Landscape-scale carbon stocks in the subtropical thicket of the Baviaanskloof, South Africa

Neha Kooverjee

A dissertation submitted to the Faculty of Science, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science.

28 August 2024 in Johannesburg, South Africa

Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any other degree or examination at any other university.

Neha Kooverjee

28th day of August 2024 in Johannesburg, South Africa

Abstract

South Africa's subtropical thicket biome has garnered interest for its potential for carbon sequestration through the restoration of degraded land, funded locally and internationally by the carbon market. Accurate carbon estimation of pre- and post-restoration carbon storage is key to monitoring the progress of restoration efforts and determining accurate estimates of carbon increase. Most past thicket studies have based landscape-scale carbon estimates on plot data alone, without accounting for the spatial variation in factors such as soil depth, resulting in overestimates of the average potential carbon that can be stored.

The aim of this research was to estimate and create maps showing the spatial distribution of the thicket carbon stocks in the Baviaanskloof Nature Reserve, South Africa, by calculating the amount of carbon stored in the soil, woody biomass, root biomass and litter biomass across the thicket area of the reserve using plot data with remote sensing imagery.

Soil organic carbon was estimated using soil profile data collected in the same primary catchment as the Baviaanskloof and extrapolated across the landscape using a Random Forest-based regression model. Woody carbon was estimated using previously recorded *in situ* carbon recordings. This data was then extrapolated across the landscape using raster data for vegetation height and cover, climate data, and elevation as predictor variables. Root and litter carbon were then calculated individually based on the woody carbon estimates and ratios of root and litter carbon to woody carbon from a past study.

The average soil organic carbon (37.7 ± 29 t ha^{-1}), woody carbon (18.1 ± 4 t ha^{-1}), root carbon (3.1 ± 0.7 t ha^{-1}), and litter carbon (2.4 ± 0.5 t ha^{-1}) estimated in this study for intact thicket are all lower to varying degrees than those of past thicket studies that were based solely on plot data, indicating the importance of accounting for variation in the landscape and its effect on carbon stocks.

The results of this study indicate that slope position, a proxy for soil depth, has a significant effect on thicket carbon stock. Woody carbon, root carbon and litter carbon estimates significantly decreased downslope, but soil organic carbon, the largest carbon pool in thicket, significantly increased downslope. In general, the results also indicate an increase in carbon after restoration, however, an illogical trend of lower potential root and litter carbon compared to current carbon in degraded thicket is present, indicating that the results of this study are not reliable for restoration planning and decision-making. This may be due to the inaccuracy of global Light Detection and Ranging (LiDAR) products, such as the Global Land Analysis and Discovery (GLAD) canopy height dataset, over non-forested areas such as thicket which are much shorter.

Accurate estimates of current and potential carbon and accurate monitoring of restoration is important in tracking South Africa's progress towards its biodiversity conservation goals under the Convention on Biological Diversity, and carbon emission reduction goals under the Paris Agreement. With access to locally captured LiDAR imagery that is suited to the short, dense structure of thicket vegetation and the topography of the landscape, and a larger database of *in situ* thicket carbon recordings, the methods used in this study could be employed to calculate more accurate carbon estimates and aid in directing restoration efforts to the most appropriate areas.

Dedication

This dissertation is dedicated to the memory of

Robert John Scholes

without whom this research wouldn't exist

Acknowledgements

I am immensely grateful to Bob Scholes, under whose supervision I began this degree. His thoughts and planning behind this research were guiding me and helping me long after he was gone, and I am so grateful for the opportunity I had to learn from him.

Thank you to my co-supervisors – Kathleen Smart and Jolene Fisher. Kathleen, you took me under your wing, without hesitation, when the future of my degree was up in the air. Your firm belief in me and this research was the encouragement that I needed to carry on when I felt like giving up. Jolene, you supported me tremendously, especially through the last leg of this degree. Thank you for your unfailing encouragement and guidance. I would not have been able to finish this without your support.

I am also very grateful to the Living Lands organisation which provided the funding for my degree and all the associated travel costs.

Mike, your MSc formed the foundation for mine and provided a valuable resource for me to refer to during my own research. Thank you for your contributions to the planning of this research and for sharing your data with me.

My deepest gratitude goes to my family for all the support and encouragement throughout this journey. I would not have been able to do any of this without you.

Contents

List of Figures

List of Tables

List of Acronyms

AGC	Aboveground carbon
ARC	Agricultural Research Council
C_{Root}	Root carbon
C_{Woody}	Woody carbon
CAM	Crassulacean acid metabolism
CBD	Convention on Biological Diversity
CDM	Clean Development Mechanism
CERs	Certified emissions reduction credits
C_{litter}	Litter carbon
C_{soil} / SOC	Soil organic carbon
DEM	Digital elevation model
ECPTA	Eastern Cape Parks and Tourism Agency
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization of the United Nations
GEDI	Global Ecosystem Dynamics Investigation
GEM	Global Ecosystem Monitoring
GHG	Greenhouse Gas
GLAD	Global Land Analysis and Discovery
GLM	Generalized Linear Model
LiDAR	Light Detection and Ranging
NASA	National Aeronautics and Space Administration
NDCs	Nationally Determined Contributions
NPP	Net primary productivity
P/E_0	Precipitation/Evaporation
SAR	Synthetic Aperture Radar
SRTM	Shuttle Radar Topography Mission
STEP	Subtropical Thicket Ecosystem Planning Project
TPI	Topographic position index
TWP	Thicket-wide plots
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

1.1 Rationale

Topics such as carbon sequestration and vegetation restoration are garnering more interest as first-hand experience of the effects of climate change continues to increase. The United Nations Framework Convention on Climate Change (UNFCCC) has declared 2021 to 2030 to be the Decade on Ecosystem Restoration, in an effort to highlight ecosystem degradation, encourage restoration efforts and combat climate change (United Nations Decade on Ecosystem Restoration, no date (a)). Globally, restoration of terrestrial ecosystems for the purpose of carbon sequestration is generally aimed at degraded forest biomes, however, the subtropical thicket biome in South Africa (hereafter referred to as thicket) has been promoted as an ideal region for restoration funded by the carbon market (Marais et al., 2009; Pierce et al., 2009). Despite the relatively small extent of the biome, restoration of thicket vegetation and ecosystem processes would also contribute to South Africa's goal of restoring 17 546 772 ha of degraded land under the United Nations) (UN) Decade on Ecosystem Restoration.

To better manage and monitor restoration efforts, it is important to have reasonably accurate estimates of the current (baseline) and potential (restored) carbon stocks within the soil and vegetation of the target area. Spatially explicit current and potential carbon estimates can inform decision makers about the most suitable areas for restoration efforts to be directed, help improve estimates of the amount of carbon that can realistically be sequestered over a given number of years, as well as better monitor the success and progress of restoration projects and how many carbon credits a particular project is worth.

Over the years, there have been many thicket studies, where *in situ* data of the vegetation, soil, litter, and other thicket features have been collected from plots. Manual data collection over large areas is highly laborious and unrealistic to achieve, particularly within thicket, given the dense and multi-stemmed structure of the vegetation. Remote sensing products such as Light Detection and Ranging (LiDAR) provide an easier way to monitor carbon storage and restoration efforts compared to *in situ* plot data collection over large areas, which is highly labour intensive and unfeasible over large areas (Goetz and Dubayah, 2011). LiDAR has been used effectively with *in situ* data to estimate aboveground biomass particularly in forest biomes (Dubayah et al., 2010; Goetz and Dubayah, 2011; Torre-Tojal et al., 2022). Many global remote sensing products are now widely accessible on platforms such as Google Earth Engine and provide various options to study thicket at larger scales and produce spatially explicit estimates that could assist in directing restoration efforts to suitable

areas. Remote sensing products such as Light Detection and Ranging (LiDAR) provide an easier way to monitor carbon storage and restoration efforts compared to *in situ* plot data collection over large areas, which is highly labour intensive. Many of these global remote sensing products are now widely accessible on platforms such as Google Earth Engine (Gorelick et al., 2017) and provide various options to study thicket at larger scales and produce spatially explicit estimates that could assist in directing restoration efforts to suitable areas.

1.2 Research aim and objective

The aim of this study was to quantify the potential and current organic carbon stocks in the vegetation and soil of the subtropical thicket within the Baviaanskloof Nature Reserve, South Africa, at a scale of several hundred kilometres and with a resolution that is compatible with the spatial variability in the landscape. This was achieved by calculating the potential and current woody carbon, root carbon, litter carbon and soil organic carbon (SOC) using previously collected *in situ* data as well as remotely sensed imagery at a resolution of 30 m.

The objective of the study was to create validated maps of current and potential carbon density (t ha^{-1}) for the thicket area of the Baviaanskloof, using the available calibration samples. This included assessing the carbon within each pool, as well as an estimate of uncertainty for each, where possible.

1.3 Background literature

Global biological diversity and carbon reduction strategies

The Convention on Biological Diversity (CBD) international treaty was established by the UN in Rio de Janeiro at the Earth Summit in 1993, to conserve biological diversity, promote sustainable use of natural resources, and ensure the equitable distribution of the benefits of genetic resources (CBD, 2012). Under the CBD, South Africa has 29 targets that are categorised into six main objectives (CBD, 2020). Of those, thicket restoration would contribute to managing biological assets and their value to the country, investing in ecological infrastructure to improve resilience, encouraging people to follow biologically sustainable practices, and conserving and sustainably managing biodiversity.

In 1997, under the Kyoto Protocol, the UNFCCC established the Clean Development Mechanism (CDM) where developed countries (Annex 1) agreed to an average greenhouse gas emission reduction target of 5% below the 1990 levels (United Nations, 1998) and developing countries (non-Annex 1), such as South Africa, had no defined emission reduction targets. In the Doha amendment, adopted in 2012 (United Nations, 2015a), new targets were set for Annex 1 countries to reduce greenhouse gas (GHG) emissions by a minimum of 18% from 1990 levels between 2013 and 2020.

The Kyoto protocol mainly promotes emission reduction at a national level, but it does allow for additional reduction measures to be implemented outside of the country through three strategies (United Nations, 1998). First is the International Emissions Trading where Annex 1 countries each have a limited number of emission units that are allowed and unused units can be traded with other countries which have exceeded their assigned limit (United Nations, 1998). The second strategy is the CDM – under which restoration projects fall – where developed countries that have binding emission reduction targets under the Kyoto Protocol can earn Certified Emission Reduction credits (CERs) by implementing emission reduction projects in developing countries (United Nations, 1998). The last strategy is Joint Implementation, where emissions are reduced by either directly reducing the emissions created, or by increasing the sequestration of emissions into a sink (United Nations, 1998).

In 2015, also under the UNFCCC, the Paris Agreement was introduced with the goal of restricting the global average increase in temperature to less than 2 °C above the pre-industrial temperature and to strive to further restrict it to below 1.5 °C (United Nations, 2015b). Unlike the Kyoto Protocol, the Paris Agreement includes all countries, regardless of the state of their development, and consists of a 5-year cycle of climate actions or Nationally Determined Contributions (NDCs) developed by each individual country, each increasingly ambitious than the previous NDCs. South Africa's NDCs are closely linked to social equity and ensuring a just transition towards climate goals. The NDCs in the 2020s are aimed at transforming the energy sector from one that is heavily reliant on inefficient coal power stations, to one that relies on a diverse set of renewable energy inputs (South Africa First Nationally Determined Contribution under the Paris Agreement, 2021). The NDCs in the 2030s are primarily aimed at transforming the transport sector to one that primarily uses low-emission vehicles (South Africa First Nationally Determined Contribution under the Paris Agreement, 2021). In 2021, South Africa submitted updated NDCs which specified that between 2021 and 2025, annual GHG emissions would be in the range of 398 to 510 Mt CO_2, and that between 2026 and 2030, annual GHG emissions would be in the range of 350 to 420 Mt CO_2, a reduction from the first NDCs set (South Africa First Nationally Determined Contribution under the Paris Agreement, 2021).

Carbon sequestration through thicket restoration would contribute towards South Africa's carbon reduction goals under the Paris Agreement, biological diversity goals under the CBD, and aid in achieving South Africa's target of rehabilitating and managing 87 621 ha of thicket while progressing towards the larger goal of achieving land degradation neutrality in the thicket biome by 2030 (Department of Environmental Affairs, 2018). Given the small spatial extent of thicket – 2 672 761 ha (Lloyd et al., 2002) – it is acknowledged that its potential contribution to national carbon storage is small (National Terrestrial Carbon Sink Assessment, 2015); however, restoration in this region also

has the potential to improve ecosystem services, contribute local job opportunities, and possibly generate more income than goat pastoralism (Mills and Cowling, 2006). An important step in this process of achieving these goals is monitoring.

Ecosystem restoration and monitoring

Ecological restoration involves any activity that is aimed at assisting the recovery of a degraded ecosystem to a state that is comparable with an appropriate intact reference ecosystem – an approximation of the state of the ecosystem had it not been degraded (Gann et al., 2019). Ecosystem restoration has many benefits including protecting biodiversity, improving ecosystem services, and mitigating climate change, but it often requires a long time to be achieved (Gann et al., 2019). Some degraded systems can recover just through passive restoration (the removal of the cause of degradation) as was the case in the United States where discontinuation of agriculture resulted in the recovery of deciduous forests (Vaughn et al., 2010). However, it is well established that restoring the vegetation and function of thicket requires active restoration methods (Mills et al., 2007; Pierce et al., 2009) such as planting *Portulacaria afra* (spekboom) cuttings as well as ensuring browser exclusion.

Monitoring of the ecosystem is an important aspect of any restoration initiative. The Society for Ecological Restoration developed eight principles for ecological restoration, three of which relate to baseline conditions and monitoring - Principle 3, Principle 5, and Principle 6. Principle 3 emphasizes the importance of baseline measurements – the condition of the target area prior to the implementation of restoration strategies – which inform targets and are used to determine the impact of restoration (Gann et al., 2019). Principle 5 addresses the importance of monitoring the recovery of an ecosystem to track the progress of restoration initiatives. Regular monitoring informs which practices work and which do not, which would enable adaptive management, and be used to continually improve restoration practices (Gann et al., 2019). Quantitative monitoring is also essential for formal assessments of the improvement of an ecosystem (Gann et al., 2019) for assessing the progress towards restoration and carbon commitments under the various international treaties. Principle 6 consists of tools to report restoration changes in an ecosystem from the baseline conditions, such as the ecological recovery wheel (Gann et al., 2019). The ecological recovery wheel is a tool used to visualize restoration progress by describing the status of the different ecosystem attributes in a diagram. This tool encourages high restoration goals even if full restoration is not possible at the start. The final principle, Principle 8, deals with another useful restoration tool referred to as a restorative continuum which consists of a range of management steps towards full ecosystem recovery (Gann et al., 2019). This allows decision-makers to implement the most appropriate restoration approach given the specific conditions of the target ecosystem.

The importance of baseline measurements as references – such as the 1990 carbon baselines upon which national emission reduction targets are based in the Kyoto Protocol (UNFCCC, 1998) – is well-established in science. In restoration and carbon accounting, baseline data provide information on the starting state and carbon stock of an ecosystem, and a reference point for measuring ecosystem restoration and carbon loss (degradation) or carbon gain (restoration) (United Nations Development Programme, 2013; Gann et al., 2019). Ecosystem monitoring and baseline measurements involve ground recordings and remote sensing data which are generally used in conjunction with one another especially when studying large spatial areas. Site measurements provide reliable ground-truth data, and remote sensing provides a way of upscaling monitoring over large areas without the labour-intensive task of manual data collection (Goetz and Dubayah, 2011).

The Global Ecosystems Monitoring (GEM) project is a prime example of environmental monitoring. At least 294 GEM plots are located globally, including Africa, the Amazon and Malaysia, and involve repeated measurements of plant functional traits within one-hectare plots of tropical forest around the world (Malhi et al., 2021). The purpose of GEM is to study the functions of tropical forests and monitor how they are affected by climate change, as well as to provide insight into carbon dynamics by recording and monitoring carbon cycling in the plots (Malhi et al., 2021). Together with multispectral, hyperspectral and LiDAR remote sensing imagery, GEM plot data can be used to create detailed maps of tropical forest function (Malhi et al., 2021).

Globally, forests are the most targeted biome for restoration, and it is estimated that deforestation has resulted in the loss of 420 million ha of forests worldwide since 1990 (Food and Agriculture Organization of the United Nations (FAO), 2020) making forests a popular biome for restoration projects. Various restoration strategies have been employed to restore forests, including introducing dead wood to create space in the canopy for the establishment of highly light-dependent species and provide resources for species that inhabit wood; using controlled high- and low-intensity fires to create disturbance and promote the re-establishment of diverse forest species in the Northern European boreal forests (Halme et al., 2013), and active planting of seedlings in Australia. One of the key considerations identified by Halme et al. (2013) was the importance of identifying achievable structures and functions of the ecosystem to restore, because not all areas and aspects of a degraded system are feasible to recover. Certain methods of restoration, such as controlled burning, are expensive and unfeasible to perform at a landscape-scale (Halme et al., 2013). Planting seedlings incurs nursery costs, and the maintenance and ongoing management of the seedlings is labour-intensive (Summers et al., 2015).

Another important aspect of restoration that was repeatedly identified in forest restoration studies globally was the value of involvement and support by locals in restoration efforts (Melo et al., 2013; Höhl et al., 2020; Laudari et al., 2022). Multiple survey respondents in one study cited the involvement of local communities as a critical component of forest restoration success (Höhl et al., 2020). Restoration is a long-term process and a disconnect between ecological interests and the needs of locals eventually results in failure (Laudari et al., 2022).

In South Africa's thicket biome, restoration lessons have been learnt through the Thicket-Wide Plot (TWP) experiment which was created to assess the potential of thicket restoration. The experiment consisted of 330 50 m by 50 m plots of degraded thicket that were actively restored using spekboom in 2008 and 2009 (Spekboom Restoration Research Group (SRRG), no date). Many of these plots have not been monitored or maintained, and the fences around some plots have been removed, exposing the area to further grazing, and preventing the potential restoration of the thicket within (SRRG, no date). According to the SRRG (no date), 62% of the plots are situated in unsuitable habitats resulting in the failure of many spekboom cuttings. Some plots – such as P0065 – have flourished and resemble the dense nature of intact thicket. These plots are noticeable when viewed on Google Maps and are distinct from the surrounding degraded land. Important lessons for thicket restoration have been learnt through this experiment, including the importance of regular management and monitoring of restoration sites to ensure the exclusion of browsers and prevent further degradation and, most importantly, how crucial it is to select appropriate areas to restore. These are issues where remote sensing and mapping of thicket and carbon storage potential can be highly useful.

Remote sensing of carbon

Remote sensing provides an alternative to manual ground data collection by detecting and recording a range of electromagnetic energy over large areas of the earth's surface from sensors onboard aircrafts or satellites National Aeronautics and Space Administration (NASA), 2019). This is a practical and easily repeatable way to study various aspects of a large site. Sensors can be divided into two categories – passive and active. Passive sensors only detect energy that is reflected off the target surface, whereas active sensors send a pulse of energy towards the target surface and record changes in the energy that is reflected (NASA, 2019).

Synthetic Aperture Radar (SAR) and Light Detection and Ranging (LiDAR) are two types of remotely sensed data that are commonly used in aboveground carbon estimation (Lu et al., 2016) and they are both collected using active sensors. SAR images are captured by transmitting microwave signals to the target area and recording the energy that is reflected to the sensor. SAR is particularly useful for

capturing data about canopy structure under cloudy conditions because of its ability to penetrate through clouds, but it is prone to speckle noise which reduces the accuracy of the data (Lu et al., 2016). LiDAR data collection involves pulses of light transmitted to the target area, where the time taken for the light to be reflected is used to determine various aspects about vegetation structure such as canopy height. The fastest return generally indicates the top of the vegetation canopy, and the latest return is typically reflected by the ground. The difference between those recordings provides an indication of the top height of the canopy. LiDAR is particularly suitable for studying aboveground biomass in forests (Patenaude et al., 2004; He et al., 2013; Kankare et al., 2013; Stovall et al., 2017), but in areas of dense vegetation, LiDAR may not be able to reach the ground (Kulawardhana et al., 2017), resulting in inaccurate recordings of vegetation height.

In thicket, where *in situ* data collection is laborious and not feasible to carry out over large portions of the landscape, remote sensing products such as LiDAR can be useful. At this time, there is no locally captured and openly accessible LiDAR imagery over the thicket region, however Global Ecosystem Dynamics Investigation (GEDI) (Dubayah et al., 2021) and Global Land Analysis and Discovery (GLAD) (Potapov et al., 2021) are two freely available global alternatives. These products provide a remote way of studying landscapes around the globe, including the thicket region of South Africa, but come with drawbacks such as coarser resolution for global imagery compared to small-scale, localized imagery, and an incompatibility with local biomes such as the shorter stature of thicket compared to other biomes like forests.

The STEP project (Lloyd et al., 2002) was a major step forward in studying the spatial aspects of South Africa's thicket region. Landsat Thematic Mapper imagery was used to determine the spatial extent of the thicket area and classify the levels of degradation (Lloyd et al., 2002). Since then, especially in recent years, there has been an increase in the number of studies using remote sensing to map various aspects of thicket. Galuszynski et al. (2022) utilized aerial imagery and machine learning to classify spekboom canopy over small areas of thicket – a potentially useful way of monitoring restoration and reduce labour and sampling costs. In 2021, Harris et al. produced very high-resolution (0.34 m) maps of aboveground carbon (AGC) over the central region of the Baviaanskloof. LiDAR and SAR imagery were not used in this study due to cost and spatial resolution constraints, so high resolution multispectral Worldview-3 data were used in conjunction with 10 m by 10 m ground plots in linear regression models to map AGC (Harris et al., 2021). The results produced high R^2 values (0.89 and 0.85) when comparing modelled AGC against ground recordings and indicates that Worldview-3 can be a suitable option for assessing AGC in thicket. However, these images incur costs per unit of coverage required, are made available for use by a limited number of

projects and have a much finer resolution than necessary for this project, making Worldview-3 unsuitable in this context.

Subtropical thicket

South Africa's thicket biome extends across the Eastern and Western Cape Provinces (Figure 1.1).

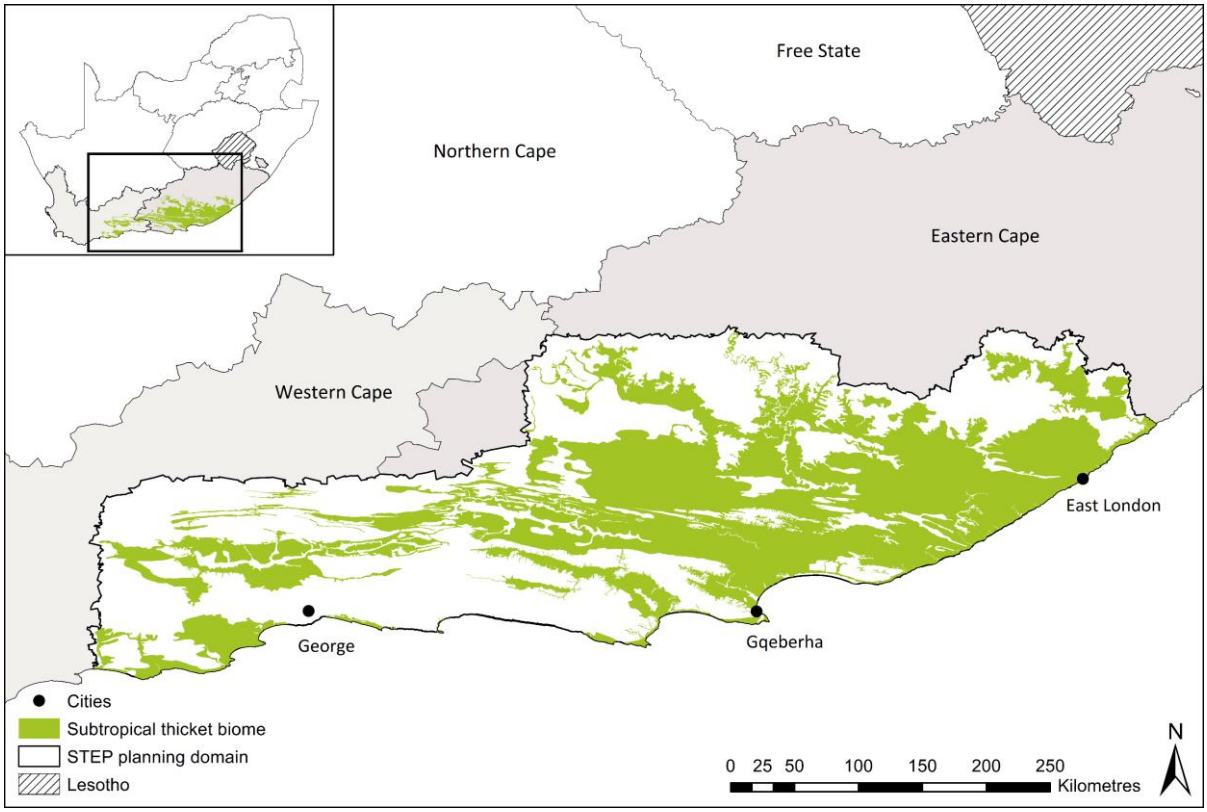

Figure 1.1 The extent of the Subtropical Thicket biome which extends across the Eastern and Western Cape Provinces of South Africa, as defined by the Subtropical Thicket Ecosystem Planning project (STEP) (Lloyd et al., 2002).

