TOC (and in the carbon cycle) is TSOC (or in the soils) (DEA 2015). Soil organic carbon is greatly affected by land use and land cover changes over longer timescales (Guo & Gifford 2002;

Sanderman et al. 2018). Previous work has shown that the degradation of an area (e.g. by overgrazing) or its conversion to cropland has decreased TSOC (Smith 2008). In contrast, the transformation from forest to grassland or vice versa has had mixed results. Overall, human land use over the last few thousand years has led to the loss of soil organic carbon (Sanderman et al. 2018). The higher levels of TSOC in PAs show they are effective in protecting the country's soils and their TSOC. This contrast may be due to the sequestration of carbon inside PAs or the loss of TSOC outside of PAs. Either way, these results show that enlarging the PA network effectively enhances the TSOC in South Africa. In addition to the threat posed by land cover change, future increases in air temperature may decrease TSOC through increased rates of decomposition and the release of CO_2 (Wiesmeier et al. 2016). If TSOC is not effectively protected, a positive feedback system could be created, leading to soils becoming sources of carbon emissions rather than carbon sinks.

While TBOC contributes only a small portion of carbon to the TOC of an area, it is an important indicator of land use management. A study by Sintayehu et al. (2020) showed that aboveground carbon stocks are dependent on land cover and that natural and biodiverse areas are higher in carbon. The TBOC data was calculated by subtracting TSOC from TOC and consisted of aboveground and belowground woody and herbaceous carbon and litter carbon (DEFF 2020). Therefore, TBOC indicates more recent patterns of land use management, whereas TSOC indicates the changes in carbon stocks over a longer time frame. The higher TBOC values in PAs show they are more effective in protecting vegetation cover, which is supported by evidence from previous studies (Ament & Cumming 2016; Shumba et al. 2020).

The carbon differences depend on the original land cover and new land cover types (SANBI 2018). People may transform an area and utilise the land for agriculture or forestry. This results in carbon stock values that may be higher or the same as the previous land cover rather than lower (DEA 2015). The results of this study show that transformed areas in South Africa have greater carbon stock values than natural areas. South Africa's carbon sinks report (DEA 2015) shows that carbon values for plantation forests are higher than all the other land cover classes except indigenous forest, of which there is little area. The large size of cultivated and plantation forest land cover and low carbon value of the larger natural land cover classes (Savanna, Nama Karoo and Succulent Karoo) supports this study's findings of higher carbon stock value for transformed land cover areas than for natural land cover areas. However, the study's results also show that natural land cover inside PAs has a higher TOC, TSOC and TBOC average than transformed land cover outside of PAs. These higher values provide evidence that PAs offer effective restoration, protection or management of natural areas resulting in higher carbon stock values that are specifically biodiversity aligned. PAs can provide climate change resilience while protecting biodiversity (Watson et al. 2014; Shumba et al. 2020), which shows that PAs can provide effective forms of Ecosystem-based Mitigation (EbM) and Nature-based Solutions (NbS) (Cohen-Stacham et al. 2016).

The other part of the results shows that even though carbon stock values are higher in PAs, there is still a substantial area of carbon stocks of high value that need to be protected. The PA network covers nearly 10% of the country. It protects close to 15% of strategic water source areas (SWSAs), just over 20% of its strategic total organic carbon areas (STOCAs) and nearly 30% of the combined strategic carbon and water areas. Additionally, the country protects 43.6% of the SWSA & STOCA areas that are both groundwater and surface water SWSAs. Since the study by Nel et al. (2017) and Le Maitre et al. (2018), PAs now protect nearly 2% more of the SWSAs, which may be due to the enlargement of the PA network. While this may indicate some progress, there is still the need for more formal protection. South Africa’s total PA network area does not meet the 2020 17% target established by the Aichi 11 target (Secretariat of the Convention on Biological Diversity 2020) or the proposed 30% target (Hannah et al. 2020; CBD 2021).

However, the higher percentage of protection of strategic carbon and water areas (relative to the protection of the country) demonstrates that PAs are already partly located in areas that are strategic for climate change resilience and not just biodiversity or wildlife needs. Historically, PAs have been placed in inaccessible areas rather than solely for biodiversity or wildlife needs (Joppa & Pfaff 2009), which is being countered in the modern era. Considering this bias, it is likely that South African PAs have restored or maintained high carbon stock values better than areas outside of PAs. Calculating where the strategic carbon and water areas are may allow conservation planners to include these areas when designing PAs. For example, PAs could expand to cover a greater percentage of the groundwater and surface water SWSA & STOCA areas to protect areas important for carbon stocks and water resources.

4.2. Provincial category and Management Authority patterns

The inclusion of provincial categories and management authorities allows for an assessment of carbon stock values and PA coverage of SWSAs and STOCAs at a finer scale, which may be useful for policy-makers or conservation managers (Chape et al. 2005). PAs have higher carbon stock values, but Mpumalanga has lower TSOC values inside PAs, while KwaZulu-Natal and the Western Cape have lower TBOC values inside PAs. This shows that PAs effectively protect their carbon stocks in most provincial contexts. Although the type of biome could influence the carbon value, it was included as an environmental variable in order to control for any effect it might have on the model.

The high carbon values outside PAs for the three provinces above could be due to the proportion of unprotected STOCAs or high carbon stock values of transformed land cover in their provinces. The Western Cape protects half of its STOCAs but still has a large area open for protection. It could be that the STOCAs not yet covered are higher in carbon stock value. In KwaZulu-Natal, there are patches of transformed land throughout the province. This transformed land includes agricultural land such as sugarcane production, orchards and plantation forestry (Jewitt et al. 2015). Plantation forestry is high in carbon and has a large area in South Africa (DEA 2015), so the presence of forestry may be why TBOC is higher outside of PAs than inside PAs. The results show that there are valuable natural areas not yet protected in KwaZulu-Natal, as indicated by only 22.4% of the STOCAs being protected in the province.