Of the 2 672 761 ha of thicket in South Africa, 46% has been moderately degraded, and 31% has been severely degraded (Lloyd et al., 2002) due to overgrazing by livestock, particularly goats (Mills et al., 2005a). In its intact state, thicket has high biodiversity (Hoare et al., 2006) and is a dense and impenetrable collection of multi-stemmed shrubs and woody succulents usually between 2 to 5 m high, with a carbon-rich topsoil accompanied by a thick layer of litter (Cowling et al., 2005; Mills et al., 2005a). According to Vlok et al. (2003), thicket can be separated into two main categories, based on geography (Dune and Mainland thicket) each of which consists of multiple subcategories of thicket, based on biogeography and thicket structure.

The importance of the biome can be divided into its ecological value and its socio-economic value. While thicket does support a variety of mammals, birds, and reptiles, it boasts an especially high level of botanical biodiversity with 20% of thicket species classified as endemic (Vlok and Euston-Brown, 2002). The socio-economic benefits of thicket include its agricultural value, ecotourism opportunities, and the ecosystem services that it provides such as soil erosion prevention, clean air, and carbon storage (Berliner et al., no date).

Carbon pools in terrestrial ecosystems

Globally, the terrestrial biomes with the highest total carbon densities are forests, grasslands, and wetlands (Prentice et al., 2001). Plant biomass in forests is generally divided into five carbon pools – aboveground biomass, belowground biomass, litter, soil, and coarse woody debris (DiRocco et al., 2014). Aboveground biomass consists of live biomass above the soil (foliage), belowground biomass consists of live biomass below the soil (roots), litter is dead biomass lying above the soil, soil consists of organic carbon stored in the live and dead biomass of fine (< 2 mm) roots in the soil, and coarse woody debris consists of larger pieces of dead wood (> 10 cm) above the soil, such as upright or fallen stumps (DiRocco et al., 2014). Like forests, carbon pools in thicket also consist of aboveground (woody) biomass, belowground (root) biomass, litter, and soil but unlike forests, thicket generally consists of smaller, multi-stemmed species, so coarse woody debris – a significant component of forests, but negligible component of thicket (Powell, 2009; Harris et al., 2019) – is classified as litter.

As is the case in most of South Africa's ecosystems (National Terrestrial Carbon Sinks Assessment, 2020), soil represents the largest carbon pool in thicket. Soil itself is made up of sub-pools, classified by their rate of decomposition (FAO, 2017). The active pool has the fastest decomposition rate (years) and consists of the organic carbon from fresh litter and other organic matter (FAO, 2017). The passive pool consists of inputs from the active pool and is more resistant to further decomposition (decades to centuries (FAO, 2017)). The sub-pool that is most resistant to decomposition is the slow (recalcitrant) fraction of SOC which can take centuries or more to decompose (FAO, 2017). As a result of the slow decomposition of the passive and recalcitrant fractions of SOC, the active pool is the most important one to consider when studying degradation and restoration and their effect on the SOC stock of a landscape over a shorter period of time (decades).

The amount of SOC that can be stored is affected by soil properties such as clay content and soil depth, however, soil depth is one property that is seldom accounted for in thicket SOC estimates. A large proportion of SOC is generally found within the topsoil which is often very shallow at the crests of slopes and deeper in the valleys. As soil depth recordings are scarce, especially within thicket, the need for a proxy is apparent. In this study, slope position was used as an indicator of soil depth.

In other ecosystems around the world, slope position has been found to affect the amount of SOC that is stored (Hao et al., 2002; Wei et al., 2010; Singh and Benbi, 2018) but the trends are not consistent across different vegetation types and land uses. A reasonable expectation is that deeper soils, generally found in lower slope positions, have a larger capacity for SOC storage – a trend that is supported by a study in Gedo Forest, Ethiopia, which found that the largest mean carbon stock was found in lower slopes and the lowest mean carbon stock was found in upper slopes (Yohannes et al., 2015). A study in the Himalayas by Singh and Benbi (2018) assessed the effect of slope position and land use on SOC stocks, but the two variables were not independent of one another. A single slope was assessed where each slope position differed in the vegetation cover. The hillslope was forested, middle slope was highly eroded, lower slope was covered in grass and the valley contained crops. The results indicated that the highest SOC stocks were located at the crest and lower slope, but the type of vegetation differed so vastly along the slope that it is difficult to say how SOC is affected by land use or vegetation cover and how it is affected by the slope position. In another study, performed in China, it was found that for slopes covered in a deciduous shrub, the SOC stock increased downslope, but for a forested slope, the SOC stock was highest at the middle slope and lowest in the lower slopes (Wei et al., 2010). This indicates that the type of vegetation affects how much SOC is stored and how it's distributed along a slope. Currently, there are no studies looking into how SOC in thicket changes along a slope which is an important factor to estimate SOC more accurately.

Aboveground biomass (live biomass above the soil surface – referred to as woody biomass in this document) is the second largest carbon pool in thicket and often garners the most interest from the public because it is visible, and more tangible compared to the belowground biomass and soil. Given the dense structure of thicket vegetation, the lack of aboveground biomass is highly noticeable in degraded areas (Figure 1.2) and provides an indication of the level of degradation. As overgrazing is the main cause of thicket degradation, aboveground biomass is usually the first carbon pool that is affected.

Figure 1.2 A picture of the stark contrast between vegetation cover in degraded thicket (left) and intact thicket (right) across a fence in Kirkwood, located in the Eastern Cape Province of South Africa (Powell, 2009).

The belowground biomass carbon pool, consisting of carbon in the roots of the vegetation, is often one that is not of primary consideration in carbon sequestration. Degradation of this pool is not visibly noticeable, and its biomass and carbon storage are tedious to measure.

Litter is the smallest carbon pool but plays an important role in the thicket ecosystem. Intact thicket with closed canopies is often accompanied by a thick litter layer (up to 10 cm deep), mainly due to the high litter production by spekboom (2500 kg ha^{-1} yr^{-1}) (Lechmere-Oertel et al., 2008). In spekboom-dominated intact thicket, the total litter production of 4100 kg ha^{-1} yr^{-1} is comparable to some forest ecosystems such as tropical seasonal forests (Lechmere-Oertel et al., 2008). Litter plays an important role in improving the soil condition by protecting it from exposure to erosion and evaporation. Then, as the litter breaks down, it is incorporated into the soil as soil organic matter and provides a source of organic carbon that can then be accumulated within the soil.

The sum of these four carbon pools gives the total carbon stored within the thicket ecosystem. Past estimates of total carbon storage in intact thicket range widely between 83.1 t ha^{-1} (Powell, 2009) and 245 t ha^{-1} (Mills et al., 2005b), and are significantly higher than the estimates of total carbon storage in degraded thicket which range between 30.5 t ha^{-1} (Powell, 2009) and 114 t ha^{-1} (Mills et al., 2005a) The difference in these two categories of estimates – current and restored (referred to as potential carbon in this document) gives an indication of the increase in carbon storage that restoration can generate.

Past studies of carbon in thicket

Based on a review of restoration literature as well as the UN Decade on Ecosystem Restoration list of 50 founding initiatives (United Nations Decade on Ecosystem Restoration, no date (b)), globally, forests are the most targeted biome in restoration efforts as they generally support more carbon than any other terrestrial biome. In South Africa, restoration literature is generally centred around the thicket and fynbos biomes (Ruwanza et al., 2013; Holmes et al., 2020; Boxriker et al., 2022) given their high levels of biological diversity, with some research into the grassland (Carbutt and Kirkman, 2022) and Karoo biomes (Milton and Dean, 2021). Past studies of thicket have suggested that the biome has a higher-than-expected potential for carbon storage, despite the relatively dry climate in which it occurs. These studies have compared the total carbon stock within restored thicket to that of mesic forests (Mills et al., 2005b; Mills and Cowling, 2006) and has led to an increase in local and scientific interest in thicket restoration over the years.

Many previous studies of carbon stocks in thicket have focussed on one or two pools such as aboveground biomass carbon (van der Vyver and Cowling, 2019) or belowground biomass carbon (Mills and Cowling, 2009). Estimates from the few studies of total carbon stock within intact thicket are very high, with some estimates higher than those for forests (Table 1.1). This has been attributed to the presence of spekboom, however, the sample plots on which they have typically been produced are mostly in landscape positions low in the catena (Mills and Cowling, 2006) where the soil is generally deeper, more clayey and has a lower stone content compared to the crest. The application of carbon stock estimates from plots that were not representative of the variations in the landscape which influence carbon stocks could explain the unexpectedly high values (Powell, 2009).

The availability of *in situ* thicket carbon plot data is generally abundant, and there are many sources of published estimates for all thicket carbon pools (Table 1.1). However, the majority of these estimates have been solely based on averaging *in situ* data from study plots without accounting for variations in the physical characteristics of the landscape such as soil depth. Extrapolations without qualification can result in overestimates or underestimates and could lead to restoration efforts being directed to areas unsuitable for carbon sequestration. Given the large amount of existing *in situ* data available for different areas of thicket, the wide variety of publicly accessible remotely sensed imagery, and the lack of large-scale spatially explicit estimates of thicket carbon pools, this research is designed to employ methods of utilizing these existing datasets in a manner that could be applied to other areas of thicket where past *in situ* data has already been collected.

Table 1.1 Past estimates of carbon stocks within the intact and degraded subtropical thicket of South Africa (SA), as well as other biomes around the world for comparison.*

			Carbon (t ha^{-1})	
Carbon pool	**Biome, location**	**Source**	**Intact**	**Degraded**
Woody biomass	Forest, Argentina	Conti et al. (2014)	22.1 ± 2.3	4.6 ± 1.3
	Thicket, SA	Powell (2009)	27.4 ± 4.01	4.9 ± 0.9
	Thicket, SA	Harris et al. (2021)	30.4 ± 7.8	17.9 ± 6.8
	Thicket, SA	Mills et al. (2005a)	40 ± 3	7 ± 1
	Forest, Bangladesh	Ullah and Al-Amin (2012)	96.5	Not assessed
Litter	Thicket, SA	Powell (2009)	3.7 ± 0.7	1.4 ± 0.3
	Forest, Bangladesh	Ullah and Al-Amin (2012)	4.2	Not assessed
	Forest, Argentina	Conti et al. (2014)	6.2 ± 0.6	1.9 ± 0.5
	Thicket, SA	Harris et al. (2021)	9.2 ± 3.6	4 ± 2.3
	Thicket, SA	Mills et al. (2005a)	11 ± 1	1 ± 0.4
Root biomass	Thicket, SA	Powell (2009)	4.7 ± 0. 7	2.6 ± 0.6
	Thicket, SA	Mills and Cowling (2009)	11 ± 2	2.7 ± 0.3
	Grassland, SA	Mills et al. (2005b)	11.4	Not assessed
	Forest, Bangladesh	Ullah and Al-Amin (2012)	14.6	Not assessed
	Thicket, SA	Mills et al. (2005a)	25 ± 1.3	11 ± 0.7
	Thicket, SA	Mills et al. (2005b)	25.4	Not assessed
Soil	Karoo, SA	Mills et al. (2005b)	26	Not assessed
	Thicket, SA	Powell (2009)	47.4 ± 4.4	21.6 ± 1.7
	Forest, Argentina	Conti et al. (2014)	86.9 ± 5	93.7 ± 12.3
	Thicket, SA	Mills and Cowling (2009)	93 ± 7	31 ± 2
	Thicket, SA	Mills et al. (2005a)	133 ± 27	95 ± 15
	Grassland, SA	Mills et al. (2005b)	164	Not assessed
	Thicket, SA	Mills et al. (2005b)	168	Not assessed
	Forest, Bangladesh	Ullah and Al-Amin (2012)	168.2	Not assessed
Total carbon stock	Karoo, SA	Mills et al. (2005b)	**30**	Not assessed
	Thicket, SA	Powell (2009)	**83.1 ± 5.8**	**30.5 ± 2.1**
	Grassland, SA	Mills et al. (2005b)	**172**	Not assessed
	Thicket, SA	Mills et al. (2005a)	**209 ± 28**	**114 ± 14**
	Thicket, SA	Mills et al. (2005b) *	**245**	Not assessed
	Forest, Bangladesh	Ullah and Al-Amin (2012)	**283.8**	Not assessed

* Woody carbon and litter carbon were not separately assessed in this study, so the estimates for those individual pools are not included in this table.

1.4 Structure of the dissertation

This document follows a dissertation format, with individual chapters dedicated for each main section of the study. Chapter 1, the introduction, lays the foundation of the study and consists of a background of the current knowledge, and the specific aim of this study. Chapter 2 consists of a description of the characteristics of the study site, followed by descriptions of the methods, equations and data that were used to calculate the current and potential carbon estimates for each carbon pool. Chapter 3 provides the average carbon estimates that were calculated for each pool, as well as maps showing the spatial distribution of each carbon pool within the thicket area of the Baviaanskloof Nature Reserve. Lastly, Chapter 4 consists of a discussion of the results, including comparisons to past studies, future research areas, and a conclusion.

2 Methods

2.1 Study site

The Baviaanskloof Nature Reserve (BNR) is located across the border of the Eastern and Western Cape Provinces, South Africa, between the towns of Uniondale and Uitenhage (Figure 2.1).

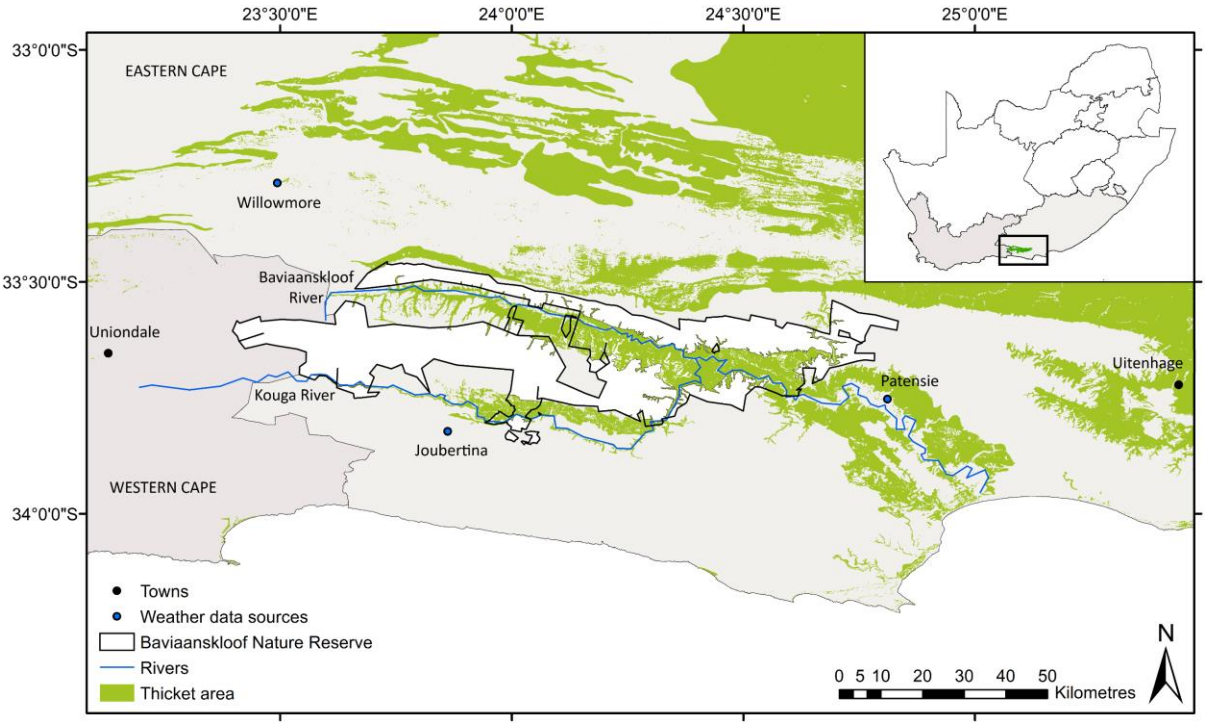

Figure 2.1 The location of the Baviaanskloof Nature Reserve and nearby towns in the Eastern Cape and Western Cape Provinces, South Africa, including the locations from which weather data were sourced, and the extent of the Thicket biome in the reserve and surroundings areas.

The inland subtropical thicket region has a highly variable climate with large temperature ranges where the annual average minimum and maximum temperatures range between 0.9 °C and 3.9 °C, and 31.2 °C and 32.6 °C, respectively (Vlok et al., 2003). Mean annual precipitation ranges between 293 mm and 576 mm and while the thicket area does not have a distinct rainfall season, winter rainfall tends to occur in the western regions and summer rainfall in the eastern areas (Vlok et al., 2003). With the Kouga Mountains to the south and the Baviaanskloof Mountains to the north, the reserve has highly variable altitude ranging between 85 m and 1744 m, creating many crests and valleys (Figure 2.2). The variation in topography affects the occurrence of orographic rainfall and contributes to an increase in aridity from south to north in the BNR (Euston-Brown, 1994).

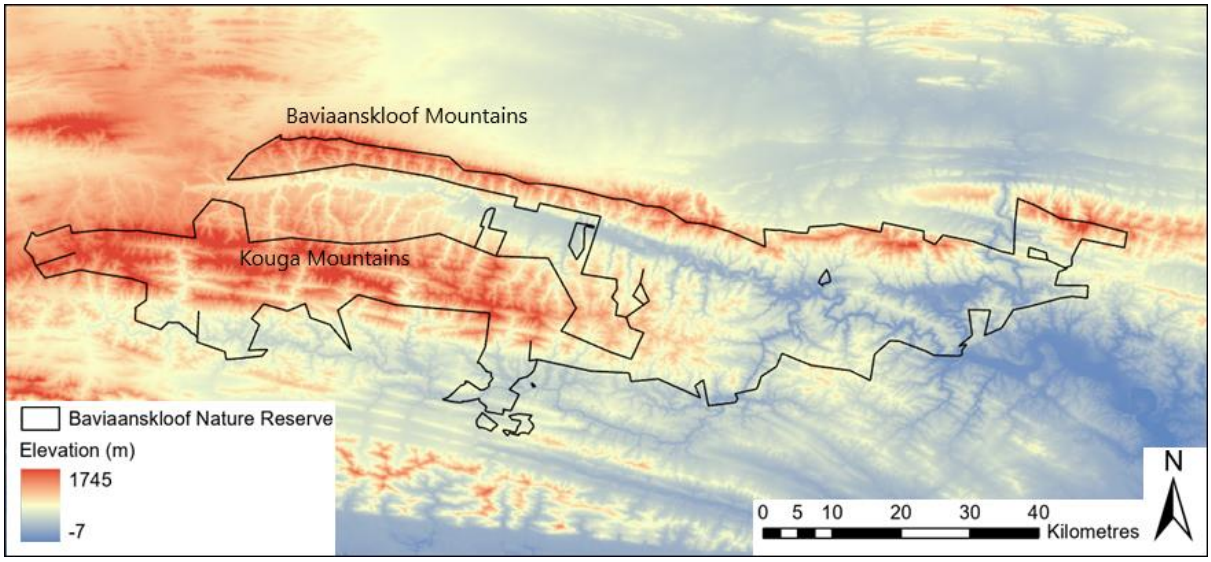

Figure 2.2 The elevation of the Baviaanskloof Nature Reserve and the surrounding areas in the Eastern and Western Cape Provinces, South Africa, at a 30 m resolution according to the Shuttle Radar Topography Mission (STRM) digital elevation model.

The variable topography and climate promote high biological diversity which is evident by the occurrence of seven biomes (Subtropical Thicket, Grassland, Fynbos, Nama Karoo, Succulent Karoo, Savanna, and Forest) in the broader BNR region and the conservative estimate of 1161 different plant species present (Boshoff et al., 2001). As part of the Cape Floral Kingdom, the BNR achieved World Heritage Status in 2004 in recognition of the high level of biodiversity that it supports (Boshoff, 2005). The BNR itself encompasses 207 000 ha, of which 48 058 ha are comprised of twelve different thicket types (Figure 2.3), according to the Subtropical Thicket Ecosystem Planning project (STEP) (Lloyd et al., 2002). Descriptions of these thicket types are provided in the STEP Handbook (Pierce and Mader, 2006).

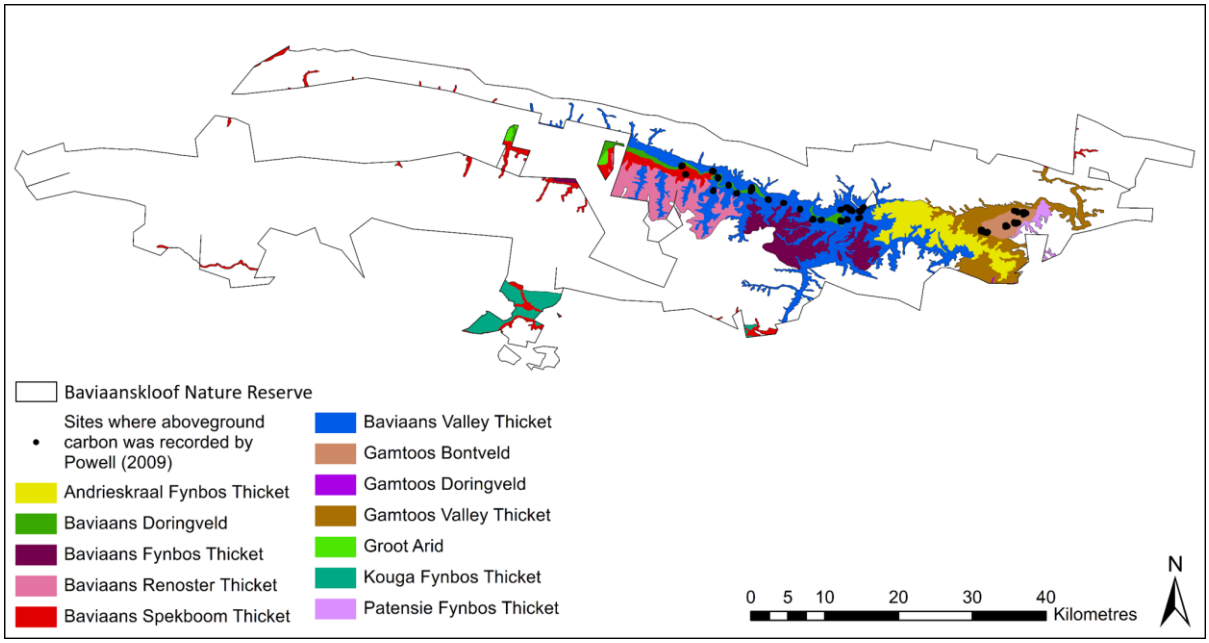

Figure 2.3 The extent of the different thicket types within the Baviaanskloof Nature Reserve, South Africa, from the Subtropical Thicket Ecosystem Planning project, and the locations of the 191 sites where *in situ* aboveground carbon was previously recorded (Powell, 2009). These sites are only located in five of the 12 thicket types – Baviaans spekboom thicket, Baviaans valley thicket, Baviaans doringveld, Gamtoos valley thicket and Gamtoos bontveld.

Most of the land in the reserve is protected and falls under the jurisdiction of the Eastern Cape Parks and Tourism Agency; however, there are some private farms – most of which have been used for grazing by livestock such as goats and sheep (Jansen, 2008). According to the STEP data, 26 527 ha of thicket in the BNR are moderately degraded, 3 502 ha are severely degraded, and 12 381 ha are intact. Degraded thicket has been described as savanna-like or shrubland-like, a shift that has been associated with a decline in soil quality and soil carbon (Mills and Fey, 2004; Mills et al., 2005a), and a change in the soil bacterial communities (Schagen et al., 2021).