The Limpopo, Eastern Cape, KwaZulu-Natal, Western Cape and Gauteng provinces all have high carbon stock values but particularly so inside their PAs (except for KwaZulu-Natal and the Western Cape for TBOC). In terms of the percent cover of STOCA, the Western Cape, Mpumalanga, Limpopo, KwaZulu-Natal and Gauteng provinces performed the best. The Western Cape, KwaZulu-Natal, Mpumalanga, Eastern Cape and Limpopo provinces performed the best in terms of area covered. Of all the PAs in the provinces, Limpopo is the most effective in terms of the protection it provides to its carbon stocks, while the Western Cape protects the greatest area and percentage of STOCAs. It appears that Limpopo, Eastern Cape, KwaZulu-Natal and the Western Cape PAs perform the best in terms of coverage and effectiveness in protecting their carbon stocks. Mpumalanga PAs perform well in terms of area covered, but they do not have high carbon stocks inside.

In terms of SWSAs, the Western Cape PAs protect the greatest percentage of their province for groundwater, surface water and combined categories. The Western Cape, Mpumalanga, Limpopo, KwaZulu-Natal and Eastern Cape PAs are the only provinces where PAs protect groundwater and surface water SWSAs. The Western Cape protects the greatest percentage as well as area, but KwaZulu-Natal has the largest SWSA area available for protection in the province. KwaZulu-Natal's unprotected areas have the highest TOC and TSOC values of all the province's unprotected areas, followed by the Eastern Cape. These two provinces also have the largest available STOCA.

Limpopo's unprotected areas have the highest TBOC, followed by KwaZulu-Natal. It appears that the east coast of South Africa below Lesotho (where the Eastern Cape and KwaZulu-Natal meet) requires more PAs to cover STOCAs and SWSAs. The recently proposed PA in the Eastern Cape will contribute to the protection of water resources and may contribute to the greater protection of these strategic carbon areas (SANParks 2021). It also appears that there is potential for expanding PAs to cover STOCAs for TBOC in Limpopo. It may make sense to increase protection in the provinces with a large carbon stock value outside the PAs. Conversely, it may also make sense to increase protection of degraded areas with low carbon stock values. Some areas low in carbon value may have the potential for higher carbon value if they are protected.

The broadly grouped PA management authorities have higher carbon stock values than unprotected areas. SANParks PAs have the highest TOC and TSOC carbon stock values of all the management authorities, while Private PAs have the lowest TOC and TSOC values. However, Private PAs have the highest TBOC values. Private PAs better protect the carbon stocks (TBOC) affected by more recent changes in land use. This finding supports Shumba et al. (2020), who showed higher natural land cover and biodiversity intactness inside Private PAs. These results also show that Private PAs are effective in protecting carbon stocks. The same can be said for PAs operating at the collective local scale and SANParks, which operates at the national scale.

The results show that SANParks is not performing as well in terms of the total area or percentage of strategic ecosystem service areas protected compared to Private PAs or the state-owned PAs, grouped as 'Other' in this analysis. SANParks protects far fewer of the

SWSAs (1.2%) than the other PAs, and though SANParks protects more of the STOCAs than Private PAs, its total area is more extensive than private PAs. One must consider that SANParks is one authority that must operate at the national scale (van Wilgen & Herbst 2016). The other two categories contain many different authorities (i.e., Ezemvelo KwaZulu-Natal Wildlife or CapeNature) that need only operate at the provincial or regional level. The results show that Other state-owned PAs protect large proportions of SWSAs, STOCAs and SWSA & STOCA areas. Provincial PA authorities and small municipality PAs contribute to this protection. Furthermore, the size of the protected strategic ecosystem service areas is proportionately higher than the total protected area of these Other PAs. This means the Other PAs are more strategically placed than those of Private PAs and SANParks. However, this may be due to SANParks PAs and Private PAs being placed in more arid provinces of the country where there are fewer SWSAs and lower carbon.

Other PAs may be more strategically placed, but they have lower carbon stock values than SANParks in terms of TOC and TSOC and lower values than Private PAs in terms of TBOC. SANParks has PAs in arid environments and sparsely vegetated habitats (e.g., Karoo National Park, Richtersveld, etc.) to protect their unique biodiversity features. This may be the reason for there being lower TBOC values, but these PAs are more important for their biodiversity (van Wilgen & Herbst 2016). SANParks PAs are national parks with many different animals. It could be that herbivore densities (such as elephants) reduce the vegetation cover and the carbon stock values of vegetation in PAs (Skowno et al. 2017). Reductions in vegetation cover and these carbon stocks would mean a reduction in climate change mitigation. SANParks should conduct a finer, more localised assessment to see where land cover management for water and carbon enhancement can be improved for specific PAs.

4.3. Future work and management implications

Systematic conservation planning is critical for achieving biodiversity and climate change targets (Margules & Pressey 2000; Chape et al. 2005; Hannah et al. 2020). Monitoring targets allows conservationists and managers to gauge progress for specific targets and identify where management needs improvement. This study should be repeated to monitor progress in PA expansion to cover the strategic ecosystem service areas and to assess how carbon stock values change over time in the protected and unprotected areas. Changes in the carbon stocks would also indicate the amount of carbon sequestered from the atmosphere (DEFF 2020).

This would allow for a study of carbon sequestration across the country and specifically in PAs. Carbon stock information for previous years can be used to compare these assessments, but the differences in land cover data and methods used to calculate the different datasets mean that these comparisons would be limited (DEFF 2020). With advances in climate change models, it may also be possible to model future changes to carbon stocks across the country (Cao & Woodward 1998). This could then identify future PA protection of carbon stocks, which may be useful in adjusting their management plans.

Other methods of protecting SWSAs or carbon stocks should be studied. Conservation areas are another form of area-based conservation that can contribute to biodiversity success and consider local people's needs (Maxwell et al. 2020). Implementing agricultural methods through more sustainable and non-polluting land management will likely lead to healthier groundwater SWSAs. Due to their spatial information, ecosystem services and their protection patterns are easier to assess for area-based conservation methods. It would be useful to carry out a similar study for other area-based conservation methods to assess how area-based conservation contributes to climate change resilience fully.