Subtropical thicket is a biodiversity hotspot with many flora species including succulents such as *Aloe ferox*, woody species such as *Acacia karroo* and *Pappea capensis* and herbaceous shrubs, with 20% of the plant species endemic to the region (Vlok et al., 2003). But, in thicket restoration, *Portulacaria afra* (spekboom), which has been described as an 'ecosystem engineer' in that it aids in shifting the degraded system to one that resembles an intact thicket in both structure and function (van der Vyver et al., 2013), is the species of interest. Spekboom is an endemic succulent species found widespread in many thicket types (Vlok et al., 2003). Its ability to facultatively make use of Crassulacean Acid Metabolism (CAM) photosynthesis during periods of drought is suggested to result

in increased productivity compared to C_3 or obligate CAM plants (Pierce et al., 2009) and is one of the attributes that makes it ideal for use in thicket restoration. Spekboom is often accompanied by a thick litter layer below the canopy (Mills and Fey, 2004; Mills et al., 2005a; Powell, 2009), which provides soil cover, resulting in a higher soil carbon content compared to degraded sites where spekboom is sparse or absent (Mills and Fey, 2004). The canopy cover it provides has also been suggested to improve the rate of water infiltration into soil, increase soil moisture, and reduce runoff and soil erosion (Van Luijk et al., 2012), factors that are crucial given the water-stressed regions in which thicket occurs. This microclimate created by spekboom and its canopy is suggested to assist in the re-establishment of other species in degraded thicket areas (van der Vyver et al., 2013).

2.2 Total carbon

Total landscape carbon was divided into the four thicket carbon pools – soil organic carbon, woody carbon, root carbon and litter carbon. Figure 2.4 provides an overview of the broad process by which each estimate was calculated, as well as the corresponding equations which were used for each component of the study. The subsequent sections provide detail into these methods and equations.

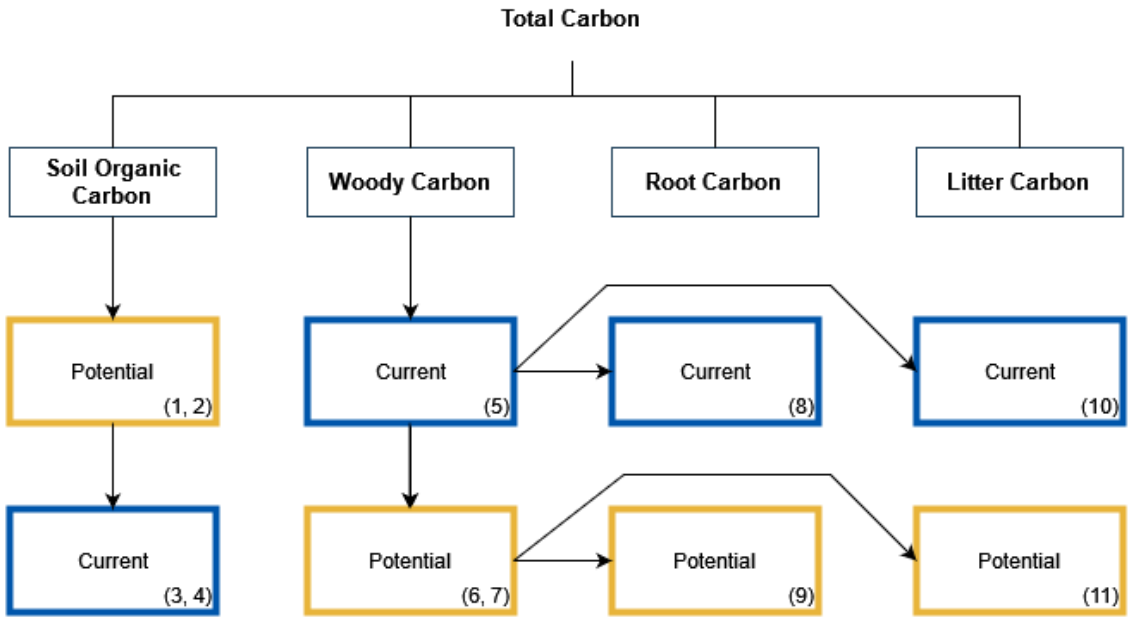

Figure 2.4 The process by which current (blue) and potential (yellow) carbon estimates in the Baviaanskloof Nature Reserve, South Africa, were calculated for each pool, which estimates were based on previous results, and the corresponding equation numbers that were used in each step.

2.3 Soil Organic Carbon

The following subsection provides descriptions of the methods employed to estimate the potential and current soil organic carbon within the BNR thicket area. For this component, the potential soil organic carbon (SOC) needed to be calculated first because there was an insufficient number of soil pit plots to subset them into the three different levels of degradation.

Potential Soil Organic Carbon

In situ Agricultural Research Council (ARC) soil profile data (ARC–ISCW, no date) for Primary Catchment L, within which the BNR is located, were used to calculate estimates of potential SOC in each 30 m pixel of thicket in the reserve according to the following equation (Schütte et al. ,2019; RJ Scholes, personal communication):

$$C_{soil,\ potential} = \int_0^z \rho_{soil} \times f_{matrix} \times f_{soc}\ \delta z \qquad (1)$$

Where:

z is the depth of the soil horizon (m),

ρ_{soil} is the bulk density of the soil volume not occupied by gravel (t m^{-3}),

f_{matrix} is the fraction of the total soil volume that is not occupied by stones,

and f_{SOC} is the fractional SOC content of sieved soil.

Information about all the data that were used to calculate potential soil organic carbon is provided in Table 2.1. The ARC soil data consists of 276 soil pit locations (Figure 2.5) and included measurements and descriptions of soil properties for each soil horizon at each location. Each point was also accompanied by a description of the land use – natural, cultivated pastures, disturbed land etc. The ARC dataset includes the slope position (terrain unit) at which each soil pit was dug: Valley Bottom, Lower Footslope, Footslope, Upper Footslope, Lower Midslope, Midslope, Upper Midslope, Crest. The dataset includes eight slope positions, which is overrefined for the purposes of this study and would result in too few recordings per position. Therefore, the number of the classes were adjusted to five slope positions based on Table 2.2. A sample of the original ARC dataset is shown in Table 2.3 and further analysis of the ARC dataset is provided in Appendix A.

Table 2.1 The datasets, their sources, and the software that were used to process the data and estimate potential soil organic carbon across the thicket area of the Baviaanskloof Nature Reserve, South Africa.

Dataset	Source	Software
Soil profile data	Agricultural Research Council	ArcMap 10.6 and ArcGIS Pro 3.1
Digital elevation model (30 m)	Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007)	

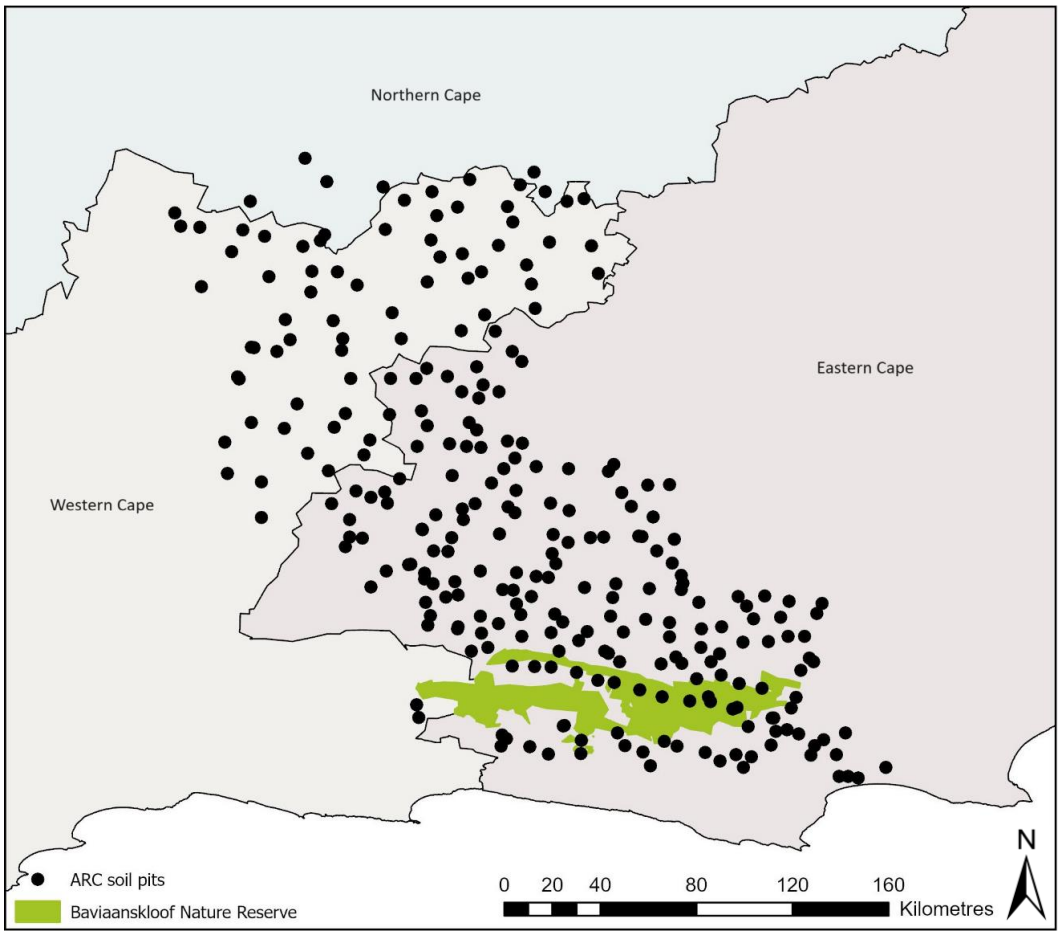

Figure 2.5 Locations of the 276 soil profiles in Primary Catchment L, South Africa, from the Agricultural Research Council dataset.

Table 2.2 The original slope positions (terrain unit) from the Agricultural Research Council soil profile dataset and the corresponding simplified slope positions that were used in this study.

Original terrain unit	Simplified slope position
Valley bottom	Valley
Lower footslope	Lower slope
Footslope	
Upper footslope	
Lower midslope	Midslope
Midslope	
Upper midslope	Upper slope
Crest	Crest

To calculate potential carbon, plot points in undisturbed and natural land, which are located within the broader thicket extent from the STEP map were selected, and the calculations described below were performed on this subset to estimate the potential SOC in the BNR thicket area.

Table 2.3 A sample of the data provided in the ARC soil profile point shapefile for Primary Catchment L in South Africa that were relevant to this analysis, and the meaning of the soil texture shorthand.

NATPROF	Longitude	Latitude	Land Use	Master Horizon	Upper Depth (mm)	Lower Depth (mm)	Carbon (f_{SOC})	coSa	meSa	fiSa	vfiSa	coSi	fiSi	Clay
2036	24.390278	-33.181944	-	A1	0	100	0.2	1.7	6	30.1	34.7	16.6	4.8	6.7
2036	24.390278	-33.181944	-	B21	100	400	0.2	4.2	4.2	14.4	31	22.8	12.8	12
2036	24.390278	-33.181944	-	B22	400	600	0.3	4.2	4.6	24.8	17.4	7.5	8.3	32.9
2038	24.895833	-33.325	Shrubveld	A1	0	100	0.4	4	8.2	19.5	20.1	14.9	21.5	11.7
2038	24.895833	-33.325	Shrubveld	B2	100	400	0.4	5.3	8.2	20	20.5	16	5.6	20.1
2048	24.345833	-33.411111	-	A1	0	100	0.3	4.4	4.2	26.9	20.9	9.9	16.5	18.9
2048	24.345833	-33.411111	-	B21	100	300	0.2	3.2	3.3	9.6	19.9	17	9.9	38.6
2056	24.8	-33.678333	Fynbos	A/E	0	200	1.5	16.6	20.7	17.7	6.8	17.8	6.9	9.3
2056	24.8	-33.678333	Fynbos	B2	200	500	1	8.4	19.4	18.3	5	14.4	14.4	18.3
2057	24.827778	-33.775	Fruit trees	A1	0	200	0.5	4.7	17.9	17.2	10.8	18.7	14	18.1
2057	24.827778	-33.775	Fruit trees	B21	200	500	0.4	4.6	15.5	15.8	11	19.9	14.8	17.7
2057	24.827778	-33.775	Fruit trees	B22	500	900	0.2	2.1	5.9	9.3	12	24.9	27.6	17.7
2058	25.002778	-33.772222	Plantation	A1	0	200	0.8	4.1	18.8	19.8	18.7	17.9	8.4	9.7
2058	25.002778	-33.772222	Plantation	B21	400	700	0.3	3.8	14.6	14.3	14.2	17.6	9.2	26.6
2058	25.002778	-33.772222	Plantation	B22	700	1000	0.2	2.2	12.1	11.2	11.3	12.5	6.8	41.1
2058	25.002778	-33.772222	Plantation	E	200	400	0.3	3.5	19.2	19.5	18.9	17.5	7.9	12.2

coSa	meSa	fiSa	vfiSa	coSi	fiSi	Clay
Proportion of coarse sand	Proportion of medium sand	Proportion of fine sand	Proportion of very fine sane	Proportion of coarse silt	Proportion of Fine silt	Proportion of Clay

As the ARC data did not include bulk density recordings, a method employed by Schütte et al. (2019) where a previously established relationship between the percentage of clay (pClay) and bulk density based on South African data (Van der Merwe, 1973; Hutson, 1984; Schulze, 1995) was used to calculate bulk density (ρ_{soil}):

$$\boldsymbol{\rho_{soil} = 0.0079 \times pClay + 1.7243} \quad (2)$$

Where:

$\boldsymbol{\rho_{soil}}$ is bulk density,

and **pClay** is the proportion of soil that is composed of clay.

Next, for each soil horizon, the sum of the proportion of sand, silt and clay was calculated to determine f_{matrix}. With these calculated data and the corresponding carbon recordings for each plot, the potential C_{soil} was calculated for each horizon as described by equation 1, and then summed for each site to determine the total potential C_{soil} for the entire soil profile at each location.

As a proxy for soil depth to extrapolate SOC estimates for the BNR, the 30 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) was classified into five slope positions (Figure 2.6). The Topographic Position Index (TPI) value for each pixel was determined by first using the Focal Statistics tool in ArcMap 10.6 to calculate each pixel value as a mean of all the elevation pixel values within a 20-cell neighbourhood, and then subtracting that from the DEM using the Raster Calculator. Given the high variability of the reserve's topography, a large neighbourhood size of 1000 m was selected to minimise grain in the slope position classification. A raster of TPI values over the entire area of Primary Catchment L was created and then used to determine the slope positions based on an established method of classifying the TPI values in intervals of 0.5 standard deviations (Jenness et al., 2013) (Table 2.4).

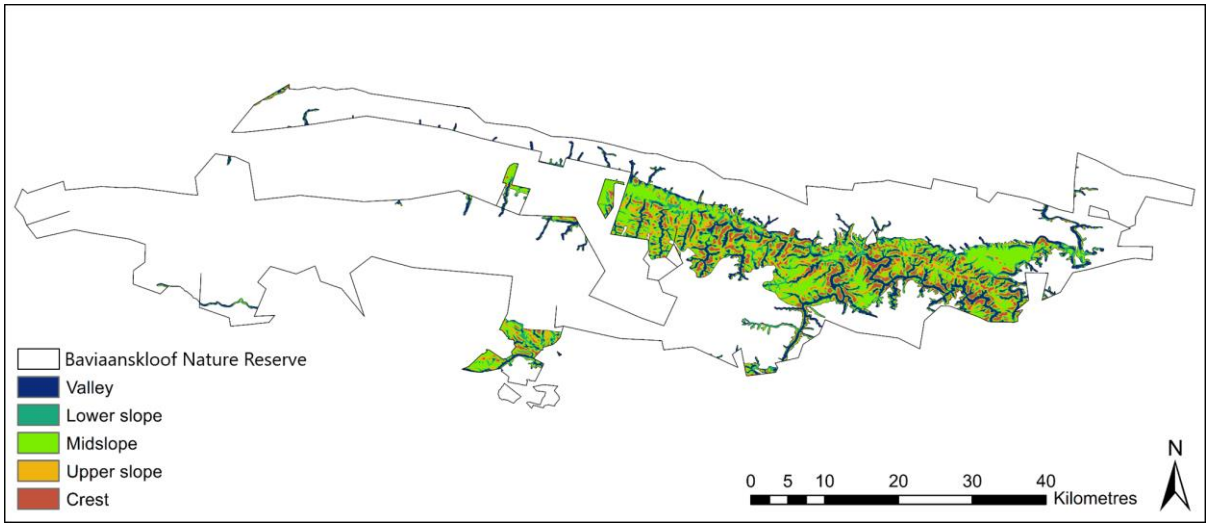

Figure 2.6 The Shuttle Radar Topography Mission (SRTM) 30 m digital elevation model classified into five slope positions based on 0.5 standard deviation of the calculated Topographic Position Index values over the thicket area in the Baviaanskloof Nature Reserve, South Africa.

Table 2.4 The classification of Topographic Position Index (TPI) values to slope positions within the thicket area of the Baviaanskloof Nature Reserve, South Africa, based on standard deviation intervals.

Standard deviation intervals	Topographic Position Index range	Slope position
TPI < -1	< -48.8	Valley
-1 < TPI < -0.5	-48.8 to -24.6	Lower slope
-0.5 < TPI < 0.5	-24.6 to 23.7	Mid slope
0.5 < TPI < 1	23.71 to 47.9	Upper slope
TPI > 1	> 47.9	Crest

Three Generalized Linear Models (GLMs) were then performed using the Generalised Linear Regression tool in ArcGIS Pro 3.1 to model potential SOC using the subset of ARC soil profile data, and elevation (from the SRTM dataset) and slope position (TPI) as explanatory variables, separately and together. The response data were right-skewed, so a log-transformation was used to achieve a normal distribution and the GLMs were performed on the transformed data. The best model was selected based on the highest R^2 value and a Jarque-Bera p value of less than 0.5, indicating that the

model residuals were distributed normally. The selected model was then used to predict potential SOC across the BNR thicket area.

A potential option for estimating potential SOC is SoilGrids (Poggio et al., 2021) – a machine-learning predictive soil model that is based on data from 230 000 soil profiles around the world which have been collated into the World Soil Information Service (WoSIS). The SoilGrids website (https://soilgrids.org/) includes maps of soil organic carbon stocks, bulk density, and various soil content properties (coarse fragments, sand, silt, and clay content). In theory, it should provide an estimate of the potential SOC stock because it takes the physical characteristics of the landscape and soil from soil pit data (which are generally collected in undisturbed sites) into account, but not land use or degradation status.

Current Soil Organic Carbon

Estimates of current SOC were calculated as described by the following equation, based on the fractions of active, passive and recalcitrant carbon (Mills and Fey, 2004), and a standard first order decay model to calculate the change in the amount of carbon in the active pool (RJ Scholes, personal communication):

$$C_{Soil,\ current} = (1 - f_{residual}) \times C_{Soil,\ potential} \times e^{-kt} + f_{residual} \times C_{Soil,\ potential}) \quad (3)$$

Where:

$f_{residual}$ is the sum of the passive and recalcitrant fractions of soil organic carbon,

$C_{Soil,\ potential}$ is the potential soil carbon estimate calculated above,

k is the exponential decay rate of the active soil organic carbon pool,

and **t** is the estimated time since degradation occurred.

Information about all the data that were used to calculate current soil organic carbon is provided in Table 2.5

.

Table 2.5 The datasets, their sources, and the software that was used to estimate the current soil organic carbon across the thicket area of the Baviaanskloof Nature Reserve, South Africa.

Dataset	Source	Software
Potential C_{soil} (30 m)	This study	ArcMap 10.6
Nitrogen content recordings for intact and degraded thicket – used as a proxy for the rate of soil decomposition (k) as described below	Mills and Fey (2004)	
$f_{residual}$		
Time since degradation began	Zandvlakte (No date)	

Mills and Fey (2004) assessed the total organic carbon within thicket soil, as well as the fraction of total carbon that was comprised of active organic carbon (0.5). Since there are three main soil organic carbon pools – active, passive and recalcitrant, if the fraction of SOC consisting of active carbon is 0.5, then the sum of the passive and recalcitrant fractions ($f_{residual}$) can be calculated as 1 - 0.5.

While there have been a few studies recording the rate of litter decomposition in thicket, currently, there are no studies of the rate of soil decomposition in thicket. So, recordings of Nitrogen content in intact and degraded thicket from Mills and Fey (2004) were substituted into a standard first-order decay model to solve for k:

$$N_t = N_0 \times e^{(-k \times t)} \quad (4)$$

Where:

N_t is the remaining Nitrogen content, in this case, the Nitrogen content that was recorded in degraded thicket,

N_0 is the initial Nitrogen content, in this case, the amount of Nitrogen recorded in intact thicket,

t is the time since degradation which was estimated as the number of years between the best estimate of the start of thicket degradation – 1982 (Zandvlakte, no date) – and the year that the Nitrogen content was recorded (2003),
and **k** is the rate of soil decomposition.

2.4 Woody Carbon

The following subsection describes the methods employed to calculate estimates of the current and potential aboveground Woody C within the thicket of the BNR.

Current Woody Carbon

Current Woody C was estimated according to the following function (RJ Scholes, personal communication):

$$\mathbf{C_{Woody,\ current} \sim vegetation\ volume + elevation + degradation\ status} \quad (5)$$

Where:

vegetation volume, is the canopy height (m) multiplied by the canopy cover (m) of each 30 m pixel,
elevation is the DEM value (m) for each 30 m pixel,
and **degradation status** is the thicket status (intact, moderately degraded, and severely degraded) of each pixel as classified in the STEP map.

Information about all the data that were used to calculate current woody carbon is provided in Table 2.6.

Table 2.6 The datasets (and their resolution, where applicable) that were used to estimate current woody carbon in the thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that were used to extract and/or process them.

Dataset	Source	Software
Raster of canopy top height (30 m) (2019)	Global Land Analysis and Discovery (GLAD) (Potapov et al., 2021)	Extracted from Google Earth Engine Clipped and applied in ArcMap 10.6
Raster of canopy cover (30 m) (2015)	Landsat Global Forest Cover Change (Sexton et al., 2013)	
Digital elevation model (30 m)	Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007)	
Shapefile with *in situ* Woody C plot data	Powell (2009)	ArcMap 10.6
Shapefile with thicket status	Subtropical Thicket Ecosystem Planning (STEP) Project (Lloyd, 2002)	Pristine, moderately degraded, and severely degraded portions of the shapefile were extracted and converted into a 30 m raster file in ArcMap 10.6

The original GEDI canopy height dataset was initially explored for this analysis, however, the recordings across the BNR thicket ranged between 2 m and 140 m which is an exceptionally high maximum canopy height recording in any biome, but especially thicket which is generally around 3 m high. Woody C estimates using GEDI were exceptionally high (~450 t ha^{-1}) in areas of the study site and resulted in GEDI being rejected as a reasonable option for use in this analysis. The Global Land Analysis and Discovery (GLAD) global forest canopy height dataset is based on the Landsat land-cover time-series data and is calibrated against the GEDI data (Potapov et al., 2021). The result is a canopy height recording range of between 0 m and 25 m over the thicket area of the BNR. This range of values is a big improvement relative to GEDI, but as a canopy height of 25 m is still unreasonably high for thicket vegetation, an outlier analysis was performed (Figure 2.7), and pixels with a value larger than 8 m were excluded from the analysis.

Another problem with GLAD was that it is aimed at studying forests, so the minimum canopy height recorded is 3 m. This posed a problem because thicket generally consists of much shorter vegetation (around 2 to 5 m high) compared to forests, so GLAD recordings of 0 m, could lie between 0 and 3 m. For the purpose of this analysis, a best estimate of 1 m was made for pixels with a value of 0. Once the canopy height data was prepared, each pixel was multiplied by the corresponding canopy cover value to calculate a 30 m raster of the volume of vegetation.