This study shows that PAs have higher carbon stock values than unprotected areas and effectively protect carbon stocks inside their borders. This indicates that management techniques inside PAs successfully protect carbon stocks. In particular, the Limpopo, Eastern Cape, KwaZulu-Natal and the Western Cape PAs should be studied further given their coverage of and effectiveness in protecting carbon stocks. SANParks PAs may be protecting soil carbon stocks better, or have in the past, while Private PAs are effectively protecting other carbon stocks. The PAs in all these areas may be using management techniques that could be shared across all PAs and outside of PAs too. PAs may be essential for climate change mitigation and a form of EbM that can be used under the NbS umbrella (Cohen-Stacham et al. 2016). While the management techniques of PAs should be evaluated, this study also shows that PAs need to expand their total area and their coverage of SWSAs, STOCAs and SWSA & STOCA areas to realise their full potential in protecting areas important for climate change resilience as well as other biodiversity targets.

The global PA network needs to expand to protect natural capital for biodiversity and societal benefits (Dasgupta 2020; Secretariat of the Convention on Biological Diversity 2020). Before COVID-19, the nature conservation sector was a net contributor to the global economy through tourism. Terrestrial PAs received around 8 billion visits per year, generating US $600 billion in direct expenditure in the country of the PA visited (Balmford et al. 2015). According to pre-COVID data, expanding the global PA network's area to 30% would generate greater revenues than without expansion, resulting in an extra $64 billion - $454 billion per year by 2050 while needing a minimum increased annual investment of ~$79 billion (Waldron et al. 2020). Expanding the PA estate would result in biodiversity, ecosystem service and economic benefits for global and local societies.

PA management authorities effectively protect natural and, therefore, biodiversity-aligned carbon stocks. Conservation managers should consider STOCAs with SWSAs and other ecosystem service metrics. These would be useful for systematic planning that may consider other biodiversity metrics, such as biodiversity hotspots (Myers et al. 2000) or ecological condition (Skowno et al. 2019). The most strategic areas to cover are the overlapping SWSA & STOCA areas. These are important for water and carbon stocks. I could not assess whether SWSA quality is higher in PAs or not. Groundwater may be better protected through changes to land management rather than protection status, but PAs do offer valuable protection (Le Maitre et al. 2018). Either way, this study identifies SWSA & STOCA areas that are groundwater, surface water, and ground and surface water. Expanding areas to protect carbon stocks would increase EbM, while expanding areas to protect water resources would increase Ecosystem-based Adaptation (EbA). Both would be considered NbS with increased protection leading to greater societal resilience towards climate change impacts (Cohen-Stacham et al. 2016; Dasgupta 2020).

The Eastern Cape and KwaZulu-Natal provinces have a large area of STOCAs, SWSAs and SWSA & STOCA areas that are not protected. These provinces have high carbon stock values in and outside of their PAs. Limpopo has fewer available STOCAs and SWSAs but a high value of TBOC outside its PAs. The Eastern Cape and KwaZulu-Natal provinces would be the best choices for PA expansion, as would the Limpopo province. It is also sensible to expand PAs in areas where the PAs are smaller and less effective such as in the Free State, Northern Cape and North West Provinces.

4.4. Limitations

Decisions about methods and data will have influenced the results of this study. Unfortunately, the necessary square-root transformation of the data limits interpretability. The differences in carbon stocks must be interpreted on the square-root scale, limiting comparisons to carbon stock values of other studies such as the carbon sink reports (DEA 2015; DEFF 2020). Additionally, the carbon stock data's coarse resolution (1 km2) is a caveat of the analysis. As a result of coarse-scale data, fine-scale spatial details are lost. This may have affected the carbon stock values and their comparison of the inside and outside PAs in the linear models. In particular, this may have affected the assessment of differences in carbon stocks where PAs were smaller and/or where areas of natural and transformed land cover types are close to each other.

Ament & Cumming (2016) found a similar result in their large-scale study on land cover in national parks. While this large-scale study uses coarse data, it is still useful in providing a proxy of carbon stock patterns across PAs and the country. The proxy is not flawless, but this does not mean it is without value (Shumba et al. 2020). More recent soil organic data exists at the 30 m^2 resolution (Venter et al. 2021), but there is not the equivalent data to form a dataset on TOC at the same resolution. These data would be very useful in allowing for a finer-scale assessment in the future.

Another limitation that links to the above is the data’s reliability. I encountered some errors in the SAPAD data when managing the data. These included incorrect province classifications of PAs and incorrect overlaps in some instances (e.g. Cape Floral Region Protected Areas covering Agulhas National Park). I corrected every error encountered, but it does raise the issue of trust in the data. Similar issues were found in the data cleaning stage for a report on natural capital accounting for South Africa’s protected areas (Statistics South Africa). The report concluded that there is high confidence in the PA data after 2000 but less confidence in the data from before. There is sometimes a degree of sampling error in field sampling and sometimes issues in mapping. It may still be possible that some errors have not been picked up, but SAPAD is continuously revised, and the errors that I and others found will be resolved.

In this study, I created a 10 km buffer zone around all the PAs to account for spill-over effects of PAs. However, spill-over effects change according to a range of factors, including the land cover type outside of the PA, the size of the PA and the distance from the PAs (Ament & Cumming 2016). Ament & Cumming (2016) show that natural cover was highest in the 10 km^2 closest to PAs, which is why that size was used. Therefore, the 10 km buffer zone was used for all of the PAs in the country, even though it may not be the best size for smaller PAs or PAs surrounded by different land-use areas. However, this made the most sense for a national-scale assessment. Future studies could include the buffer zone as an additional category to "Protected" and "Unprotected" areas.

Invasive alien plant (IAP) species may influence the high values of carbon stocks in some regions of the country. Invasive alien species drive biodiversity loss (Salafsky et al. 2008) and have various additional impacts, such as the reduction of water flows (Le Maitre et al. 2016). These species are present throughout the country and its national parks (van Wilgen & Herbst 2016). However, there are not yet data on the spatial extent of these species across the country, so I was unable to consider the influence of IAPs on the values of carbon stocks. Woody IAP species, such as the wattle Acacias, have larger biomass and more carbon. Therefore, higher carbon stock values inside PAs may be due to the presence of alien plants. With access to spatial data on the extent of invasive plants, future studies can better consider the variable's influence on carbon stocks across PAs.