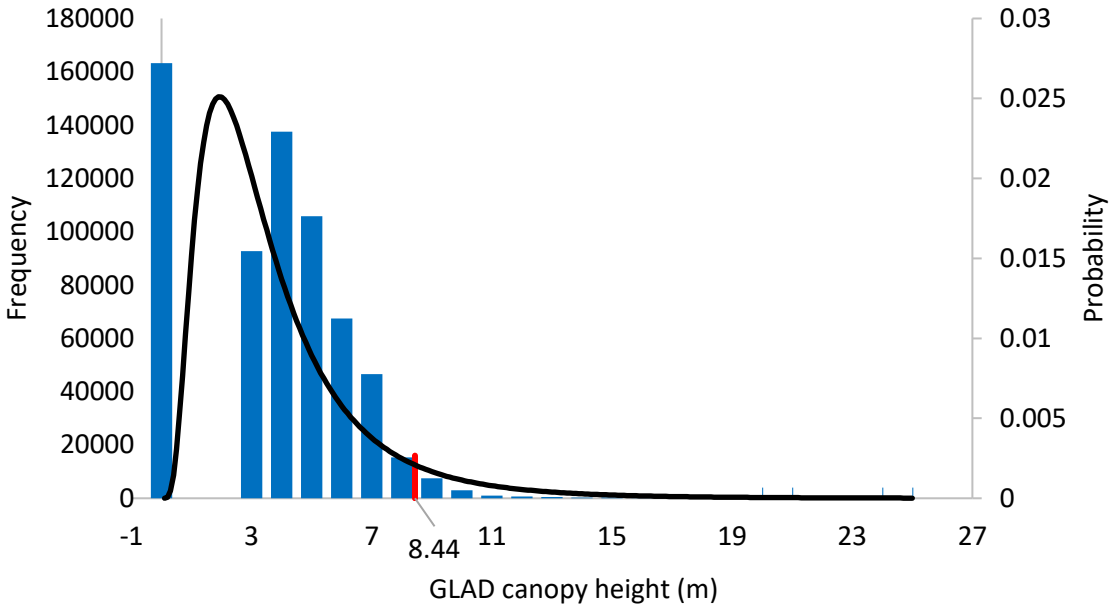

Figure 2.7 A graph of the Global Land Analysis and Discovery (GLAD) canopy height 30 m pixel values over the Baviaanskloof Nature Reserve, South Africa. Recordings of 0 m could actually be 1 or 2 m due to the minimum height threshold of 3 m recorded by the sensor. The probability density function of a log-normal distribution fit to the GLAD canopy height observations was overlaid in black. The red line indicates the 95th percentile outlier cut-off value of 8.44 m.

An outlier analysis was also performed for the 191 Woody C recordings (Figure 2.8). An exponential function was fitted to the data and an outlier cutoff value was calculated at the 95th percentile.

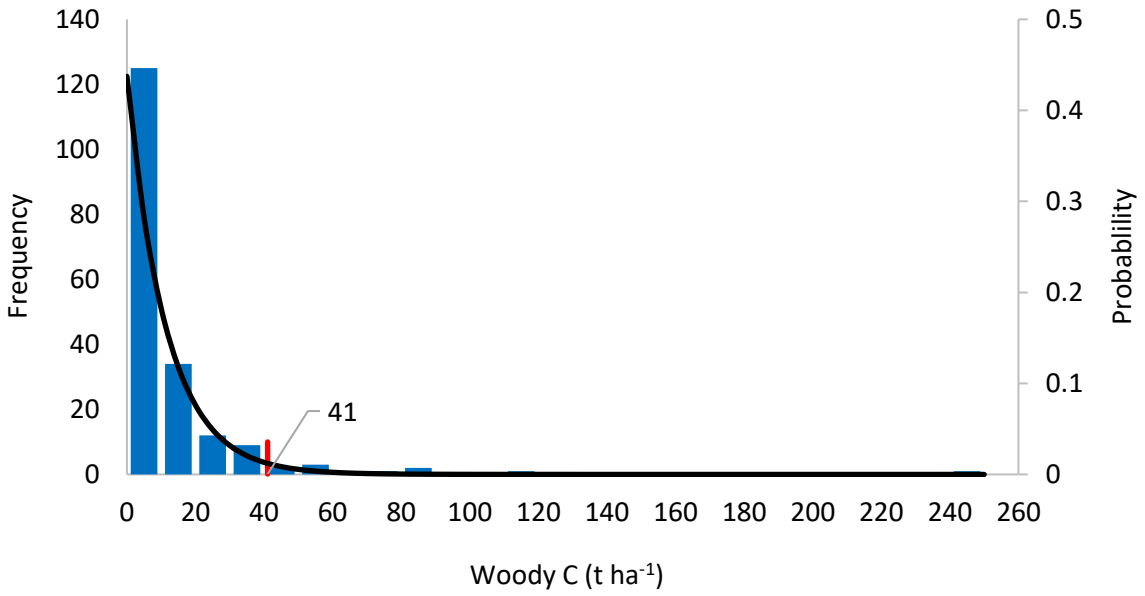

Figure 2.8 The frequency of the *in situ* woody carbon recordings in the Baviaanskloof Nature Reserve, South Africa, by Powell (2009). An outlier cutoff value (41.03), indicated by the red line, was calculated at the 95th percentile of an exponential function that was fitted to the data and all recordings that exceeded 41.03 were excluded and the remaining 181 data points were used for the analysis.

As the carbon data were not normally distributed, a Forest-based Classification and Regression model (ArcGIS Pro 3.1) for Woody C as a response variable was run for all possible combinations of the potential explanatory variables: vegetation volume, degradation status, slope position and elevation. One hundred validation runs were performed and 20% of the training data were excluded for model validation. The best model was chosen based on the highest median R^2 value of the model estimates versus the excluded validation data. When running the selected model to predict to a raster, none of the data was excluded from the model, as suggested by ESRI in a workshop on the Forest-based Classification and Regression tool (Esri Events, 2019).

Potential Woody Carbon

Potential Woody C was estimated according to the below function (RJ Scholes, personal communication):

$$\mathbf{C_{Woody,\ potential} \sim Annual\ P/PE + Wet\ P/PE + Dry\ P/PE + slope\ position} \quad (6)$$

Where:

Annual P/PE is average annual water availability,
Wet P/PE and Dry P/PE are the average water availability in the wettest and driest quarters of the year, respectively,
and **slope position** is a proxy for soil depth.

Information about all the data that were used to calculate potential woody carbon is provided in Table 2.7.

Table 2.7 The datasets (and their resolution, where applicable) that were used to estimate potential woody carbon in the thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that were used to extract and/or process them.

Dataset	Source	Software
Daily precipitation recordings from 2000 to 2022	South African Weather Service	Microsoft Excel and ArcGIS Pro 3.1
Daily minimum and maximum temperature recordings from 2000 to 2022		
Slope position raster (30 m)	This study	ArcGIS Pro 3.1
Current C_{Woody} in intact thicket		

The daily minimum temperature, maximum temperature, and rainfall records from 2000 to 2022 were requested from the South African Weather Service for three surrounding towns: Patensie, Joubertina and Willowmore. To gap-fill the records, a linear regression was performed for all combinations of the three sites (Patensie and Joubertina, Joubertina and Willowmore, Willowmore and Patensie) using data from all days where both sites had data. The equation of the linear trendline with the highest R^2 value was then used to gap-fill missing daily temperature and rainfall recordings for each site. The average rainfall, minimum temperature and maximum temperature for each month was interpolated into individual 30 m resolution raster images across the reserve using the Kriging interpolation tool in ArcGIS Pro 3.1, although interpolation may not be ideal over mountainous areas such as the BNR (Workneh et al., 2024). The average minimum and maximum temperature pixel values for each month were calculated and used to determine R_{ann} below. Potential evaporation was calculated for each pixel using the Linacre equation (Linacre, 1977) in the Raster Calculator tool as described below:

$$E_0 \text{ (mm day}^{-1}) = \frac{(700T_m/(100 - A)) + 15(T - T_d)}{(80 - T)} \quad (7)$$

Where:

$(T - T_d)$ = 0.0023 z + 0.37 T + 0.53 R + 0.35 R_{ann} − 10.9°C,

T_m is T + 0.006 × z,

T_d is the mean dew-point temperature (°C),

T is mean temperature (°C),

A is the latitude at the site (33°),

z is the elevation (m) from the SRTM DEM,

R is the mean temperature range,

and R_{ann} is the difference between the warmest and coldest months of the year.

Once the potential evaporation raster files for each month were created as described above, the precipitation raster images were divided by the corresponding PE raster images to create images of P/PE across the reserve. The average monthly P/PE pixel values were calculated and used to determine which quarter of the year is the wettest (has the lowest average P/PE value) and driest (has the highest average P/PE value). The raster images for these quarters were then averaged to create P/PE raster files for the driest and wettest quarters.

To estimate potential Woody C, the current Woody C estimates in intact thicket were isolated and used as input into the model. There were insufficient *in situ* recordings in intact thicket to use to model potential Woody C as none of the plots were located in the upper slopes or crests. The current Woody C estimates in intact thicket were strongly left skewed and unsuitable for a Generalised Linear Model (GLM). Despite reflecting the data, transforming the data, and testing different families and link functions in R Studio (R version 4.2.3), the residuals of all models based on all combinations of the explanatory variables were not normally distributed. As Forest-based Classification and Regression in ArcGIS Pro 3.1 is suitable for data that are not normally distributed, this tool was used. All combinations of the explanatory variables were used with 20% of the training data excluded for validation. The best model was selected based on the highest R^2 value of model estimates vs input data and the lowest mean squared error value. When using the selected model to predict to a raster, none of the training data were excluded for validation.

2.5 Root Carbon

The following subsection describes the methods employed to calculate the current and potential root carbon in the thicket of the BNR.

Current Root Carbon

The following equation (RJ Scholes, personal communication) was applied to each pixel of estimated current woody carbon to calculate the current root carbon:

$$C_{Root,\ current} = C_{Woody,\ current} \times f_{RootC} \quad (8)$$

Where:

$C_{Woody,\ current}$ is the estimate of current woody carbon calculated above for each pixel, and f_{RootC} is the ratio of C_{root} to C_{Woody} calculated from past literature (Powell, 2009).

Information about all the data that were used to calculate current root carbon is provided in Table 2.8.

Table 2.8 The datasets (and their resolution, where applicable) that were used to estimate current root carbon in the thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that was used in the analysis.

Dataset	Source	Software
Current woody carbon (30 m)	Calculated in this study	ArcMap 10.6
Average root carbon recorded in intact thicket	Powell (2009)	
Average root carbon recorded in moderately degraded thicket		
Average root carbon recorded in severely degraded thicket		

Individual f_{RootC} values were calculated using the average Woody C and Root C recordings in intact, moderately degraded and severely degraded thicket from Powell (2009) to determine the average tonnes of Root C to one tonne of Woody C for each degradation status (Table 2.9).

The $\mathbf{f_{RootC}}$ ratio for intact thicket was applied to each pixel of current Woody C calculated in this study in intact thicket, the $\mathbf{f_{RootC}}$ ratio for degraded thicket was applied to each pixel of current Woody C in moderately degraded thicket, and the $\mathbf{f_{RootC}}$ for Old Lands was applied to each pixel of current Woody C in severely degraded thicket.

Potential Root Carbon

Root carbon was calculated using the following equation (RJ Scholes, personal communication):

$$\mathbf{C_{Root,\ potential} = C_{Woody,\ potential} \times f_{RootC}} \quad (9)$$

Where:

$\mathbf{C_{Woody}}$, potential is the potential Woody C calculated in the previous section, and $\mathbf{f_{RootC}}$ is the average ratio of Root C to Woody C in intact thicket.

f_{RootC} was calculated using the *in situ* average Woody C and Root C data for intact thicket that was used in the current Root C analysis (Powell, 2009). This ratio was then applied to each 30 m pixel of estimated potential Woody C in pixels located in moderately and severely degraded thicket using the Raster Calculator tool in ArcMap 10.6 to calculate potential Root C. Information about all the data that were used to calculate potential root carbon is provided in Table 2.10.

Table 2.10 The datasets (including resolution, where applicable) that were used to estimate the potential root carbon in the degraded thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that were used to apply them.

Dataset	Source	Software
Current woody carbon estimate (30 m)	Calculated in this study	ArcMap 10.6
Average root carbon recorded in intact thicket	Powell (2009)	

2.6 Litter Carbon

The following subsection describes the methods used to calculate estimates of the current and potential litter carbon within the BNR thicket.

Current Litter Carbon

Current litter carbon per pixel of thicket was calculated using the following equation (RJ Scholes, personal communication):

$$C_{litter,\ current} = C_{Woody,\ potential} \times f_{litterC} \quad (10)$$

Where:

> $C_{Woody,\ current}$ is the estimate of current woody carbon calculated above for each pixel, and $f_{LitterC}$ is ratio of Litter C to C_{Woody} calculated from past literature (Powell, 2009).

The data that were used are specified in Table 2.11. Separate $f_{LitterC}$ values were calculated using the average Woody C and Litter C recordings in intact, moderately degraded, and severely degraded thicket from Powell (2009) to determine the average tonnes of Litter C to one tonne of Woody C for each degradation status (Table 2.12).

Table 2.11 The datasets (and their resolution, where applicable) that were used to estimate current litter carbon in the thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that were used in the analysis.

Dataset	Source	Software
Current woody carbon (30 m)	Calculated in this study	ArcMap 10.6
Average litter carbon recorded in intact thicket	Powell (2009)	
Average litter carbon recorded in moderately degraded thicket		
Average litter carbon recorded in severely degraded thicket		

Table 2.12 The ratios of Litter C to Woody C, calculated from past carbon recordings in the thicket of the Baviaanskloof Nature Reserve, South Africa (Powell, 2009).

Degradation status	Woody C	Litter C
Intact thicket	1	0.14
Moderately degraded thicket	1	0.35
Severely degraded thicket	1	0.25

The $\mathbf{f_{LitterC}}$ ratio for intact thicket was applied to each pixel of current Woody C calculated in this study in intact thicket, the $\mathbf{f_{LitterC}}$ ratio for degraded thicket was applied to each pixel of current Woody C in moderately degraded thicket, and the $\mathbf{f_{LitterC}}$ for severely degraded thicket was applied to each pixel of current Woody C in severely degraded thicket.

Potential Litter Carbon

The potential litter carbon stocks were calculated according to the following equation (RJ Scholes, personal communication):

$$\mathbf{C_{litter,\ potential} = C_{Woody,\ potential} \times f_{litterC}} \quad (11)$$

Where:

> $\mathbf{C_{Woody,\ potential}}$ is the potential Woody C estimate calculated in this study for each pixel, and $\mathbf{f_{LitterC}}$ is the average ratio of litter carbon to Woody C in intact thicket within the BNR.

$f_{LitterC}$ was calculated using the average *in situ* Woody C and Litter C data for intact thicket that was used in the current Litter C analysis (Powell, 2009). This ratio was then applied to each 30 m pixel of estimated potential Woody C in pixels located in moderately and severely degraded thicket using the Raster Calculator tool in ArcMap 10.6 to calculate potential Litter C. Information about all the data that were used in this calculation is provided in Table 2.13.

Table 2.13 The datasets (including resolution, where applicable) that were used to estimate the potential litter carbon in the degraded thicket of the Baviaanskloof Nature Reserve, South Africa, and the corresponding software that were used to apply them.

Dataset	Source	Software
Current woody carbon estimate (30 m)	Calculated in this study	ArcMap 10.6
Average litter carbon recorded in intact thicket	(Powell, 2009)	

2.7 Statistical analysis

For each map of current and potential carbon estimates for each of the four thicket pools, the average and standard deviation of all the pixel values were calculated to compare the results. For each individual carbon pool, a multi-factor Analysis of Variance (ANOVA) was performed with slope position, degradation status and ecosystem state (current and potential) as independent variables. A Tukey post-hoc test was then performed to determine any significant differences ($\alpha = 0.05$) between the average carbon pixel value at each slope position, degradation status and ecosystem state for each carbon pool.

For woody carbon and litter carbon, for which individual plot measurements were available, a correlation analysis was performed for each to compare the recorded carbon values by Powell (2009) against the carbon estimates calculated in this study. As the data were not normally distributed, Spearman's rank correlations were performed.

3 Results

3.1 Soil organic carbon

The estimated mean current SOC was 20.3 ± 21.7 t ha^{-1} and the mean potential SOC was 29.7 ± 26.1 t ha^{-1} across the entire thicket area of the BNR. The current SOC estimates were lower than the potential SOC estimates (Table 3.1); however, the severely degraded estimates are higher than the moderately degraded estimates for both current and potential carbon (Table 3.1).

Table 3.1 The average current and potential soil organic carbon pixel values over the thicket area of the Baviaanskloof Nature Reserve, South Africa, for each current thicket degradation status.

Original degradation status	Average current soil organic carbon ± 1 SD (t ha^{-1})	Average potential soil organic carbon ± 1 SD (t ha^{-1})
Intact	37.7 ± 29	-
Moderately degraded	13.2 ± 12.1	26.3 ± 24.1
Severely degraded	14 ± 11.6	28 ± 23.1
All thicket	**20.3 ± 21.7**	**29.7 ± 26.1**

The potential SOC estimates at each slope position (Table 3.2) followed the expected trend of increasing downslope – also evident in Figure 3.2 as well as the current SOC estimates in Figure 3.3. There is a difference between the two slope extremes with valleys having 20 times the average amount of potential SOC than the crests.

The best model for potential SOC, based on the highest R^2 and Jarque Bera values, included slope position and elevation (two related variables) as explanatory variables to predict carbon. However, this resulted in a single carbon estimates per slope position, and no other variation, therefore no statistics could be performed on this data.

Table 3.2 The potential soil organic carbon (t ha^{-1}) pixel values over the thicket area of the Baviaanskloof Nature Reserve, South Africa, estimated at each of the five slope positions.

Slope position	Potential soil organic carbon (t ha^{-1})
Valley	78.1
Lower slope	36.8
Mid-slope	17.4
Upper slope	8.2
Crest	3.9
All	**29.7**

According to the SoilGrids model (Figure 3.1), the average SOC across thicket in the BNR is 48.4 ± 5.2 t ha^{-1} – much higher compared to the average value of 29.7 ± 26 t ha^{-1} estimated in this study. SoilGrids is available at a 250 m resolution, which is very coarse given the highly variable topography of the BNR and may be insufficient to account for changes in the landscape such as soil depth.

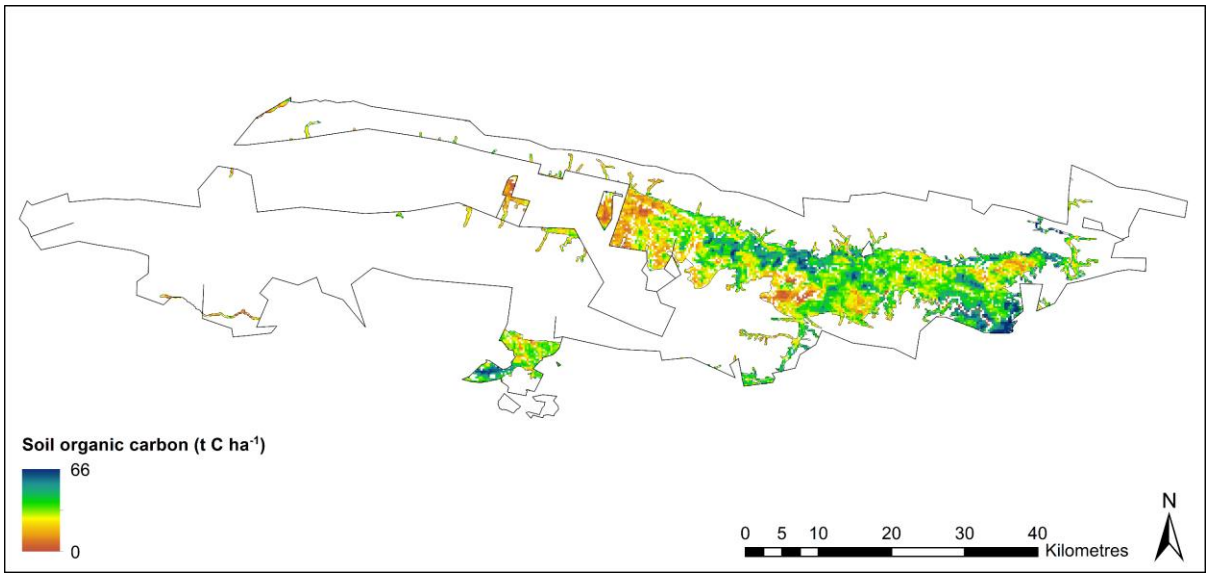

Figure 3.1 Potential soil organic carbon estimates within the thicket area of the Baviaanskloof Nature Reserve, South Africa, as predicted by the SoilGrids model at a resolution of 250 m.

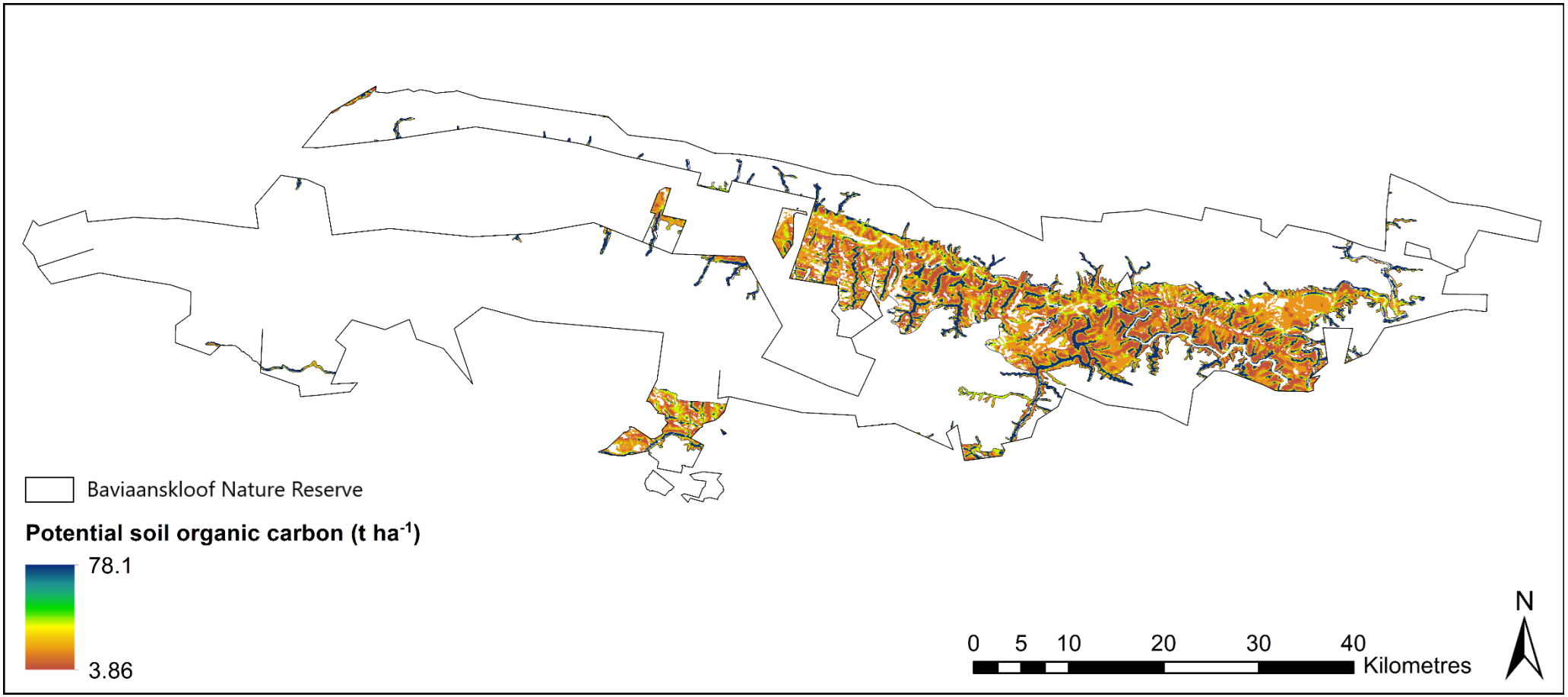

Figure 3.2 Estimated potential soil organic carbon in each 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, based on the ARC soil profile data in primary catchment L, the classified slope positions, and a digital elevation model.