4.5. Conclusion

This study set out to investigate the performance of South Africa's protected area network in protecting its carbon stocks and water resources. The results provide evidence that PAs have higher carbon stock values than areas outside of PAs, indicating that they effectively protect carbon stocks. Furthermore, natural areas inside PAs are higher in carbon than unprotected transformed or natural areas. The management techniques of PAs need to be studied to apply their success to other PAs and areas outside of PAs. In particular, Eastern Cape, KwaZulu-Natal, Limpopo and Western Cape PAs performed the best in protecting their carbon stocks. Private PAs should be evaluated for their current land use management. The effective protection of carbon stocks demonstrates that PAs contribute toward climate change mitigation and resilience under the Nature-based Solutions (NbS) umbrella. PAs need to expand to meet international targets and protect more of the STOCAs, SWSAs and SWSA &

STOCA areas. Expanding protection is essential for improving the mitigation and adaptation of South Africa and the world to climate change impacts.

This study assesses two metrics of PA performance in protecting PAs – effectiveness and land area coverage. It should be repeated to monitor PAs' effectiveness in protecting carbon stocks and carbon sequestration over time. Repeating the study will also allow the monitoring and guidance of PAs in meeting land area coverage of strategic ecosystem service areas. PAs are strategically placed, but large areas of the country still require protection. The Eastern Cape and KwaZulu-Natal provinces have large strategic ecosystem service areas available for protection and have high carbon stock values inside and outside their PAs, while Limpopo has large carbon stock values inside and outside their PAs. Therefore, the Eastern Cape and KwaZulu-Natal provinces would be the best choices (followed by Limpopo) for PA expansion to increase climate change resilience. Considering the new PA to be established in the Eastern Cape, the next step may be to expand PAs in KwaZulu-Natal.

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Supplementary Information

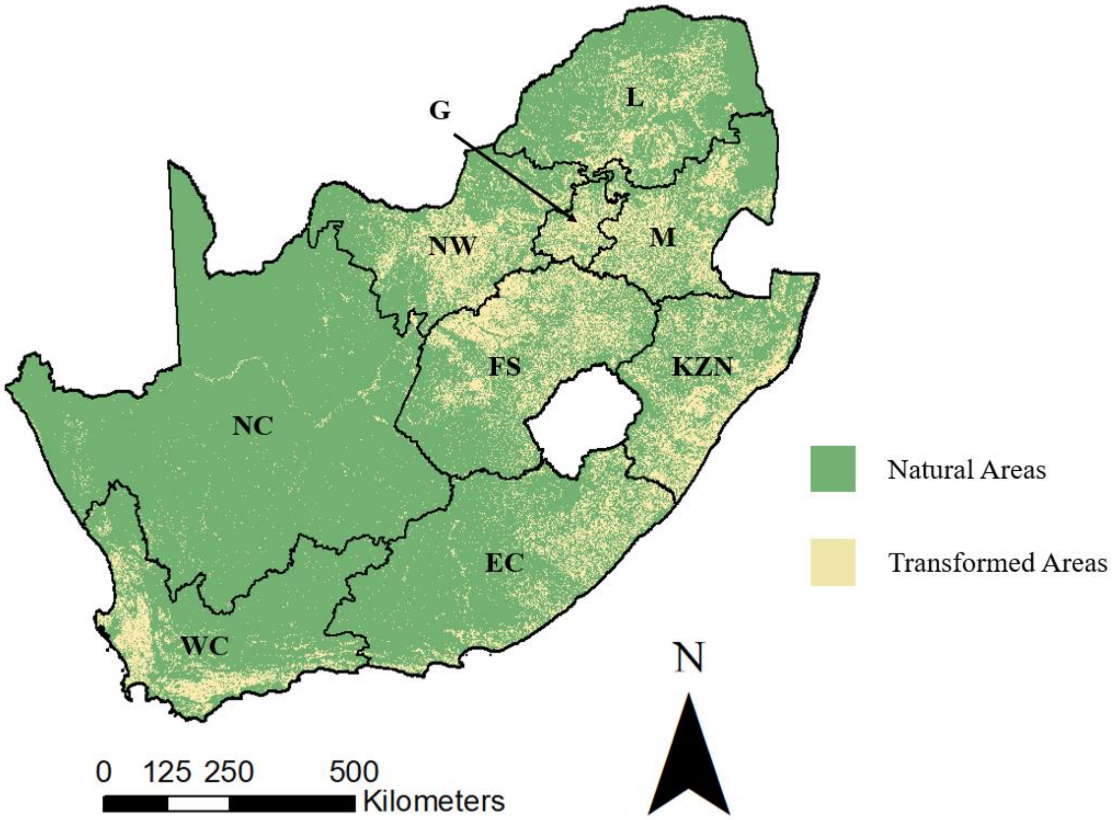

Figure A1. Map of South Africa's natural and transformed areas. The provinces of the country include Limpopo (L), North West (NW), Gauteng (G), Mpumalanga (M), the Northern Cape (NC), Free State (FS), KwaZulu-Natal (KZN), Western Cape (WC) and Eastern Cape (EC).