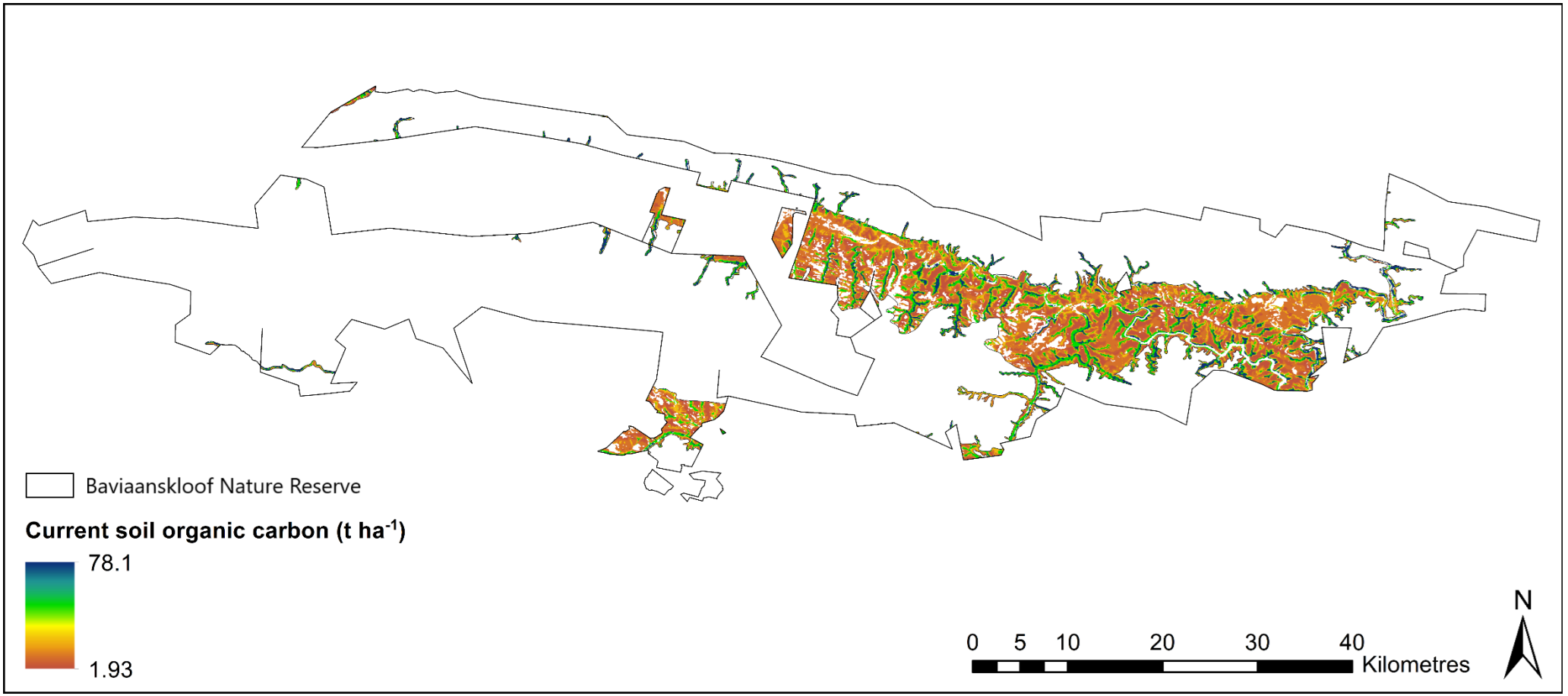

Figure 3.3 Estimated current soil organic carbon in each 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, based on the potential soil organic carbon estimates and a first-order decay model of Nitrogen.

3.2 Woody carbon

The average current woody carbon (Woody C) estimated in this study across all levels of degradation was 15.7 ± 6.4 t ha^{-1} (Table 3.3) and the average potential Woody C estimated in this study was 18.4 ± 2.9 t ha^{-1}. The values of the lowest estimates in Figure 3.4 and Figure 3.5 show an increase of 8 t ha^{-1} in areas of low current carbon, and the values in Table 3.3 indicate that severely degraded thicket has the highest potential of carbon increase compared to moderately degraded thicket.

On average across the reserve and both levels of degradation, the potential carbon estimates are higher than the current carbon estimates (Table 3.3), however, some pixels across the reserve have a lower estimate of potential Woody C compared to current Woody C (discussed below).

Table 3.3 The average current and potential woody carbon pixel values over the thicket area of the Baviaanskloof Nature Reserve, South Africa, for each current thicket degradation status.

Original degradation status	Average current woody carbon ± 1 SD (t ha^{-1})	Average potential woody carbon ± 1 SD (t ha^{-1})
Intact	18.1 ± 4	-
Moderately degraded	15.6 ± 6.7	18.7 ± 2.3
Severely degraded	8 ± 4.6	17.6 ± 2.5
All thicket	**15.7 ± 6.4**	**18.4 ± 2.9**

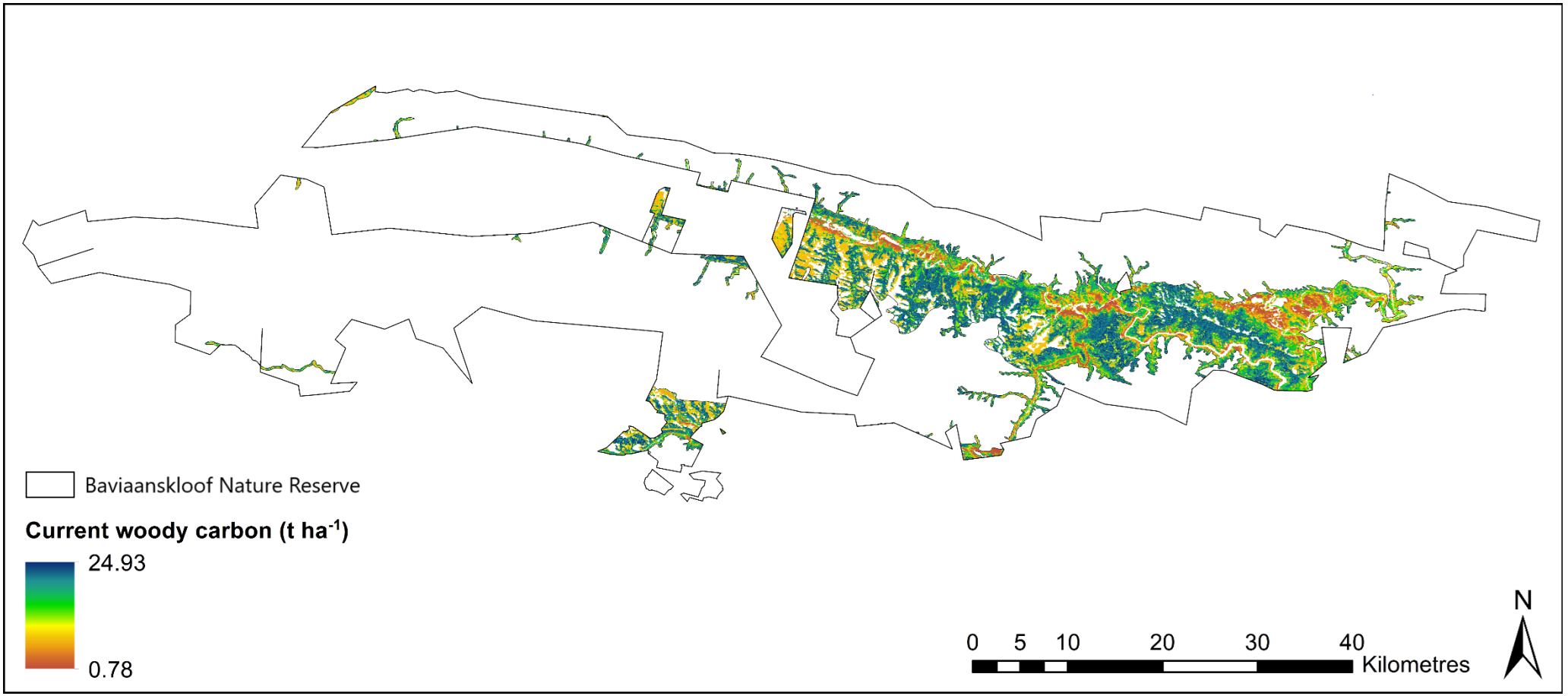

Figure 3.4 The best estimate of current woody carbon in each 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, as predicted using the Forest-based Classification and Regression tool in ArcGIS Pro 3.1.

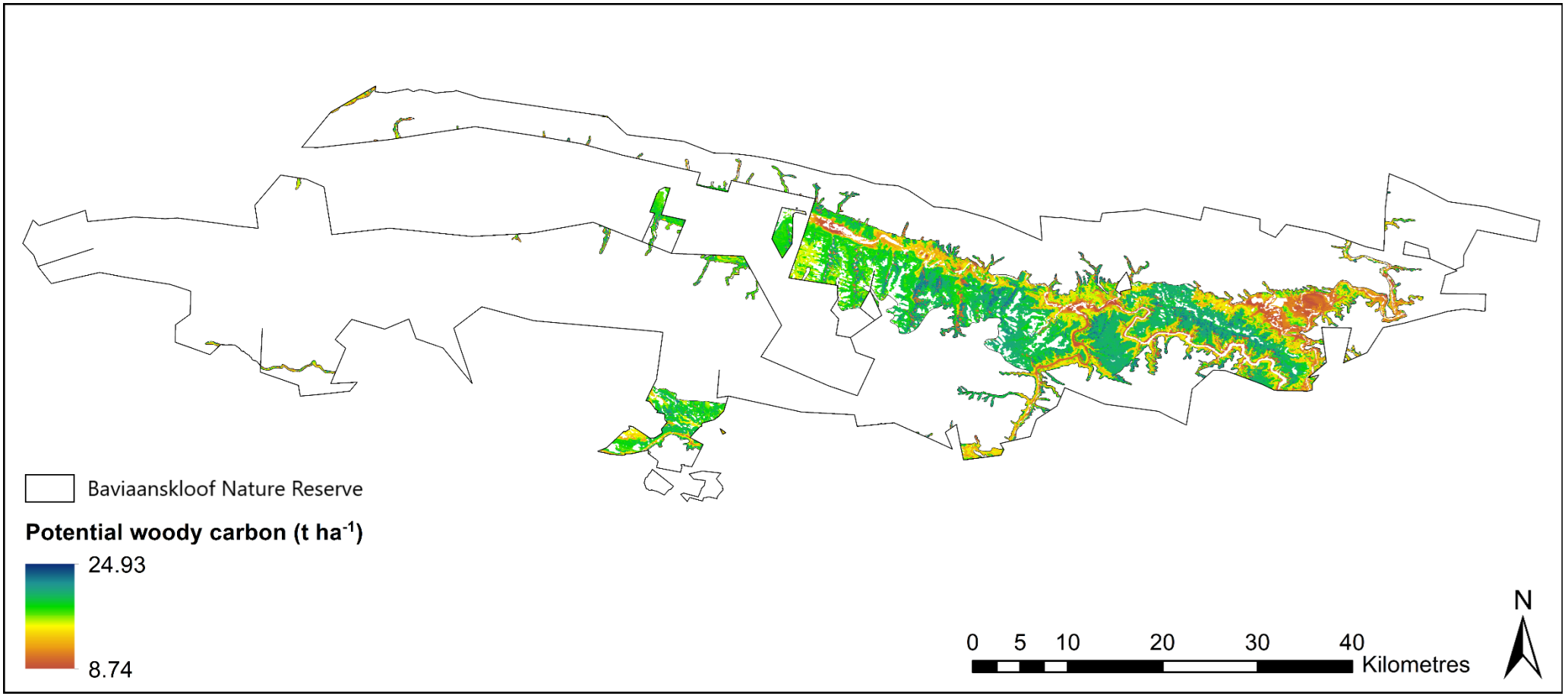

Figure 3.5 The estimated potential woody carbon in the thicket of the Baviaanskloof Nature Reserve, South Africa based on the current woody carbon estimates in intact thicket.

When comparing the *in situ* recordings of Woody C with the model estimates of current Woody C from the corresponding pixels, the positive Spearman's rank correlation coefficient of 0.66 (S = 331491, $p < 0.01$) (Figure 3.6) indicates a good fit.

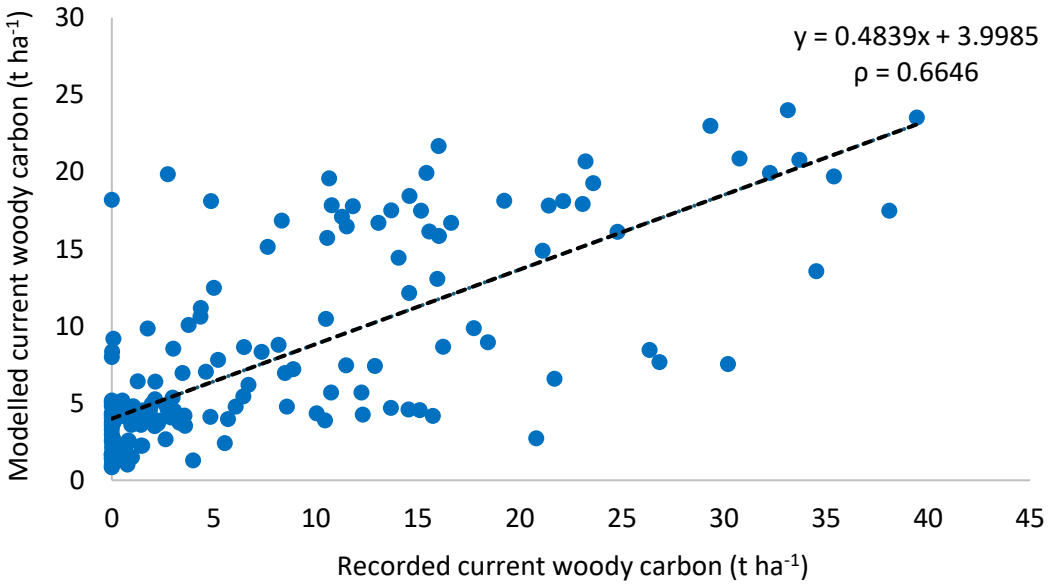

Figure 3.6 The available *in situ* woody carbon recordings collected by Powell (2009) in the thicket area of the Baviaanskloof Nature Reserve, South Africa, plotted against the corresponding woody carbon 30 m pixel estimates from the best-fit model in this study. The Spearman's rank correlation coefficient – ρ – is 0.6646 (S = 331491, $p < 0.01$).

3.3 Root carbon

The average current root carbon (Root C) estimated across the thicket area of the reserve was 6.5 ± 3.8 t ha^{-1}, and the average potential Root C was 3.2 ± 0.5 t ha^{-1}. For both moderately and severely degraded thicket, the average potential carbon estimates are lower than the average current carbon estimates (Table 3.4).

Table 3.4 The average current and potential root carbon pixel values over the thicket area of the Baviaanskloof Nature Reserve, South Africa, for each current thicket degradation status.

Current degradation status	Average current root carbon ± 1 SD (t ha^{-1})	Average potential root carbon ± 1 SD (t ha^{-1})
Intact	3.1 ± 0.7	-
Moderately degraded	8.3 ± 3.6	3.2 ± 0.4
Severely degraded	4.4 ± 2.5	3.0 ± 0.4
All thicket	**6.5 ± 3.8**	**3.2 ± 0.5**

Figure 3.7 and Figure 3.8 show the spatial distribution of current and potential carbon, respectively, across the thicket area of the reserve. Low current carbon estimates in the valleys (Figure 3.7) can be explained by the presence of degraded thicket, but this trend is also present in the map of potential carbon estimates (Figure 3.8) where red and yellow pixels, indicating low carbon stocks, are concentrated in the valleys.

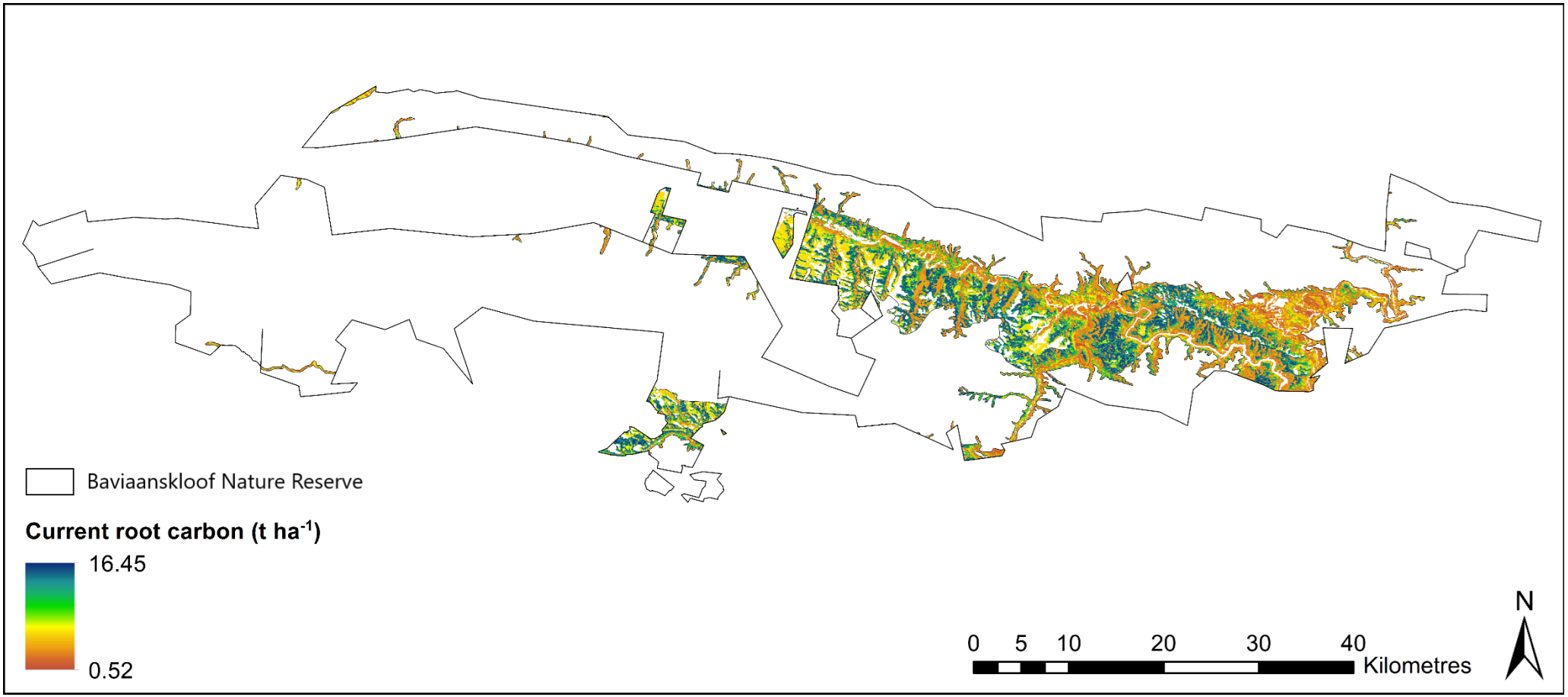

Figure 3.7 The estimated current root carbon in each 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, based on the best estimate of woody carbon in this study and the ratio of root carbon to woody carbon.

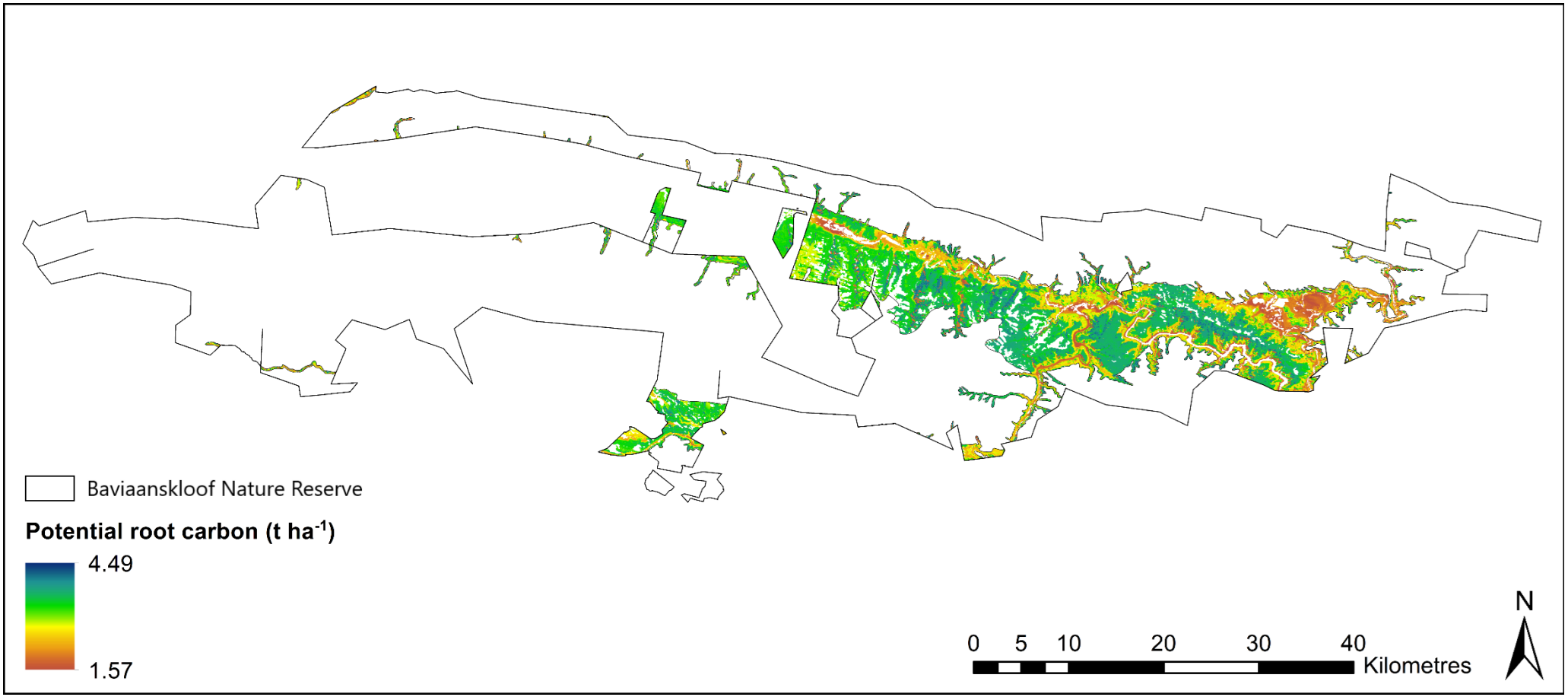

Figure 3.8 The estimated potential root carbon in each 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, based on the potential woody carbon estimates and the ratio of root carbon to woody carbon.

3.4 Litter carbon

The average current litter carbon (Litter C) estimated across the thicket of the reserve was 3.6 ± 1.9 t ha^{-1} and the average potential Litter C carbon was 2.6 ± 0.4 t ha^{-1}. Like the Root C estimates, the average potential Litter C in moderately degraded thicket areas was lower than the average current carbon estimate (Table 3.5) indicating that these estimates need to be improved in order to be used for decision-making. However, when plotting the modelled estimates against the corresponding recordings, the positive Spearman's rank correlation coefficient of 0.41 ($S = 583914$, $p < 0.01$) (Figure 3.9) indicates a relatively good fit.

Table 3.5 The average current and potential litter carbon pixel values over the thicket area of the Baviaanskloof Nature Reserve, South Africa, for each current thicket degradation status.

Original degradation status	Average current litter carbon ± 1 SD (t ha^{-1})	Average potential litter carbon ± 1 SD (t ha^{-1})
Intact	2.4 ± 0.5	-
Moderately degraded	4.4 ± 1.9	2.5 ± 0.3
Severely degraded	1.7 ± 1	2.4 ± 0.3
All thicket	**3.6 ± 1.9**	**2.6 ± 0.4**

Low litter carbon estimates appear to be concentrated in the valley regions (Figure 3.10 and Figure 3.11). Given that most severely degraded thicket is concentrated in and near the valleys, it is expected for there to be lower current litter carbon estimates there, however, potential litter carbon estimates are also low downslope, and high upslope.