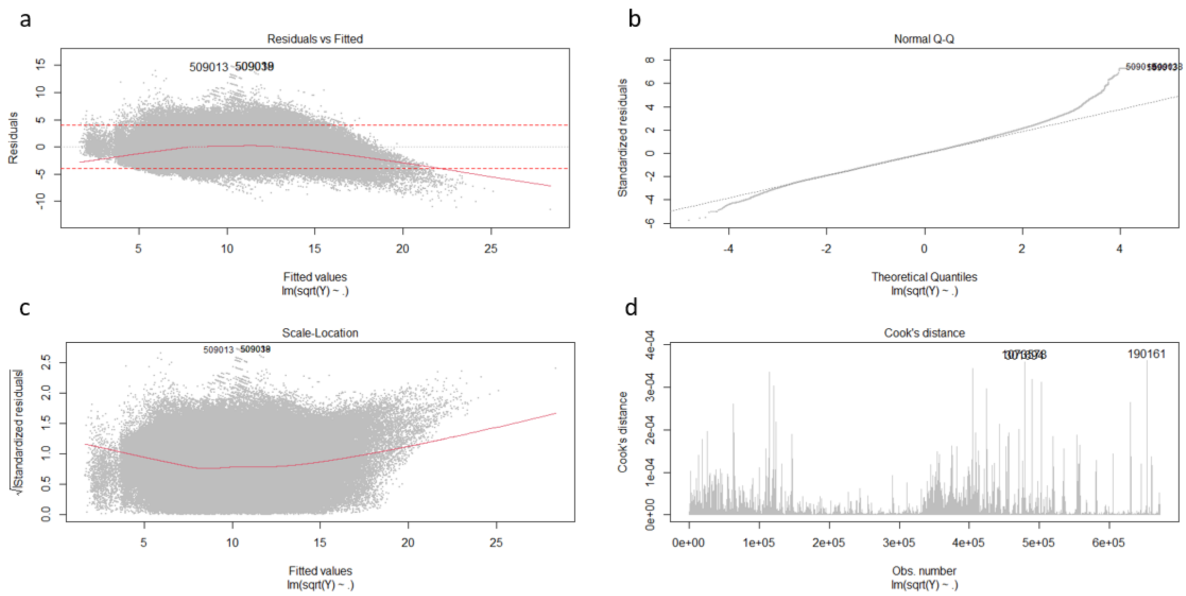

Figure A2. Diagnostic plots for a piecewise linear model using matched data. The model was for the square root of total organic carbon (TOC) (t/ha) in response to treatment ("Protected" versus "Unprotected"). The model used data that was matched according to environmental variables, including biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). Diagnostic plots a) Residuals vs Fitted, b) a quantile-quantile, c) Scale-Location, and d) Cook's distance were used.

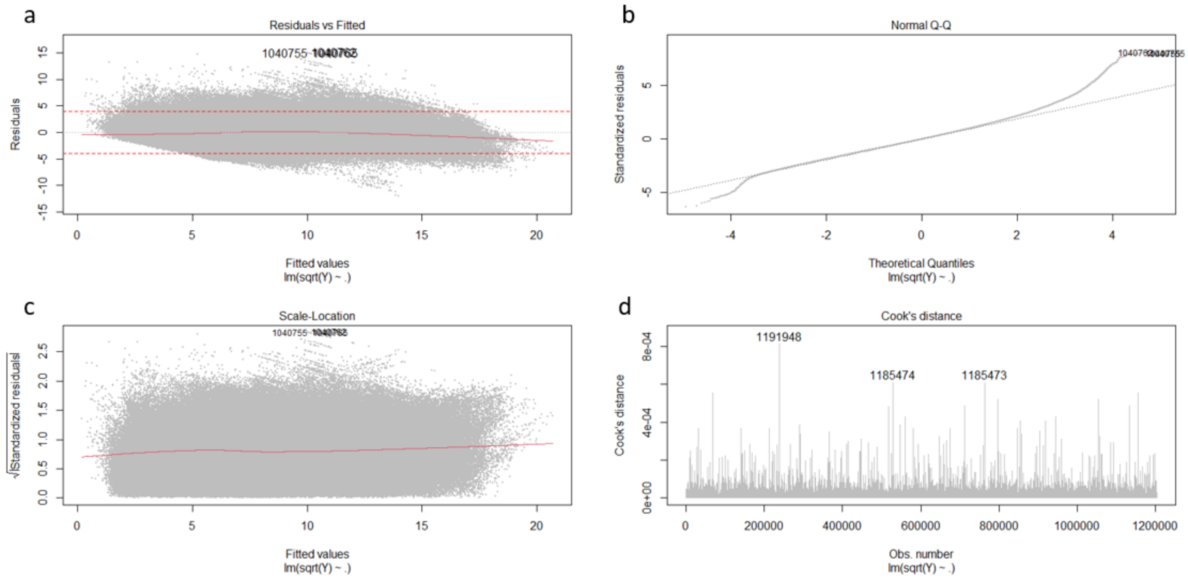

Figure A3. Diagnostic plots for a piecewise linear model using unmatched data. The model was for the square root of total organic carbon (TOC) (t/ha) in response to treatment ("Protected" versus "Unprotected"). Multiple environmental variables are also included. The environmental variables include biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). Diagnostic plots a) Residuals vs Fitted, b) Normal Q-Q (or quantile-quantile), c) Scale-Location, and d) Cook's distance were used.

Table A1. Number of South African protected areas (PA), and the percentage (%) and area (km^2) of South Africa's mainland protected categorised according to broad PA management authorities

PA Authorities	Nnumber of Protected Areas	% Area	Area (km^2)
Other	600	4.2	51866
Private	901	2.1	26113
SANParks	43	3.4	42085
Grand Total	1544	9.8	120064

Table A2. **Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the interaction between treatment ("Protected" versus "Unprotected") and land-cover state ("Transform" versus "Natural).** Multiple environmental variables are also included. The environmental variables include biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). The baseline biome designation is "Albany Thicket". P-values designated as NS are non-significant. The variables in bold refer to the 'knots' where the relationship of the piecewise model changes.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	TreatmentProtected:SANLCNatural	0.487	0.017	28.648	<0.001
	TreatmentProtected	0.417	0.016	25.341	<0.001
	SANLCNatural	-0.125	0.009	-13.583	<0.001
	BiomeAzonal Vegetation	-1.034	0.017	-61.185	<0.001
	BiomeDesert	-0.431	0.028	-15.241	<0.001
	BiomeForests	0.819	0.022	36.934	<0.001
	BiomeFynbos	1.096	0.014	79.944	<0.001
	BiomeGrassland	-1.910	0.014	-138.847	<0.001
	BiomeIndian Ocean Coastal Belt	-0.301	0.030	-9.915	<0.001
	BiomeNama-Karoo	-0.246	0.013	-18.485	<0.001
	BiomeSavanna	-2.093	0.012	-167.925	<0.001
	BiomeSucculent Karoo	0.636	0.014	43.922	<0.001
	MAP	0.251	0.000	532.773	<0.001
	Slope	0.313	0.001	412.425	<0.001
	Elevation	-0.001	0.000	-60.437	<0.001
	Road_dist	0.000	0.000	-11.608	<0.001
	Places_near	0.000	0.000	20.565	<0.001
	MAP_31	-0.155	0.001	-278.446	<0.001
	MAP_76	-0.127	0.001	-122.598	<0.001
	Slope_9.614593	-0.265	0.001	-239.856	<0.001

	Elevation_1156	0.003	0.000	167.801	<0.001
sqrt(TSOC)	TreatmentProtected:SANLCNatural	0.392	0.016	24.020	<0.001
	TreatmentProtected	0.309	0.016	19.579	<0.001
	SANLCNatural	-0.081	0.009	-9.153	<0.001
	BiomeAzonal Vegetation	-0.823	0.016	-50.675	<0.001
	BiomeDesert	-0.303	0.027	-11.205	<0.001
	BiomeForests	0.799	0.021	37.538	<0.001
	BiomeFynbos	1.065	0.013	80.874	<0.001
	BiomeGrassland			-	
		-1.691	0.013	128.313	<0.001
	BiomeIndian Ocean Coastal Belt	-0.284	0.029	-9.813	<0.001
	BiomeNama-Karoo	-0.012	0.013	-0.935	NS
	BiomeSavanna			-	
		-2.085	0.012	174.395	<0.001
	BiomeSucculent Karoo	0.704	0.014	50.700	<0.001
	MAP	0.209	0.000	504.701	<0.001
	Slope	0.285	0.001	391.698	<0.001
	Elevation	0.000	0.000	-20.938	<0.001
	Road_dist	0.000	0.000	-3.414	<0.001
	Places_near	0.000	0.000	13.773	<0.001
	MAP_80			-	
		-0.137	0.001	111.333	<0.001
	MAP_33			-	
		-0.113	0.001	225.217	<0.001
	Slope_9.657719			-	
		-0.240	0.001	227.065	<0.001
	Elevation_1197	0.003	0.000	163.830	<0.001
sqrt(TBOC)	TreatmentProtected:SANLCNatural	0.237	0.009	25.989	<0.001
	TreatmentProtected	0.224	0.009	25.442	<0.001
	SANLCNatural	-0.143	0.005	-28.934	<0.001
	BiomeAzonal Vegetation	-0.720	0.009	-79.692	<0.001
	BiomeDesert	-0.884	0.015	-59.002	<0.001
	BiomeForests	0.398	0.012	33.575	<0.001
	BiomeFynbos	0.484	0.007	65.721	<0.001
	BiomeGrassland			-	
		-0.955	0.007	130.341	<0.001
	BiomeIndian Ocean Coastal Belt	0.098	0.016	6.104	<0.001
	BiomeNama-Karoo	-0.615	0.007	-86.415	<0.001
	BiomeSavanna	-0.489	0.007	-73.309	<0.001
	BiomeSucculent Karoo	-0.087	0.008	-11.379	<0.001

MAP	0.112	0.000	574.814	<0.001
Slope	0.145	0.000	361.893	<0.001
Elevation			-	
	-0.001	0.000	158.966	<0.001
Road_dist	0.000	0.000	-24.439	<0.001
Places_near	0.000	0.000	35.432	<0.001
MAP_39			-	
	-0.113	0.000	253.594	<0.001
MAP_91	0.096	0.001	78.898	<0.001
MAP_50	-0.032	0.000	-74.109	<0.001
Slope_9.844008			-	
	-0.130	0.001	220.573	<0.001
Elevation_1145	0.001	0.000	85.458	<0.001

Table A3. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the interaction between the treatment ("Protected" versus "Unprotected" status) and South Africa's provincial designation. Multiple environmental variables are also included. The provinces include the Eastern Cape (the baseline category), Free State, Gauteng, KwaZulu-Natal, Limpopo, Mpumalanga, North West, Northern Cape and Western Cape. The environmental variables include biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). The baseline province is the Eastern Cape, and the biome designation is "Albany Thicket". P-values designated as NS are non-significant. The variables in bold refer to the 'knots' where the relationship of the piecewise model changes.

Response Variable	Explanatory Variables	Estimate	Standard Error	t value	P-value
sqrt(TOC)	TreatmentProtected:ProvinceFree.State	-0.189	0.018	-10.310	<0.001
	TreatmentProtected:ProvinceGauteng	1.286	0.035	36.873	<0.001
	TreatmentProtected:ProvinceKwaZulu.Natal	-0.368	0.019	-19.155	<0.001
	TreatmentProtected:ProvinceLimpopo	0.452	0.018	25.170	<0.001
	TreatmentProtected:ProvinceMpumalanga	-0.728	0.021	-35.200	<0.001
	TreatmentProtected:ProvinceNorth.West	0.190	0.020	9.472	<0.001
	TreatmentProtected:ProvinceNorthern.Cape	0.046	0.025	1.808	NS
	TreatmentProtected:ProvinceWestern.Cape	-0.202	0.018	-11.033	<0.001
	TreatmentProtected	0.769	0.014	54.036	<0.001
	ProvinceFree State	-1.202	0.010	-121.597	<0.001
	ProvinceGauteng	-1.564	0.024	-63.930	<0.001
	ProvinceKwaZulu-Natal	0.315	0.011	28.324	<0.001
	ProvinceLimpopo	-0.037	0.012	-3.137	0.002
	ProvinceMpumalanga	-0.553	0.013	-43.347	<0.001
	ProvinceNorth West	-1.682	0.010	-173.364	<0.001
	ProvinceNorthern Cape	-0.553	0.009	-63.100	<0.001
	ProvinceWestern Cape	-0.142	0.011	-12.926	<0.001
	BiomeAzonal Vegetation	-0.997	0.017	-60.237	<0.001
	BiomeDesert	-0.855	0.028	-30.708	<0.001
	BiomeForests	1.069	0.022	49.045	<0.001