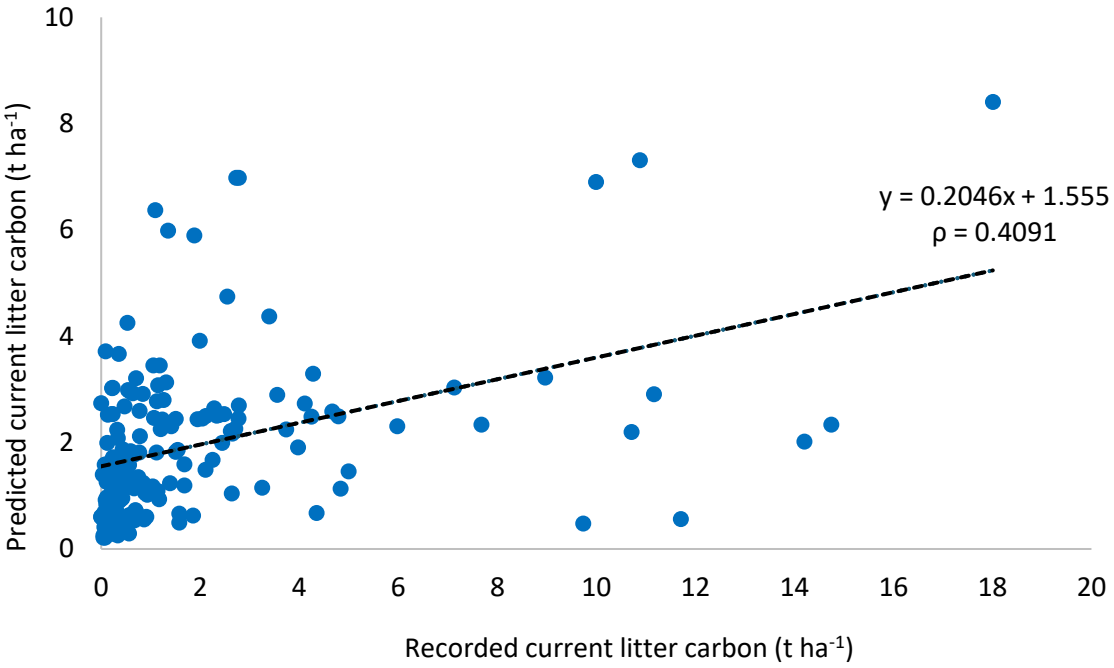

Figure 3.9 The available *in situ* current litter carbon recordings collected by Powell (2009) in the thicket area of the Baviaanskloof Nature Reserve, South Africa, plotted against the corresponding current litter carbon 30 m pixel estimates from this study. The Spearman's rank correlation coefficient – ρ – is 0.4091 ($S = 583914$, $p < 0.01$).

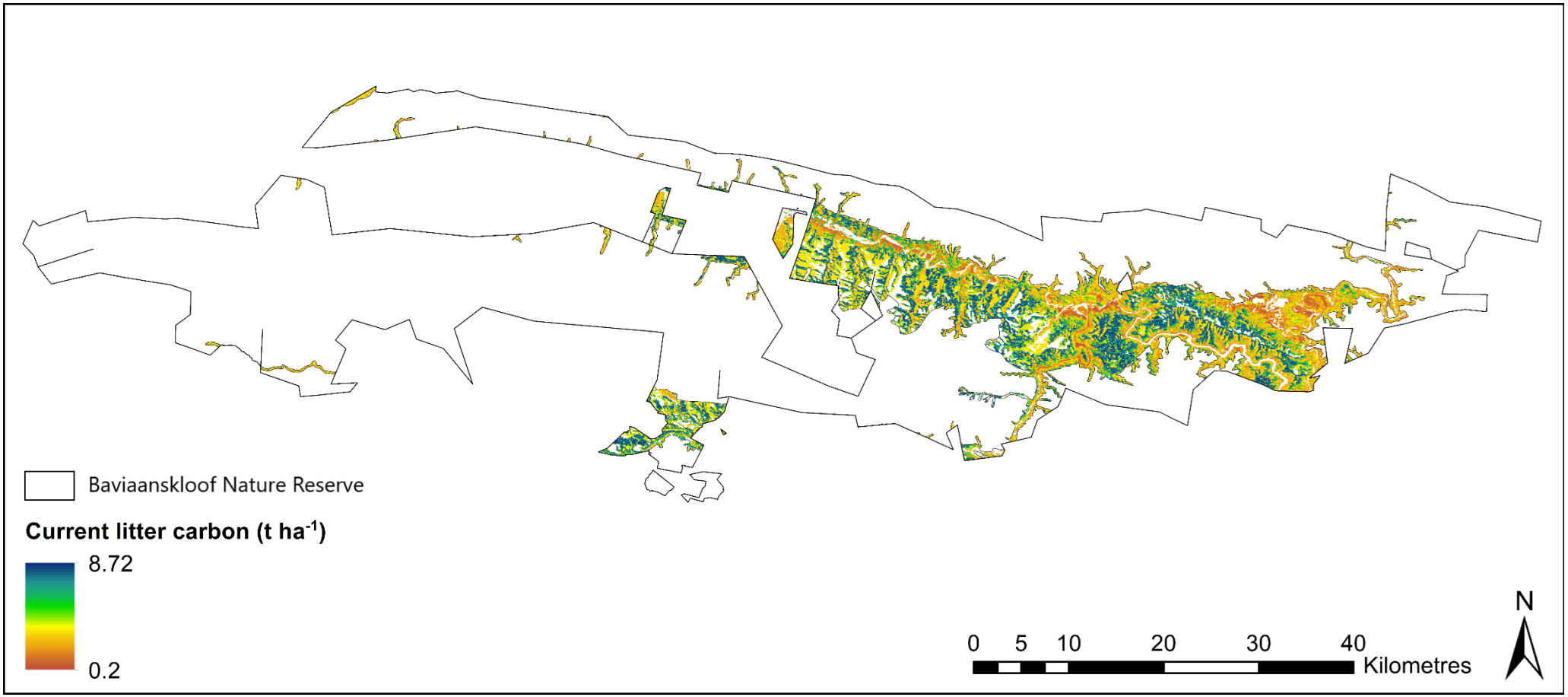

Figure 3.10 The current litter carbon estimates per 30 m pixel of thicket in the Baviaanskloof Nature Reserve, South Africa, based on the current woody carbon estimates and the ratio of litter carbon to woody carbon.

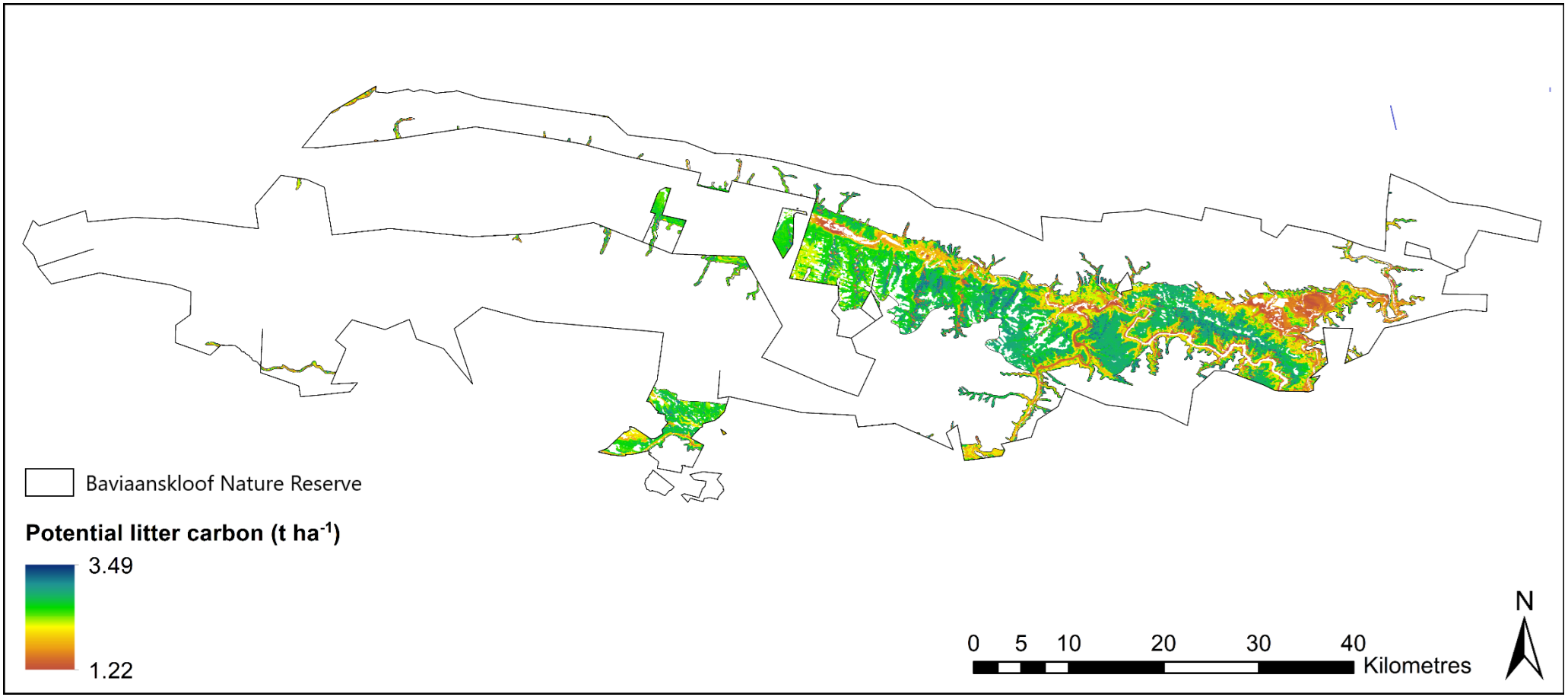

Figure 3.11 The potential litter carbon estimates for each 30 m pixel in the thicket area of the Baviaanskloof Nature Reserve, South Africa, based on the potential woody carbon estimates and the ratio of litter carbon to woody carbon.

3.5 Carbon trends

Carbon vs slope position

As expected, the average soil organic carbon (SOC) estimates significantly increased downslope ($F_{(4,862282)}$ = 939324375, p <0.01], however, woody carbon ($F_{(4,862282)}$ = 6776.83, p <0.01], root carbon ($F_{(4,862\ 282)}$ = 11005.4, p <0.01), and litter carbon ($F_{(4,862282)}$ = 9930.0, p <0.01) all increased significantly upslope (Figure 3.12), which was not expected.

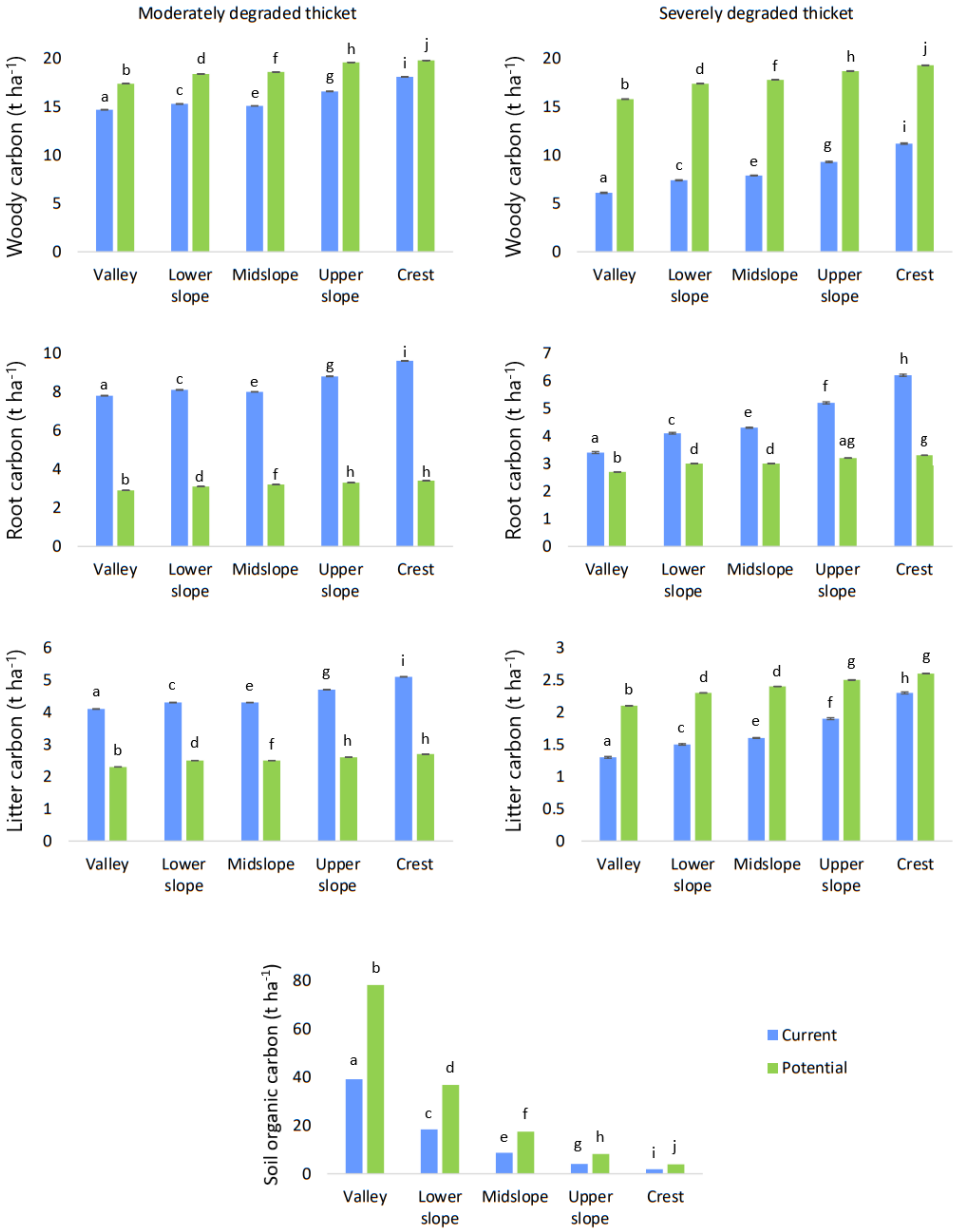

Figure 3.12 The average (± SE) current and potential carbon at each slope position for both degrees of degradation of each thicket carbon pool in the Baviaanskloof Nature Reserve, South Africa. The results of the Tukey post-hoc test to determine significant differences between carbon at different slope positions for all carbon (current and potential) are indicated by the adjacent letters.

Current carbon vs degradation status

The expected trend was for the current carbon estimates in each pool to be highest in intact thicket, lower in moderately degraded thicket, and lowest in severely degraded thicket. This was the case for woody biomass ($F_{(2,862282)}$ = 39872.03, p <0.01); however, the average root carbon ($F_{(2,862282)}$ = 137762.9, p <0.01) and litter carbon ($F_{(2,862282)}$ = 95255.8, p <0.01) estimates were highest in moderately degraded thicket (Figure 3.13).

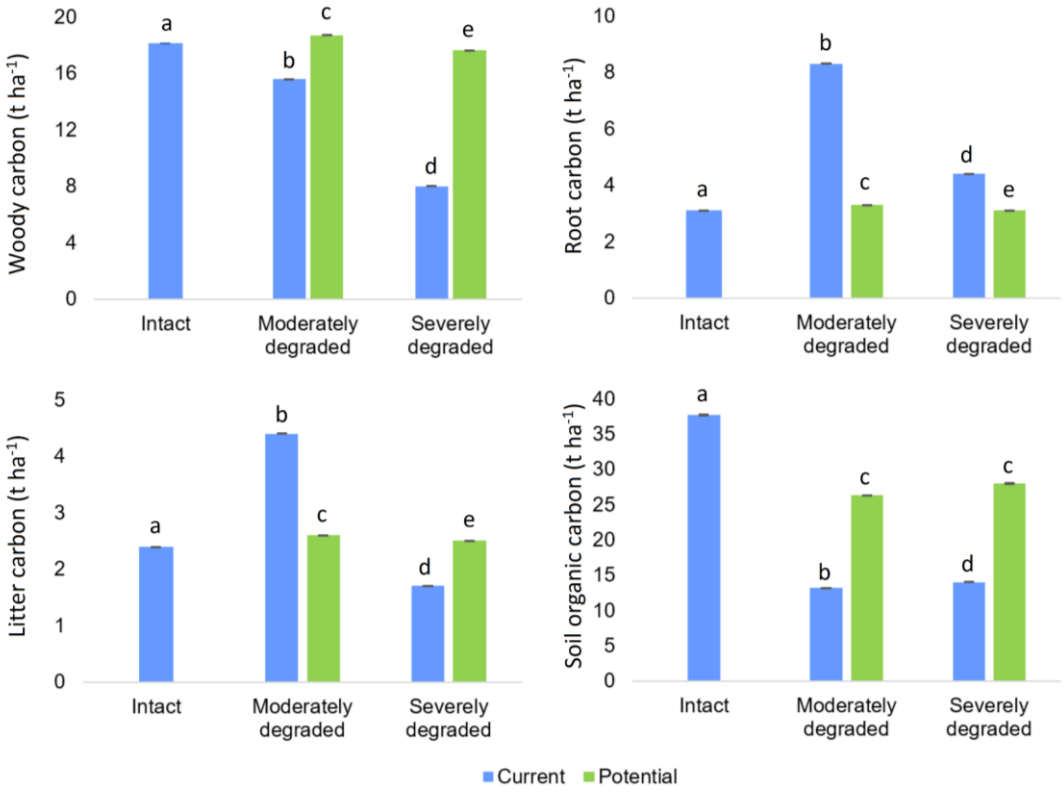

Figure 3.13 The average and standard error of the current and potential carbon pixel values for each pool and each degradation status in the thicket area of the Baviaanskloof Nature Reserve, South Africa. The results of the Tukey post-hoc test to determine significant differences between the current and potential carbon at the different degradation states are indicated by the adjacent letters.

Current vs potential carbon estimates

In most carbon pools, the average current carbon was lower than the average potential carbon, as expected. The opposite trend was shown in the root carbon of moderately and severely degraded thicket, and the litter carbon of moderately degraded thicket (Figure 3.13). The average current root carbon ($F_{(1,862282)}$ = 525679.1, p <0.01) and litter carbon ($F_{(1,862282)}$ = 190941.6, p <0.01) in moderately degraded thicket was significantly higher than the average carbon estimated in intact thicket, which suggests that moderately degraded thicket has been over-estimated in this study. As most thicket in

the reserve is classified as moderately degraded, according to the Subtropical Thicket Ecosystem Planning (STEP) project, high current carbon estimates relative to potential carbon estimates results in an illogical decrease in carbon post-restoration across almost the entire area of the reserve, as shown in Figure 3.14.

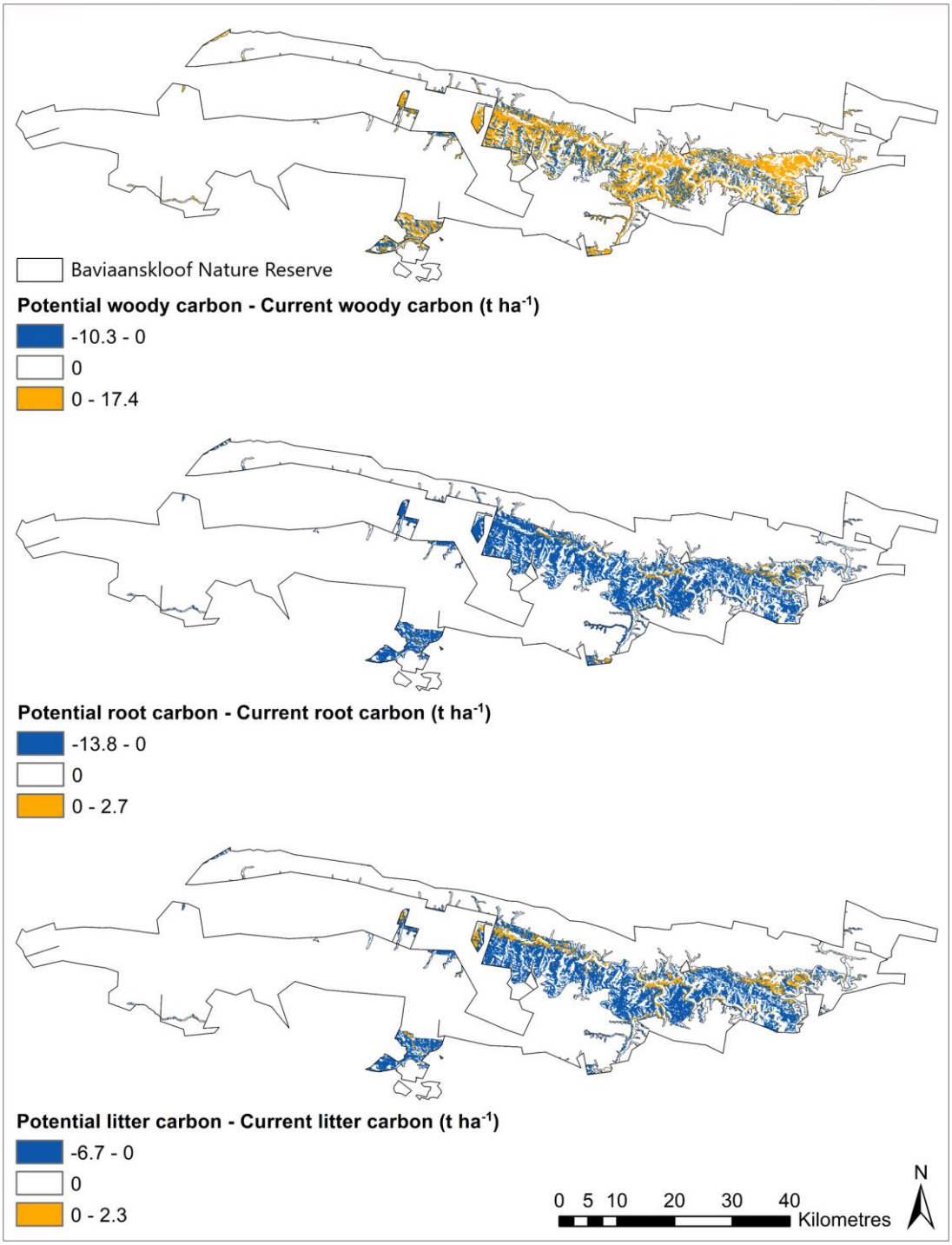

Figure 3.14 The difference between the current and potential woody, root, and litter carbon for each pixel of thicket in the Baviaanskloof Nature Reserve, South Africa. Orange indicates an increase in carbon, and blue indicates a decrease in carbon.

Modelled carbon vs recorded carbon

When plotting the model estimates against the corresponding *in situ* recordings and comparing the results against a 1:1 line (Figure 3.15), the result is a cluster of over-estimated model results at low carbon recordings (< 5 t ha^{-1}) in moderately and severely degraded thicket. This trend could be related to the unexpectedly high average root and litter carbon estimates in moderately degraded thicket mentioned above.

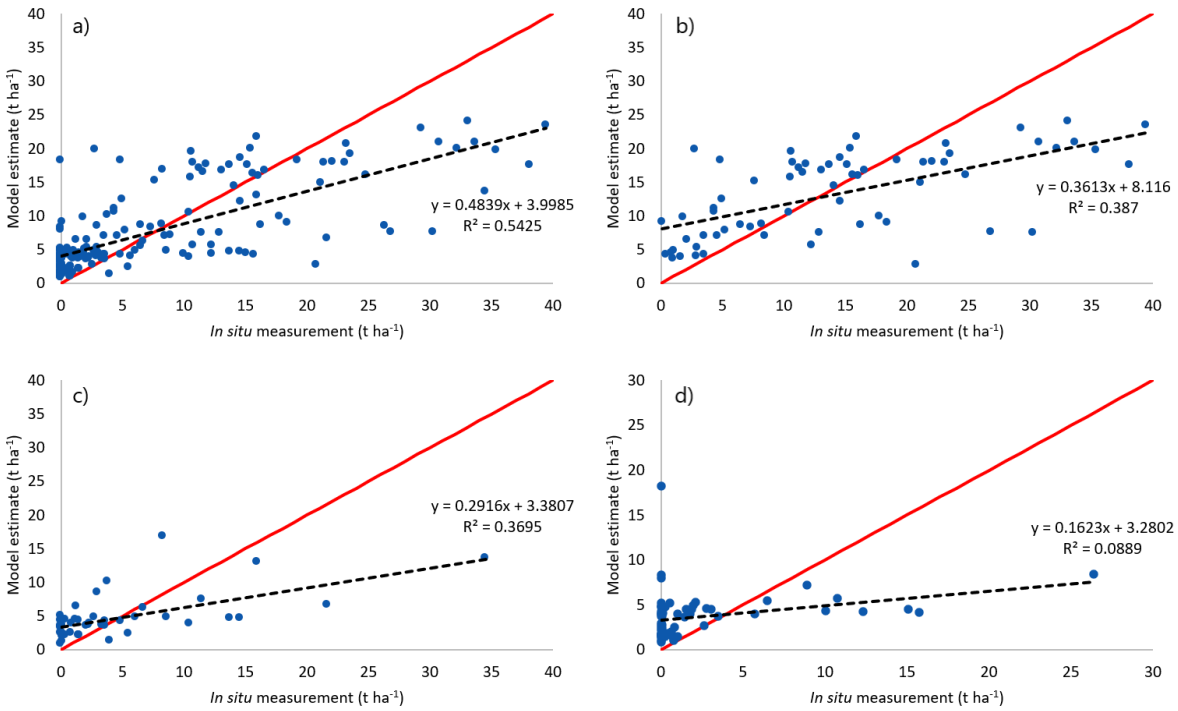

Figure 3.15 The pixel values across the thicket area of the Baviaanskloof Nature Reserve, South Africa, from the model of current woody carbon, plotted against the corresponding *in situ* recordings for a) all the plots, b) only the plots in intact thicket, c) only the plots in moderately degraded thicket, and d) only the plots in severely degraded thicket. The dashed black lines represent the linear trendline of the data, and the red line is a 1:1 relationship between model estimates and actual recordings.