	BiomeFynbos	1.302	0.015	85.861	<0.001
	BiomeGrassland	-1.841	0.014	-133.705	<0.001
	BiomeIndian Ocean Coastal Belt	-0.010	0.029	-0.353	NS
	BiomeNama-Karoo	-0.448	0.013	-33.741	<0.001
	BiomeSavanna	-2.035	0.013	-156.127	<0.001
	BiomeSucculent Karoo	0.503	0.015	34.628	<0.001
	MAP	0.188	0.001	271.327	<0.001
	Slope	0.033	0.003	9.469	<0.001
	Elevation	0.000	0.000	-4.784	<0.001
	Road_dist	0.000	0.000	-10.831	<0.001
	Places_near	0.000	0.000	-11.098	<0.001
	MAP_31	-0.274	0.002	-158.776	<0.001
	MAP_77	-0.107	0.001	-99.069	<0.001
	MAP_26	0.169	0.002	84.665	<0.001
	Slope_9.614593	-0.279	0.001	-223.494	<0.001
	Slope_2.102442	0.288	0.004	73.513	<0.001
	Elevation_1156	0.004	0.000	163.974	<0.001
	Elevation_1468	-0.003	0.000	-85.049	<0.001
sqrt(TSOC)	TreatmentProtected:ProvinceFree.State	-0.011	0.018	-0.625	NS
	TreatmentProtected:ProvinceGauteng	1.396	0.034	41.336	<0.001
	TreatmentProtected:ProvinceKwaZulu.Natal	-0.237	0.019	-12.785	<0.001
	TreatmentProtected:ProvinceLimpopo	0.641	0.017	36.808	<0.001
	TreatmentProtected:ProvinceMpumalanga	-0.685	0.020	-34.200	<0.001
	TreatmentProtected:ProvinceNorth.West	0.120	0.019	6.195	<0.001
	TreatmentProtected:ProvinceNorthern.Cape	0.259	0.024	10.607	<0.001
	TreatmentProtected:ProvinceWestern.Cape	0.086	0.018	4.859	<0.001
	TreatmentProtected	0.605	0.014	43.922	<0.001
	ProvinceFree State	-1.075	0.010	-112.780	<0.001
	ProvinceGauteng	-1.619	0.024	-68.284	<0.001
	ProvinceKwaZulu-Natal	0.321	0.011	29.717	<0.001
	ProvinceLimpopo	-0.492	0.011	-43.171	<0.001
	ProvinceMpumalanga	-0.495	0.012	-40.012	<0.001
	ProvinceNorth West	-1.582	0.009	-169.031	<0.001
	ProvinceNorthern Cape	-0.489	0.008	-57.737	<0.001

	ProvinceWestern Cape	-0.215	0.010	-20.580	<0.001
	BiomeAzonal Vegetation	-0.736	0.016	-45.876	<0.001
	BiomeDesert	-0.250	0.027	-9.383	<0.001
	BiomeForests	0.961	0.021	45.520	<0.001
	BiomeFynbos	1.128	0.015	76.862	<0.001
	BiomeGrassland	-1.573	0.013	-118.270	<0.001
	BiomeIndian Ocean Coastal Belt	-0.102	0.028	-3.573	<0.001
	BiomeNama-Karoo	-0.146	0.013	-11.349	<0.001
	BiomeSavanna	-1.861	0.013	-147.719	<0.001
	BiomeSucculent Karoo	0.713	0.014	50.948	<0.001
	MAP	0.195	0.000	397.538	<0.001
	Slope	0.027	0.003	8.448	<0.001
	Elevation	0.000	0.000	16.891	<0.001
	Road_dist	0.000	0.000	-6.347	<0.001
	Places_near	0.000	0.000	-9.612	<0.001
	MAP_80	-0.126	0.001	-103.524	<0.001
	MAP_33	-0.105	0.001	-184.488	<0.001
	Slope_9.657719	-0.251	0.001	-205.361	<0.001
	Slope_2.202518	0.263	0.004	72.890	<0.001
	Elevation_1197	0.005	0.000	168.664	<0.001
	Elevation_1464	-0.004	0.000	-97.184	<0.001
sqrt(TBOC)	TreatmentProtected:ProvinceFree.State	-0.401	0.010	-41.535	<0.001
	TreatmentProtected:ProvinceGauteng	-0.066	0.018	-3.576	<0.001
	TreatmentProtected:ProvinceKwaZulu.Natal	-0.602	0.010	-59.565	<0.001
	TreatmentProtected:ProvinceLimpopo	-0.258	0.009	-27.290	<0.001
	TreatmentProtected:ProvinceMpumalanga	-0.174	0.011	-15.925	<0.001
	TreatmentProtected:ProvinceNorth.West	0.268	0.011	25.443	<0.001
	TreatmentProtected:ProvinceNorthern.Cape	-0.273	0.013	-20.519	<0.001
	TreatmentProtected:ProvinceWestern.Cape	-0.513	0.010	-53.063	<0.001
	TreatmentProtected	0.471	0.008	62.773	<0.001
	ProvinceFree State	-0.444	0.005	-86.333	<0.001
	ProvinceGauteng	-0.012	0.013	-0.940	NS
	ProvinceKwaZulu-Natal	0.120	0.006	20.435	<0.001
	ProvinceLimpopo	0.959	0.006	155.059	<0.001
	ProvinceMpumalanga	-0.216	0.007	-32.178	<0.001

ProvinceNorth West	-0.611	0.005	-119.830	<0.001
ProvinceNorthern Cape	-0.398	0.005	-84.770	<0.001
ProvinceWestern Cape	-0.108	0.006	-18.788	<0.001
BiomeAzonal Vegetation	-0.802	0.009	-92.140	<0.001
BiomeDesert	-1.202	0.014	-83.458	<0.001
BiomeForests	0.738	0.011	64.556	<0.001
BiomeFynbos	0.724	0.008	90.638	<0.001
BiomeGrassland	-0.889	0.007	-124.100	<0.001
BiomeIndian Ocean Coastal Belt	0.305	0.015	19.900	<0.001
BiomeNama-Karoo	-0.882	0.007	-126.539	<0.001
BiomeSavanna	-0.663	0.007	-96.869	<0.001
BiomeSucculent Karoo	-0.318	0.008	-41.918	<0.001
MAP	0.090	0.000	381.718	<0.001
Slope	0.131	0.000	335.697	<0.001
Elevation	-0.001	0.000	-127.186	<0.001
Road_dist	0.000	0.000	-2.574	0.01
Places_near	0.000	0.000	-41.565	<0.001
MAP_39	-0.114	0.000	-395.467	<0.001
Slope_9.844008	-0.115	0.001	-204.054	<0.001
Elevation_1145	-0.003	0.000	-65.903	<0.001
Elevation_1056	0.003	0.000	88.325	<0.001