Indications of model inadequacy

In addition to the unexpected results identified above, histogram plots of the carbon estimates in ArcGIS Pro 3.1 for all subsets of the data (based on pools, status, and slope positions) exhibit multimodal distributions. This indicates that there is variation in the carbon estimates that has not been accounted for in the predictive woody carbon model.

4 Discussion and conclusion

The aim of this study was to estimate and create maps of the current and potential carbon stock within the vegetation and soil of the subtropical thicket within the Baviaanskloof Nature Reserve (BNR), South Africa, for the purpose of restoration planning. The following chapter interprets the results of this study in the context of past studies, discusses the implications of the results, and identifies areas of improvement in the methods and data that were used.

4.1 Carbon pools

Soil organic carbon

When comparing the mean soil organic carbon (SOC) estimates from SoilGrids (Poggio et al., 2021) with the mean SOC in intact thicket from Powell (2009), the values are within range of each other (Table 4.1). However, the SoilGrids estimates for moderately degraded thicket (48 ± 5.1 t ha^{-1}) and severely degraded thicket (47.7 ± 5.2 t ha^{-1}) are also within the range of the SoilGrids estimates for intact thicket (49 ± 5 t ha^{-1}), indicating that it is better suited for assessing the potential SOC, not current SOC in degraded areas. This was expected, given that SoilGrids is based on physical characteristics of the landscape but not land use or degradation status. If not for the coarse resolution of the SoilGrids map (250 m) compared to the resolution in this study (30 m), it may have been an option for estimating the potential SOC after restoration.

For intact thicket, the Venter et al. (2021) SOC map estimates are within the range of other estimates (Mills et al., 2005a; Mills et al., 2005b; Mills and Cowling, 2009), but more than double the average estimate in this study (Table 4.1) and nearly double the average estimate from plot data in the BNR (Powell, 2009). The mean SOC estimates over moderately degraded thicket and severely degraded thicket by Venter et al. (2021) are also high relative to past estimates, apart from those by Mills et al. (2005a). Given that the Venter et al. (2021) map is a national map and not specifically designed to model SOC in thicket, the estimates may need to be calibrated against ground SOC data in thicket to verify and potentially use it in thicket restoration planning.

The average SOC estimated for all levels of degraded thicket in this study were the lowest compared to all other estimates (Table 4.1). However, there are two notable issues with these estimates. Firstly, the model of potential SOC only generated a single value for each slope position because slope position and elevation were the only two factors that were used to predict SOC. This is discussed further in section 4.3 about future research. Secondly, for each degradation status, the standard deviation values are high compared to the mean SOC values, indicating that there is high variation in

the estimates for each level of degradation and is another indication that the mean SOC results from this study are not reliable.

When compared to the average SOC from past plot data in the BNR (Powell, 2009), the average results of this study are up to 10 t ha^{-1} lower. In this study, SOC was most notably affected by slope position (statistical tests could not be performed on the single estimates per slope position) (Figure 3.12). The model estimates of SOC consistently increased downslope; therefore, this 10 t ha^{-1} difference may be a result of most of the plots being located in lower slope positions, which could have skewed the average SOC values by Powell (2009) towards higher SOC estimates. Unfortunately, the locations of the individual SOC plots that were used in the Powell (2009) study were not accessible, so the proportions of plots at each slope position could not be investigated.

Table 4.1 Average thicket soil organic carbon estimates (± SD) from this study in the Baviaanskloof Nature Reserve, South Africa, and past thicket studies in South Africa for each degradation classification, where available. Starred studies (*) produced large scale (national and global) maps, where the results were clipped for the Baviaanskloof thicket area and averaged for the respective degradation classifications.

	Intact thicket	**Moderately degraded thicket**	**Severely degraded thicket**
Mills et al. (2005a)	133 ± 27	95 ± 15	Not assessed
Mills et al. (2005b)	168	Not assessed	Not assessed
Mills and Cowling (2009)	93 ± 7	31 ± 2	42 ± 4
Powell (2009)	47.4 ± 4.4	21.6 ± 1.7	21.4 ± 1.4
Venter et al. (2021) *	90.5 ± 11.6	79.4 ± 13.4	75.8 ± 13.8
SoilGrids (0-30cm) *	49 ± 5	48 ± 5.1	47.7± 5.2
This study	**37.7 ± 29**	**13.2 ± 12.1**	**14 ± 11.6**

Like past studies in other ecosystems (Hao et al., 2002; Wei et al., 2010; Singh and Benbi, 2018), this study found that slope position plays an important role in the distribution of SOC. Other research has found different relationships between slope position and SOC, such as highest SOC at forested crests (Singh and Benbi, 2018) and the difference in SOC distribution in slopes with different vegetation types (Wei et al., 2010). From this study, it is clear that slope position plays an important role in the amount of SOC (Table 3.2) and, as the majority of degraded thicket in the reserve is located downslope according to the Subtropical Thicket Ecosystem Planning project (STEP) map (Lloyd et al., 2002), it is expected that thicket restoration in these areas could result in a measurable increase in SOC.

Woody carbon

The average intact thicket woody carbon (Woody C) estimated in this study was lower compared to past studies (Table 4.2). Given that this study incorporated the spatial variation of aboveground biomass into the estimates, this is an understandable difference, but estimates for moderately and severely degraded thicket are more than double those of past studies (Table 4.2). The high Woody C estimates in degraded thicket is emphasized by the fact that the difference between the average Woody C in intact thicket (18.1 ± 4 t ha^{-1}) and moderately degraded thicket (15.6 ± 6.7 t ha^{-1}) in this study, was just 2.5 t ha^{-1}. In past studies the difference was much greater and ranged between 22.5 t ha^{-1} (Powell, 2009) and 33 t ha^{-1} (Mills et al., 2005a). This indicates that the current Woody C estimates for degraded thicket in this study are unreasonably high, which is supported by the fact that the average current estimates are higher than the average potential carbon estimates (Figures 3.13 and 3.14) – an illogical result.

Collectively, the Woody C model estimates compare well to the ground recordings (R^2 = 0.71, Figure 3.4), but when isolating the data for moderately and severely degraded thicket, the results indicate that in areas of low recorded Woody C (< 5 t ha^{-1}), the model produced over estimates, particularly in degraded areas of thicket (Figure 3.15). The accuracy of GEDI height data, on which the GLAD canopy height data are based, significantly decreases over steep slopes (Adam et al., 2020), so this could be a result of high canopy height values in the GLAD dataset, even after the exclusion of outliers. Potential improvements to Woody C estimates are discussed below in section 4.3 pertaining to future research.

Harris et al. (2021) mapped aboveground carbon (AGC) in a portion of the BNR using very high resolution (0.34 m) multispectral imagery instead of SAR or LiDAR due to the budget constraints of collecting local imagery over an entire 3000 ha study area. Both the univariate model (R^2 = 0.85) and multivariate model (R^2 = 0.89) produced high accuracy results overall – more accurate than the results of this study (R^2 = 0.71). However, the methods used required Worldview-3 multispectral images for the entire study area and these images are not openly accessible or available for purchase for any study. It is also not clear what the topography of this particular site in the BNR was, and how accurate this method was in estimating AGC over steep slopes.

Table 4.2 Average current thicket woody (aboveground) carbon estimates (± SD) from this study in the Baviaanskloof Nature Reserve, South Africa, and past thicket studies in South Africa for each carbon pool and each degradation classification, where available.

	Intact thicket	**Moderately degraded thicket**	**Severely degraded thicket**
Mills et al. (2005a)	40 ± 3	7 ± 1	Not assessed
Powell (2009)	26.5 ± 3.9	4 ± 0.7	3.5 ± 0.8
Harris et al. (2021)	21.2 ± 6	13.9 ± 5.9	6.4 ± 3.7
This study	**18.1 ± 4**	**15.6 ± 6.7**	**8 ± 4.6**

Root carbon

Past studies of root carbon (Root C) in thicket have all been based solely on plot data, whereas this study used plot data and remote sensing to extrapolate plot data across a landscape. As with the SOC and Woody C estimates, the Root C estimated for intact thicket in this study was lower than those of past studies (Table 4.3). An odd result was that the average Root C estimates in moderately and severely degraded thicket were higher than that of intact thicket in this study, which is illogical. This was due to the high Woody C estimates in degraded thicket discussed above and was compounded by the high ratio of Root C to Woody C that was used in this calculation. Using a single ratio of Root C to Woody C was considered but, as is evident by the Powell (2009) data which indicates that this ratio is more than three times higher in both categories of degraded thicket than intact thicket (Table 2.7), there is clearly a difference in this ratio between intact thicket and degraded thicket. This is discussed further under *Degradation status* in section 4.2.

Unlike aboveground carbon, belowground carbon maps are not as common, globally. As was done in this study, the root-to-shoot method is often used to estimate belowground biomass by determining the relationship between aboveground and root biomass from past data and applying that to aboveground biomass data in areas where the root biomass isn't known (Spawn et al., 2020). An alternative method of mapping Root C is to directly model it using Random Forests instead of estimating it based on Woody C as was done at a global scale by Huang et al. (2021). However, this requires the development of spatial data on various factors including multiple soil properties and climate variables across the BNR which fell outside of the scope of this project. To the best of my knowledge, before this study, a map of root carbon has never been produced over the thicket area in South Africa. Given the results of this study and the areas of improvement that have been identified, there is a need for future research into mapping root carbon in thicket for the purpose of monitoring restoration projects.

Table 4.3 All average current thicket root carbon estimates (± SD) from this study in the Baviaanskloof Nature Reserve, South Africa, and past thicket studies in South Africa for each degradation classification, where available.

	Intact thicket	**Moderately degraded thicket**	**Severely degraded thicket**
Mills et al. (2005a)	25 ± 1.3	11 ± 0.7	Not assessed
Mills et al. (2005b)	25.4	Not assessed	Not assessed
Mills and Cowling (2009)	11 ± 2	2.7 ± 0.3	2.6 ± 0.3
Powell (2009)	4.7 ± 0.7	2.6 ± 0.6	2.3 ± 0.4
This study	**3.1 ± 0.7**	**8.3 ± 3.6**	**4.4 ± 2.5**

Litter carbon

Past studies of litter carbon (Litter C) in thicket have all been based solely on plot data, whereas this study used plot data and Woody C maps to extrapolate plot data across a landscape. Until now, no thicket study has created a map of Litter C alone**.** Because litter is a small component of the total carbon in thicket, it is usually mapped with aboveground biomass into a combined estimate of aboveground carbon, as was done by Harris et al. (2021).

Like the current Root C estimates discussed above, the litter carbon (Litter C) estimates in this study were higher for moderately degraded thicket than for intact thicket. This odd result can be explained by the higher ratio of Litter C to Woody C for moderately degraded thicket than for intact thicket and was exacerbated by the relatively high Woody C estimates for moderately degraded thicket, as discussed above. It is well established that the main cause of thicket degradation was overgrazing by livestock (Mills et al., 2005a; Rutherford et al., 2014) which directly and visibly impacts aboveground biomass but indirectly affects belowground and litter biomass. No research has been done on the time between the loss of aboveground thicket biomass and the loss of belowground and litter biomass, but it would make sense that there is a lag. This lag could explain why the ratio of Woody C to Litter C is 1 : 0.14 in intact thicket, 1 : 0.35 in moderately degraded thicket, and 1 : 0.25 in severely degraded thicket and why the ratio of Woody C to Root C — is 1 : 0.18 in intact thicket and 1 : 0.66 in degraded thicket according to the data by Powell (2009).

The Litter C values predicted by the model and the recorded plot Litter C data were not as strongly correlated (R^2 = 0.4) as for Woody C. This may be as a result of the single Woody C to Litter C ratios that were used for each degradation status. More specific litter ratios based on thicket type and the typical species composition may be required to improve the accuracy of Litter C estimates, or it may be that the method used for litter data collection does not result in a representative measurement of

the actual Litter C present. In their study mapping AGC using data from 85 plots with remote sensing imagery, Harris et al. (2021) compared the aboveground biomass carbon (Woody C) recordings to the corresponding Litter C recordings at each plot and the result was a relatively weak relationship (R^2 = 0.42) compared to the AGC results discussed above in the Woody C section. They suggest that sampling litter in plots of 0.5 m by 0.5 m may not be representative of Litter C in the larger study plots where AGC was recorded. Similarly, in the study by Powell (2009) – from which the data used in this study was sourced – Litter C was measured in smaller plots within the sampling plots which may not represent the Litter C of the larger plots where Woody C was recorded.

Table 4.4 All average current thicket litter carbon estimates (± SD) from this study in the Baviaanskloof Nature Reserve, South Africa, and past thicket studies in South Africa for each degradation classification, where available.

	Intact thicket	**Moderately degraded thicket**	**Severely degraded thicket**
Mills et al. (2005a)	11 ± 1	1 ± 0.4	Not assessed
Harris et al. (2021)	9.2 ± 3.6	4 ± 2.3	1.9 ± 2.6
Powell (2009)	3.7 ± 0.7	1.4 ± 0.3	0.9 ± 0.2
This study	**2.4 ± 0.5**	**4.4 ± 1.9**	**1.7 ± 1**

4.2 Factors influencing carbon

The following section discusses the factors that were found to influence carbon in this study.

Topography

The estimated SOC in this study increased downslope, but for all other pools, carbon increased upslope for both current and potential estimates. Generally, increased soil depth (downslope) would correspond with an increase in nutrients and soil depth and an increased capacity to support vegetation, both mechanically and chemically (Rajakaruna and Boyd, 2019), which would subsequently result in an increase in biomass and litter downslope as well. Therefore, it is unlikely that the trend of increased Woody C, Root C and Litter C upslope that was found in this study is accurate. It may be that the sample sizes of the data used in this study for the slope extremes (13 plots in valleys and nine plots in crests) are too small to really gain an insight into how the amount of biomass and aboveground carbon storage changes across a slope.

Past carbon studies in South Africa's subtropical thicket have focused on the effect of degradation status on carbon storage (Table 3.8) but, to the best of my knowledge, no study has yet investigated the relationship between carbon and slope position in thicket; and – as is evident by the trend in SOC

estimates in this study – it is an important factor to consider for planning thicket restoration, and should be investigated further.

Studies investigating the relationship between carbon and topographic position in other countries and biomes have come to various conclusions. Unlike the results of this study, excluding the SOC results, a study in the Gedo Forest of Ethiopia found that slope position had a weak but significant inverse relationship with aboveground, belowground, and litter carbon, indicating that biomass increased downslope (Yohannes et al., 2015). Another study in India by Singh and Benbi (2018) investigated the effect of slope position and land use on SOC and found that the forested hillslopes and grassed backslopes had the highest SOC, and the eroded mid-slopes had the least SOC. The variation in SOC in the study by Singh and Benbi (2018) and this one may be influenced by the change in species composition along the slope - a topic on which there is a lack of studies in thicket. Based on the Agricultural Research Council soil profile data for Primary Catchment L, the soil depth in thicket at the crests is generally very shallow, with an average depth of 16 cm and is unlikely to be able to support a large amount of vegetation and is likely to affect the amount of carbon that can be stored.

Degradation status

All past studies of subtropical thicket recorded lower average carbon estimates in degraded thicket than intact thicket and, generally, the lowest average carbon was recorded for severely degraded thicket for all carbon pools. As highlighted in the results section above, the average current Woody C and SOC estimates in this study were lower in both categories of degraded thicket than intact thicket, which is the logical trend. However, the average value of Woody C in moderately degraded thicket is much higher (15.6 t ha^{-1}) compared to the estimates of past studies – 4 t ha^{-1} (Powell, 2009) and 7 (Mills et al., 2005a) (Table 4.2), including the study on which these estimates were based (Powell, 2009), indicating that the model overestimated the current Woody C in degraded areas.

Mills et al. (2005a) estimated the average increase in Woody C to be 30 t ha^{-1}, Powell (2009) estimated an average increase of 22.5 t ha^{-1}, but the results of this study indicate an average increase of only 2.5 t ha^{-1} in moderately degraded thicket. To be able to calculate reliable estimates of the potential increase in carbon from restoration of degraded thicket, and to be able to assign an appropriate number of carbon credits, the baseline estimates need to be as accurate as possible.

4.3 Future research

There are two main areas of improvement that have been identified in this study: the current Woody C estimates and the SOC estimates.

Woody carbon estimates

Current and potential estimates for Root C, Litter C and potential Woody C estimates were all based on the current Woody C estimates which makes it vital to have accurate and reliable values of current Woody C. In this study, there were two issues which, if addressed, could considerably improve the Woody C estimates and, subsequently, the Root C and Litter C results.

One of the challenges in calculating accurate Woody C estimates is accounting for different thicket types and their different species composition. According to STEP, there are 112 thicket types, 12 of which are present in the BNR and have varying species composition. However, the available plot data from the BNR has only been collected in five of the thicket types within the reserve. Given that different thicket types are composed of different dominant species and that spekboom (a key species in thicket carbon storage) does not naturally occur in all of them, thicket type is an important factor to account for.

With more *in situ* data, even in thicket regions outside of the reserve, there may be enough sample sizes for the different thicket types to include thicket type as a variable when modelling current Woody C. At the Thicket Forum, held in June 2022 at Addo Elephant National Park, plans to create a website where all available thicket data would be collated and made accessible for research purposes was discussed and initiated. If this is successful, it would be relatively simple to include all available ground thicket data and apply it using the methods in this study. Woody C estimates specific to each thicket type of interest could be modelled and thicket-type-specific ratios for Root C and Litter C could be explored.

Another issue in the process of estimating current Woody C is the availability of appropriate remote sensing data for thicket. The existing canopy height LiDAR data at a 30 m resolution (GEDI and GLAD) are aimed at studying forests which are much taller than most thicket vegetation, and these images either do not include recordings of short vegetation (< 3 m for GLAD), or the recordings are exceptionally high and unreliable (up to 140 m tall in GEDI pixels over thicket). Locally captured LiDAR over thicket would be a substantial improvement and the Eastern Cape Parks and Tourism Agency (ECPTA) has expressed interest in assisting with access to areas within its jurisdiction (including the BNR) for the purpose of capturing LiDAR imagery (ECPTA 2022, personal communication). A potential future study aimed at capturing and processing canopy height images over thicket could provide a more accurate input for modelling current Woody C.

One other improvement that could be made to the potential woody carbon estimates is to use the interpolation method by Workneh et al. (2024) which incorporates elevation, aspect and slope – a

more appropriate method for mountainous areas than the Kriging method used in this study – to interpolate a rainfall raster dataset over the region.

Soil organic carbon (SOC) estimates

Soil organic carbon, the second main area of improvement identified in this study, is the largest carbon pool in subtropical thicket, however it is difficult to model since there are many factors that influence it. The SOC estimates in this study are not too far off from the estimates by Powell (2009), unlike a past current SOC map by Venter et al. (2021) (Table 4.1). However, they are single average values for each slope position and have large standard deviations. As a result, it does not provide as much detail as was originally aimed for a 30 m resolution map. The national-scale map of current SOC (Venter et al., 2021) is more spatially explicit because it accounted for numerous biological, morphometric, and climatic factors in the Random Forest regression model. However, these estimates exceed the average SOC recordings in thicket from past studies for all categories of degradation.

The ARC soil plot data used in this study only included plots within Primary Catchment L, in which the BNR is located, but the thicket biome extends into nine other primary catchments. One possible improvement could be to calibrate the SOC map over the thicket area by Venter et al. (2021) against all the thicket soil data from ARC, including those in disturbed areas which were excluded for calculating potential SOC in this study. Another future study could focus on improving the SOC estimates in this study by 1) accessing all the ARC soil data from across the entire thicket biome, 2) creating a regression model for current SOC using the ARC plots as training data, 3) including slope position, degradation status and thicket type as predictor variables in in the model (depending on the sample sizes available) and any other appropriate and available predictor variables, and 4) applying it to the area of interest to predict potential SOC as done in this study. By rearranging equation 4, the potential SOC in degraded areas could then be calculated using the current SOC estimates.

4.4 Restoration

Despite the inaccuracies and issues that have been identified in the carbon estimates in this study, restoration of thicket has the potential to aid in achieving South Africa's goals for conservation under the Convention on Biological Diversity and carbon reduction Nationally Determined Contributions (NDCs) goals under the Paris Agreement.

Most ecosystems are restored for the purpose of improving ecosystem function and improving biodiversity rather than primarily for sequestering carbon. Of the 50 founding initiatives for the

United Nations (UN) Decade on Ecosystem Restoration, five are based in South Africa with one targeted at restoring grasslands, three targeted at restoring forests and one targeted at restoring thicket (UN Decade on Ecosystem Restoration, no date). All these projects are aimed at mitigating climate change and protecting biodiversity and ecosystem services. Apart from the thicket restoration project, only the Buffelsdraai forest project mentions the carbon sequestration potential of restoration, but this is over a much smaller five-year goal (100 ha) than thicket restoration (250 000 ha) (UN Decade on Ecosystem Restoration, no date).

Through this research and past research, it is clear that there are important aspects to consider in planning and monitoring thicket restoration, particularly with the aim of sequestering carbon**.** These are discussed below.

Local community involvement

Globally, past forest restoration initiatives have failed because of lack of engagement from the local communities (Laudari et al., 2022). In addition to contributing to South Africa's carbon and restoration goals under the Paris Agreement and the Convention on Biological Diversity, profit from thicket restoration could provide local landowners with the incentive to prioritize conservation and restoration as a source of income over pastoralism (Mills and Cowling, 2006). This local investment is also important in the maintenance and monitoring of restored land as was found in the Thicket-Wide Plot experiments (TWPs) where many failed because the fences aimed at preventing further degradation from browsers were not maintained or, in some cases, were removed completely (SRRG, no date).

Location

The location of restoration efforts is vital and can determine its success before it begins. This is another lesson learnt from the TWPs where many failed because they were located in unsuitable areas (SRRG, no date). This emphasizes the importance of factoring thicket type in when estimating carbon and planning restoration. As spekboom cuttings are used in active restoration of thicket, target areas need to be in thicket types where spekboom can survive and thrive. It is also important to target areas where restoration can realistically be achieved. Moderately degraded thicket has reduced biomass whereas severely degraded thicket has lost all functionality (Lloyd et al., 2002), therefore restoring moderately degraded thicket to a functioning intact state requires less active intervention and is less costly than restoring severely degraded thicket (RJ Scholes 2020, personal communication). According to the results of this study, SOC – the largest carbon pool in thicket – increases downslope. Overall, this indicates that restoration efforts should generally be directed to moderately degraded areas in lower slope positions and in thicket types where spekboom can thrive.

Remote sensing of thicket

Remote sensing, together with field validation, is a highly useful tool in calculating baseline carbon stocks and monitoring restoration efforts. Global products such as GEDI and GLAD are both openly accessible and free sources of global canopy height imagery, but they are aimed at studying forests much taller than typical thicket vegetation. This results in inaccuracies such as GEDI canopy height recordings of 140 m over the BNR which is highly unreasonable. Local small-scale imagery, such as LiDAR, incurs some cost to capture but would be more accurate than free global products which are aimed at studying forests (greater than 2 m (GEDI) or 3 m high (GLAD)) and are not as suited to the short, dense structure of typical thicket vegetation, or topographically heterogeneous areas such as the BNR where steep slopes may contribute to inaccurate data in large-scale products such as GEDI and GLAD. The dense nature of intact thicket could also inhibit the accuracy of LiDAR data by reducing the light penetration and creating difficulty in differentiating between the ground and canopy light returns (Kulawardhana et al., 2017). Field validation of canopy height over the study area could be used to highlight inaccuracies and calibrate the remote sensing canopy height data.