Table A4. Summary statistics from three piecewise linear models for the square root of total organic carbon (TOC) (t/ha), the square root of Total Soil Organic Carbon (TSOC) (t/ha) and the square-root of Total Biomass Organic Carbon (TBOC) (t/ha) in response to the treatment (protected area status) and multiple environmental variables. "Unprotected" was the control for the treatment while different Protected Area management authorities consisted of the other treatment categories. These included South African National Parks (SANParks), Private protected areas (Private), the remaining state-owned management authorities (Other). The environmental variables include biome, mean annual precipitation (MAP) (mm), slope, elevation (m), distance to roads (m) and distance to populated areas (m). The baseline biome designation is "Albany Thicket". P-values designated as NS are non-significant. The variables in bold refer to the 'knots' where the relationship of the piecewise model changes.

Response Variable	**Explanatory Variables**	**Estimate**	**Standard Error**	**t value**	**P-value**
sqrt(TOC)	Man_treatmentOther	0.830	0.007	125.088	<0.001
	Man_treatmentPrivate	0.774	0.005	151.298	<0.001
	Man_treatmentSANParks	1.261	0.016	80.625	<0.001
	BiomeAzonal Vegetation	-1.048	0.017	-62.149	<0.001
	BiomeDesert	-0.715	0.029	-25.069	<0.001
	BiomeForests	0.747	0.022	33.718	<0.001
	BiomeFynbos	1.123	0.014	82.083	<0.001
	BiomeGrassland	-1.979	0.014	-143.706	<0.001
	BiomeIndian Ocean Coastal Belt	-0.274	0.030	-9.079	<0.001
	BiomeNama-Karoo	-0.253	0.013	-19.089	<0.001
	BiomeSavanna	-2.159	0.012	-173.096	<0.001
	BiomeSucculent Karoo	0.567	0.014	39.149	<0.001
	MAP	0.212	0.001	312.532	<0.001
	Slope	0.313	0.001	412.762	<0.001
	Elevation	0.000	0.000	-46.240	<0.001
	Road_dist	0.000	0.000	58.518	<0.001
	Places_near	0.000	0.000	28.524	<0.001
	MAP_31	-0.270	0.002	-168.513	<0.001

	MAP_76	-0.119	0.001	-113.447	<0.001
	MAP_26	0.150	0.002	77.628	<0.001
	Slope_9.614593	-0.266	0.001	-242.168	<0.001
	Elevation_1179	0.003	0.000	158.972	<0.001
	Road_dist_4726.596665	0.000	0.000	-71.117	<0.001
sqrt(TSOC)	Man_treatmentOther	0.715	0.006	111.743	<0.001
	Man_treatmentPrivate	0.591	0.005	121.061	<0.001
	Man_treatmentSANParks	1.180	0.015	77.739	<0.001
	BiomeAzonal Vegetation	-0.821	0.016	-50.651	<0.001
	BiomeDesert	-0.243	0.027	-8.974	<0.001
	BiomeForests	0.700	0.021	32.827	<0.001
	BiomeFynbos	1.039	0.013	79.061	<0.001
	BiomeGrassland	-1.671	0.013	-126.684	<0.001
	BiomeIndian Ocean Coastal Belt	-0.288	0.029	-9.975	<0.001
	BiomeNama-Karoo	-0.017	0.013	-1.348	NS
	BiomeSavanna	-2.084	0.012	-174.086	<0.001
	BiomeSucculent Karoo	0.709	0.014	51.059	<0.001
	MAP	0.210	0.000	504.439	<0.001
	Slope	0.281	0.001	387.161	<0.001
	Elevation	0.000	0.000	-18.756	<0.001
	Road_dist	0.000	0.000	58.512	<0.001
	Places_near	0.000	0.000	-0.092	NS
	MAP_80	-0.142	0.001	-115.623	<0.001
	MAP_33	-0.112	0.001	-222.611	<0.001
	Slope_9.657719	-0.237	0.001	-224.776	<0.001
	Elevation_1197	0.003	0.000	161.140	<0.001
	Road_dist_4855.420970	0.000	0.000	-53.732	<0.001
	Road_dist_11286.817200	0.000	0.000	5.103	<0.001
	Places_near_16729.864530	0.000	0.000	5.039	<0.001
	Places_near_21436.319810	0.000	0.000	-15.158	<0.001
	Places_near_25781.753070	0.000	0.000	25.022	<0.001
sqrt(TBOC)	Man_treatmentOther	0.327	0.004	92.147	<0.001

Man_treatmentPrivate	0.513	0.003	183.994	<0.001
Man_treatmentSANParks	0.253	0.008	29.975	<0.001
BiomeAzonal Vegetation	-0.737	0.009	-81.442	<0.001
BiomeDesert	-0.903	0.015	-60.272	<0.001
BiomeForests	0.441	0.012	37.118	<0.001
BiomeFynbos	0.483	0.007	65.640	<0.001
BiomeGrassland	-0.975	0.007	-132.703	<0.001
BiomeIndian Ocean Coastal Belt	0.086	0.016	5.376	<0.001
BiomeNama-Karoo	-0.641	0.007	-89.775	<0.001
BiomeSavanna	-0.516	0.007	-77.152	<0.001
BiomeSucculent Karoo	-0.115	0.008	-14.861	<0.001
MAP	0.112	0.000	574.457	<0.001
Slope	0.145	0.000	363.306	<0.001
Elevation	-0.001	0.000	-160.862	<0.001
Road_dist	0.000	0.000	-22.799	<0.001
Places_near	0.000	0.000	30.735	<0.001
MAP_39	-0.113	0.000	-254.070	<0.001
MAP_91	0.094	0.001	77.398	<0.001
MAP_50	-0.030	0.000	-68.703	<0.001
Slope_9.844008	-0.129	0.001	-220.503	<0.001
Elevation_1145	0.001	0.000	87.477	<0.001