Based on the results of this study and past studies, the best remote sensing option for accurate and high-resolution mapping of aboveground carbon in thicket appears to be multispectral imagery from Worldview-3 as was done by Harris et al. (2021). The estimates produced compared well to the plot data however the imagery is costly, not available for purchase for any study, and not practical to acquire at a landscape-scale. Harris et al. (2021) suggested an approach that combines high-resolution remote sensing data with medium resolution imagery to extrapolate plot data. This minimises the cost of acquiring high resolution imagery but improves the accuracy of the estimates compared to using medium resolution imagery alone. With high-resolution locally captured remote sensing imagery, the suggested approach could improve the accuracy of the aboveground carbon maps produced in this study and be used to accurately monitor restoration progress.

4.5 Conclusion

Interest in South Africa's subtropical thicket biome and its potential in carbon sequestration has increased in recent years. This highlights the importance of being able to monitor restoration progress by accurately estimating carbon stocks and carbon sequestration. Past studies (based on plot data alone) have made grand claims of the carbon sequestration potential of degraded thicket. The aim of this study was to produce spatially explicit estimates of the current and potential carbon stocks within the four carbon pools of subtropical thicket within the Baviaanskloof Nature Reserve, South Africa, for the purpose of restoration planning. In general, the average carbon estimates in this study are lower than those of past plot-based studies but the most interesting results indicate that

topography is a significant factor to account for in restoration planning and carbon accounting. Lower slope positions are ideal for the sequestration of SOC, especially in moderately degraded thicket where restoration is generally more achievable and easier to manage.

While there are specific areas where these results need to be improved before these maps can be used for restoration planning, I believe that this project is a starting point from which more accurate thicket carbon estimates can be produced by accounting for variations in the landscape such as topography and species composition. As South Africa works towards its conservation goals under the Convention for Biological Diversity and carbon reduction goals under the Paris Agreement, accurate carbon baseline estimates and reliable monitoring of restoration progress is important. With some plausible improvements in the remote sensing data such as locally captured LiDAR canopy height imagery, and the inclusion of more ground data in the Woody C model to account for different thicket types and to inform more species-specific Root C and Litter C to Woody C ratios, this study could form the base for accurate carbon mapping over large areas of thicket which would inform restoration decision-making and improve baseline carbon estimates and restoration monitoring across various areas of thicket, including the Baviaanskloof Nature Reserve.

Appendix 1

Table A1 The average ± SD for various soil properties including soil organic carbon (SOC) at each slope position from the Agricultural Research Council soil pit dataset for Primary Catchment L, South Africa.

	n	Soil depth (mm)	Clay (%)	Bulk density (g/cm^3)	SOC ($t\ ha^{-1}$) before correcting for bulk density	SOC ($t\ ha^{-1}$) after correcting for bulk density
Valley	29	708.3 ± 430.6	14.6 ± 7.9	1.6 ± 0.06	29 ± 27.7	45.8 ± 43.1
Lower slope	147	421.8 ± 356.9	13.1 ± 9.6	1.6 ± 0.08	17.9 ± 26	27.8 ± 41.1
Midslope	57	350.2 ± 373.7	14.2 ± 8.3	1.6 ± 0.07	32.3 ± 40.8	50.1 ± 61.4
Upper slope	33	210.3 ± 231	10.5 ± 5.8	1.6 ± 0.05	20.5 ± 35.7	33.2 ± 58.8
Crest	8	161.3 ± 88	9.3 ± 4.4	1.7 ± 0.03	8.6 ± 11.7	14.1 ± 19.4

References

Adam, M., Urbazaev, M., Dubois, C. and Schmullius, C., 2020. Accuracy assessment of GEDI terrain elevation and canopy height estimates in European temperate forests: Influence of environmental and acquisition parameters. *Remote Sensing*, 12(23), pp.3948.

ARC–ISCW. 1:250 000 scale Land Type Survey of South Africa. Agricultural Research Council-Institute for Soil, Climate and Water, Pretoria, South Africa.

Berliner, D., Marais, W., Smallie, J., Branch, W., Conradie, W. and Pienke, D., No date. Biodiversity and Ecological Impacts (Terrestrial Ecosystems and Species) – Albany Thicket Biome.

Boshoff, A., Cowling, R. & Kerley, G., 2001. Baviaanskloof. *Veld & Flora,* 87(2), pp.74–77.

Boshoff, A. 2005. The Baviaanskloof Mega-Reserve: An Environmentally, Socially and Economically Sustainable Conservation and Development Initiative. TERU. University of Port Elizabeth, Port Elizabeth, South Africa.

Boxriker, M., Privett, S.D., Richardson, D.M. and Gaertner, M., 2022. Active restoration in South African fynbos–A long-term perspective from the Agulhas Plain. *Transactions of the Royal Society of South Africa*, 77(2), pp.133-143.

Carbutt, C. and Kirkman, K., 2022. Ecological grassland restoration—A South African perspective. *Land*, 11(4), pp.575.

Conti, G., Pérez-Harguindeguy, N., Quètier, F., Gorné, L.D., Jaureguiberry, P., Bertone, G.A., Enrico, L., Cuchietti, A. and Díaz, S., 2014. Large changes in carbon storage under different land-use regimes in subtropical seasonally dry forests of southern South America. *Agriculture, ecosystems & environment*, 197, pp.68-76.

Convention on Biological Diversity (CBD), 2012. Introduction. Available at: https://www.cbd.int/intro/.

Convention on Biological Diversity (CBD), 2020. National Biodiversity Strategies and Action Plans. Available at: https://www.cbd.int/nbsap/targets/.

Cowling, R.M., Procheş, Ş., Vlok, J.H.J. and Van Staden, J., 2005. On the origin of southern African subtropical thicket vegetation. *South African Journal of Botany*, 71(1), pp.1-23.

Department of Environmental Affairs, 2018. South Africa: Final country report of the LDN Target Setting Programme.

DiRocco, T.L., Ramage, B.S., Evans, S.G. and Potts, M.D., 2014. Accountable accounting: carbon-based management on marginal lands. *Forests*, 5(4), pp.847-861.

Dubayah, R.O., Sheldon, S.L., Clark, D.B., Hofton, M.A., Blair, J.B., Hurtt, G.C. and Chazdon, R.L., 2010. Estimation of tropical forest height and biomass dynamics using lidar remote sensing at La Selva, Costa Rica. *Journal of Geophysical Research: Biogeosciences*, 115(G2).

Dubayah, R., Hofton, M., Blair, J., Armston, J., Tang, H. and Luthcke, S., 2021. GEDI L2A Elevation and Height Metrics Data Global Footprint Level V002 [Data set]. NASA EOSDIS Land Processes DAAC. Accessed 2022-09-14 from https://doi.org/10.5067/GEDI/GEDI02_A.002.

Esri Events, 2019. The forest for the trees: Making predictions using forest-based classification and regression. 31 July. YouTube. [Online Video] Available at: https://www.youtube.com/watch?v=kDAL2mKnae8.

Euston-Brown, D.I.W., 1995. Environmental and dynamic determinants of vegetation distribution in the Kouga and Baviaanskloof Mountains, Eastern Cape. Master's dissertation, University of Cape Town.

FAO, 2017. Soil Organic Carbon: the hidden potential. Available at: https://www.fao.org/3/i6937e/i6937e.pdf.

FAO, 2020. Global Forest Resources Assessment 2020 – Key findings. Rome. https://doi.org/10.4060/ca8753en.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L. and Seal, D., 2007. The shuttle radar topography mission. *Reviews of geophysics*, 45(2).

Gann, G.D., McDonald, T., Walder, B., Aronson, J., Nelson, C.R., Jonson, J., Hallett, J.G., Eisenberg, C., Guariguata, M.R., Liu, J. and Hua, F., 2019. International principles and standards for the practice of ecological restoration. *Restoration Ecology*, 27(S1), pp.S1-S46.

Goetz, S. and Dubayah, R., 2011. Advances in remote sensing technology and implications for measuring and monitoring forest carbon stocks and change. *Carbon Management*, 2(3), pp.231-244.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. and Moore, R., 2017. Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote sensing of Environment*, 202, pp.18-27.

Halme, P., Allen, K.A., Auniņš, A., Bradshaw, R.H., Brūmelis, G., Čada, V., Clear, J.L., Eriksson, A.M., Hannon, G., Hyvärinen, E. and Ikauniece, S., 2013. Challenges of ecological restoration: lessons from forests in northern Europe. *Biological Conservation*, 167, pp.248-256.

Hao, Y., Lal, R., Owens, L.B., Izaurralde, R.C., Post, W.M. and Hothem, D.L., 2002. Effect of cropland management and slope position on soil organic carbon pool at the North Appalachian Experimental Watersheds. *Soil and tillage research*, 68(2), pp.133-142.

Harris, D., Bolus, C. and Reeler, J. 2019. Remote sensing of aboveground carbon in subtropical thicket, GEF-5 SLM Project, Rhodes University. Internal report.

Harris, D., Bolus, C. and Reeler, J., 2021. Very high resolution aboveground carbon mapping in subtropical thicket. *Journal of Applied Remote Sensing*, 15(3), pp.038502-038502.

He, Q., Chen, E., An, R. and Li, Y., 2013. Above-ground biomass and biomass components estimation using LiDAR data in a coniferous forest. *Forests*, 4(4), pp.984-1002.

Hoare, D.B., Mucina, L., Rutherford, M.C., Vlok, J.H., Euston-Brown, D.I., Palmer, A.R., Powrie, L.W., Lechmere-Oertel, R.G., Procheş, Ş.M., Dold, A.P. and Ward, R.A., 2006. Albany thicket biome. *The vegetation of South Africa, Lesotho and Swaziland. Strelitzia*, 19, pp.541-567.

Holmes, P.M., Esler, K.J., Van Wilgen, B.W. and Richardson, D.M., 2020. Ecological restoration of ecosystems degraded by invasive alien plants in South African Fynbos: Is spontaneous succession a viable strategy?. *Transactions of the Royal Society of South Africa*, 75(2), pp.111-139.

Höhl, M., Ahimbisibwe, V., Stanturf, J.A., Elsasser, P., Kleine, M. and Bolte, A., 2020. Forest landscape restoration—What generates failure and success?. *Forests*, 11(9), p.938.

Huang, Y., Ciais, P., Santoro, M., Makowski, D., Chave, J., Schepaschenko, D., Abramoff, R.Z., Goll, D.S., Yang, H., Chen, Y. and Wei, W., 2021. A global map of root biomass across the world's forests. *Earth System Science Data*, 13(9), pp.4263-4274.

Hutson, J. L., 1984. Estimation of Hydrological Properties of South African Soils. PhD thesis, University of Natal, South Africa. pp.232.

Jansen, H.C., 2008. Water for food and ecosystems in the Baviaanskloof Mega Reserve: land and water resources assessment in the Baviaanskloof, Eastern Cape Province, South Africa. In: Alterra Report: 1812. Wageningen University, Wageningen, Netherlands.

Jenness, J., Brost, B. and Beier, P., 2013. Land Facet Corridor Designer: Extension for ArcGIS. Jenness Enterprises. Available at: http://www.jennessent.com/arcgis/land_facets.htm.

Kankare, V., Vastaranta, M., Holopainen, M., Räty, M., Yu, X., Hyyppä, J., Hyyppä, H., Alho, P. and Viitala, R., 2013. Retrieval of forest aboveground biomass and stem volume with airborne scanning LiDAR. *Remote Sensing*, 5(5), pp.2257-2274.

Kulawardhana, R.W., Popescu, S.C. and Feagin, R.A., 2017. Airborne lidar remote sensing applications in non-forested short stature environments: a review. *Annals of Forest Research*, pp.173-196.

Laudari, H.K., Aryal, K., Maraseni, T., Pariyar, S., Pant, B., Bhattarai, S., Kaini, T.R., Karki, G. and Marahattha, A., 2022. Sixty-five years of forest restoration in Nepal: Lessons learned and way forward. *Land Use Policy*, 115, p.106033.

Lechmere-Oertel, R.G., Kerley, G.I.H., Mills, A.J. and Cowling, R.M., 2008. Litter dynamics across browsing-induced fenceline contrasts in succulent thicket, South Africa. *South African Journal of Botany*, 74(4), pp.651-659.

Linacre, E.T., 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agricultural meteorology*, 18(6), pp.409-424.

Lloyd, J.W., Van den Berg, E.C. and Palmer, A.R., 2002. Patterns of transformation and degradation in the thicket biome, South Africa. *TERU report*, 39, p.86.

Lu, D., Chen, Q., Wang, G., Liu, L., Li, G. and Moran, E., 2016. A survey of remote sensing-based aboveground biomass estimation methods in forest ecosystems. *International Journal of Digital Earth*, 9(1), pp.63-105.

Malhi, Y., Girardin, C., Metcalfe, D.B., Doughty, C.E., Aragão, L.E., Rifai, S.W., Oliveras, I., Shenkin, A., Aguirre-Gutiérrez, J., Dahlsjö, C.A. and Riutta, T., 2021. The Global Ecosystems Monitoring network: Monitoring ecosystem productivity and carbon cycling across the tropics. *Biological Conservation*, 253, p.108889.

Marais, C., Cowling, R.M., Powell, M. and Mills, A., 2009, October. Establishing the platform for a carbon sequestration market in South Africa: the working for woodlands subtropical thicket restoration programme. In *XIII World Forestry Congress, Buenos Aires*, pp.18-23.

Melo, F.P., Pinto, S.R., Brancalion, P.H., Castro, P.S., Rodrigues, R.R., Aronson, J. and Tabarelli, M., 2013. Priority setting for scaling-up tropical forest restoration projects: Early lessons from the Atlantic Forest Restoration Pact. *Environmental science & policy*, 33, pp.395-404.

Mills, A. and Fey, M., 2004. Transformation of thicket to savanna reduces soil quality in the Eastern Cape, South Africa. *Plant and Soil*, 265, pp.153-163.

Mills, A.J., Cowling, R.M., Fey, M.V., Kerley, G.I.H., Donaldson, J.S., Lechmere-Oertel, R.G., Sigwela, A.M., Skowno, A.L. and Rundel, P., 2005a. Effects of goat pastoralism on ecosystem carbon storage in semiarid thicket, Eastern Cape, South Africa. *Austral ecology*, 30(7), pp.797-804.

Mills, A.J., O'Connor, T.G., Donaldson, J.S., Fey, M.V., Skowno, A.L., Sigwela, A.M., Lechmere-Oertel, R.G. and Bosenberg, J.D., 2005b. Ecosystem carbon storage under different land uses in three semi-arid shrublands and a mesic grassland in South Africa. *South African Journal of Plant and Soil*, 22(3), pp.183-190.

Mills, A.J. and Cowling, R.M., 2006. Rate of carbon sequestration at two thicket restoration sites in the Eastern Cape, South Africa. *Restoration Ecology*, 14(1), pp.38-49.

Mills, A.J., Turpie, J.K., Cowling, R.M., Marais, C., Kerley, G.I., Lechmere-Oertel, R.G., Sigwela, A.M. and Powell, M., 2007. Assessing costs, benefits, and feasibility of restoring natural capital in subtropical thicket in South Africa. *Restoring natural capital, science, business, and practice*, pp.179-187.

Mills, A.J. and Cowling, R.M., 2009. Below-ground carbon stocks in intact and transformed subtropical thicket landscapes in semi-arid South Africa. *Journal of arid environments*, 74(1), pp.93-100.

Milton, S.J. and Dean, W.R.J., 2021. Anthropogenic impacts and implications for ecological restoration in the Karoo, South Africa. *Anthropocene*, 36, p.100307.

NASA, 2019. What is Remote Sensing? Earthdata, Accessed: November 2023, Available at: https://www.earthdata.nasa.gov/learn/backgrounders/remote-sensing.

National Terrestrial Carbon Sink Assessment, 2015. Department of Environmental Affairs, Pretoria, South Africa.

National Terrestrial Carbon Sinks Assessment: Technical Report, 2020. Department of Environment, Forestry and Fisheries, Pretoria, South Africa.

Patenaude, G., Hill, R.A., Milne, R., Gaveau, D.L.A., Briggs, B.B.J. and Dawson, T.P., 2004. Quantifying forest above ground carbon content using LiDAR remote sensing. *Remote sensing of environment*, 93(3), pp.368-380.

Pierce, S., Cowling, R., Mills, A., Powell, M. and Sigwela, A., 2009. Restoring valuable spekboomveld using the international carbon market. *BGjournal*, 6(1), pp.13-15.

Pierce, S.M. and Mader, A.D., 2006. The STEP Handbook: Integrating the Natural Environment Into Land Use Decisions at the Minicipal Level: Towards Sustainable Development. 2nd ed. Terrestrial Ecology Research Unit (TERU), University of Port Elizabeth.

Poggio, L., De Sousa, L.M., Batjes, N.H., Heuvelink, G., Kempen, B., Ribeiro, E. and Rossiter, D., 2021. SoilGrids 2.0: producing soil information for the globe with quantified spatial uncertainty. *Soil*, 7(1), pp.217-240.

Potapov, P., Li, X., Hernandez-Serna, A., Tyukavina, A., Hansen, M.C., Kommareddy, A., Pickens, A., Turubanova, S., Tang, H., Silva, C.E. and Armston, J., 2021. Mapping global forest canopy height through integration of GEDI and Landsat data. *Remote Sensing of Environment*, 253, p.112165.

Powell, M.J., 2009. Restoration of degraded subtropical thickets in the Baviaanskloof Megareserve, South Africa. Master's dissertation. Rhodes University.

Prentice, I.C., Farquhar, G.D., Fasham, M.J.R., Goulden, M.L., Heimann, M., Jaramillo, V.J., Kheshgi, H.S., Le Quéré, C., Scholes, R.J., Wallace, D.W. and Archer, D., 2001. The carbon cycle and atmospheric carbon dioxide. *Climate change 2001: the scientific basis, Intergovernmental panel on climate change*.

Rajakaruna, N. and Boyd, R.S., 2008. The edaphic factor. In 'Encyclopedia of ecology. Vol. 2'.(Eds SE Jorgensen, B Fath) pp.1201–1207.

Rutherford, M.C., Powrie, L.W. and Husted, L.B., 2014. Herbivore-driven land degradation: consequences for plant diversity and soil in arid subtropical thicket in south-eastern Africa. *Land Degradation & Development*, 25(6), pp.541-553.

Ruwanza, S., Gaertner, M., Esler, K.J. and Richardson, D.M., 2013. The effectiveness of active and passive restoration on recovery of indigenous vegetation in riparian zones in the Western Cape, South Africa: A preliminary assessment. *South African Journal of Botany*, 88, pp.132-141.

Schagen, M., Bosch, J., Johnson, J., Duker, R., Lebre, P., Potts, A.J. and Cowan, D.A., 2021. The soil microbiomics of intact, degraded and partially-restored semi-arid succulent thicket (Albany Subtropical Thicket). *PeerJ*, 9, p.e12176.

Schulze, R. E., 1995. Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria, South Africa, Report TT 69/9/95. pp 552.

Schütte, S., Schulze, R. and Paterson, G., 2019. Identification and mapping of soils rich in organic carbon in South Africa as a climate change mitigation option. *Department of Environmental Affairs, Pretoria, South Africa*.

Sexton, J.O., Song, X.P., Feng, M., Noojipady, P., Anand, A., Huang, C., Kim, D.H., Collins, K.M., Channan, S., DiMiceli, C. and Townshend, J.R., 2013. Global, 30-m resolution continuous fields of tree cover: Landsat-based rescaling of MODIS vegetation continuous fields with lidar-based estimates of error. *International Journal of Digital Earth*, 6(5), pp.427-448.

Singh, P. and Benbi, D.K., 2018. Soil organic carbon pool changes in relation to slope position and land-use in Indian lower Himalayas. *Catena*, 166, pp.171-180.

South Africa First Nationally Determined Contribution under the Paris Agreement, 2021. Available at: https://unfccc.int/sites/default/files/NDC/2022-06/South%20Africa%20updated%20first%20NDC%20September%202021.pdf.

Spawn, S.A., Sullivan, C.C., Lark, T.J. and Gibbs, H.K., 2020. Harmonized global maps of above and belowground biomass carbon density in the year 2010. *Scientific Data*, 7(1), p.112.

Spekboom Restoration Research Group, No date. Thicket-wide Plot Experiments. Available at: https://www.spekboomrestorationresearch.org.za/thicket-wide-plot-experiments.

Stovall, A.E., Vorster, A.G., Anderson, R.S., Evangelista, P.H. and Shugart, H.H., 2017. Non-destructive aboveground biomass estimation of coniferous trees using terrestrial LiDAR. *Remote Sensing of Environment*, 200, pp.31-42.

Summers, D.M., Bryan, B.A., Nolan, M. and Hobbs, T.J., 2015. The costs of reforestation: a spatial model of the costs of establishing environmental and carbon plantings. *Land Use Policy*, 44, pp.110-121.

Torre-Tojal, L., Bastarrika, A., Boyano, A., Lopez-Guede, J.M. and Grana, M., 2022. Above-ground biomass estimation from LiDAR data using random forest algorithms. *Journal of Computational Science*, 58, p.101517.

Ullah, M.R. and Al-Amin, M., 2012. Above-and below-ground carbon stock estimation in a natural forest of Bangladesh. *Journal of forest science*, 58(8), pp.372-379.

United Nations Decade on Ecosystem Restoration, No date (a). About the UN decade. https://www.decadeonrestoration.org/about-un-decade.

United Nations Decade on Ecosystem Restoration, No date (b). Explore our founding 50 initiatives. https://implementers.decadeonrestoration.org/implementers.

United Nations Development Programme, 2013. Guidance note - Standardized Baselines. Available at: https://cdm.unfccc.int/sunsetcms/storage/contents/stored-file-20150701152600271/Guidance%20note_SBL.pdf.

United Nations, 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change. Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf.

United Nations, 2015a. Doha Amendment to the Kyoto Protocol. Available at: https://unfccc.int/files/kyoto_protocol/application/pdf/kp_doha_amendment_english.pdf.

United Nations, 2015b. Paris Agreement. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

Van der Merwe AJ 1973. Physico-Chemical Relationships of Selected OFS Soils: A Statistical Approach based on Taxonomic Criteria. PhD thesis, University of the Orange Free State, South Africa.

van der Vyver, M.L., Cowling, R.M., Mills, A.J. and Difford, M., 2013. Spontaneous return of biodiversity in restored subtropical thicket: Portulacaria afra as an ecosystem engineer. *Restoration ecology*, 21(6), pp.736-744.

van der Vyver, M.L. and Cowling, R.M., 2019. Aboveground biomass and carbon pool estimates of Portulacaria afra (spekboom)-rich subtropical thicket with species-specific allometric models. *Forest Ecology and Management*, 448, pp.11-21.

Van Luijk, G., Cowling, R.M., Riksen, M.J.P.M. and Glenday, J., 2013. Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket. *Journal of arid environments*, 91, pp.14-21.

Vaughn, K. J., Porensky, L. M., Wilkerson, M. L., Balachowski, J., Peffer, E., Riginos, C. & Young, T. P. (2010) Restoration Ecology. *Nature Education Knowledge*, 3(10):66.

Venter, Z.S., Hawkins, H.J., Cramer, M.D. and Mills, A.J., 2021. Mapping soil organic carbon stocks and trends with satellite-driven high resolution maps over South Africa. *Science of the Total Environment*, 771, p.145384.

Vlok, J.H.J., Euston-Brown, D.I.W. and Cowling, R.M., 2003. Acocks' Valley Bushveld 50 years on: new perspectives on the delimitation, characterisation and origin of subtropical thicket vegetation. *South African Journal of Botany*, 69(1), pp.27-51.

Vlok, J.H.J. and Euston-Brown, D.I.W., 2002. Report by biological survey component for conservation planning for biodiversity in the thicket biome. *Unpublished report, Regalis Environmental Services, Oudtshoorn*.

Wei, X., Shao, M., Fu, X. and Horton, R., 2010. Changes in soil organic carbon and total nitrogen after 28 years grassland afforestation: effects of tree species, slope position, and soil order. *Plant and Soil*, 331, pp.165-179.

Yohannes, H., Soromessa, T. and Argaw, M., 2015. Carbon stock analysis along slope and slope aspect gradient in Gedo Forest: implications for climate change mitigation. *Journal of Earth Science & Climatic Change*, 6(09), pp.6-11.

Zandvlakte, No date. Projects. Available at: https://baviaanskloof.com/projects/.