Assessing the Green House Gas mitigation potential from habitat restoration and afforestation in the City of Cape Town

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Glossary:

- **Gross Primary Production (GPP)** denotes the total amount of Carbon (C) fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees. GPP is measured on photosynthetic tissues, principally leaves, on an hourly timescale and integrated to an annual amount. Global total GPP is about 120 Gt C yr-1.
- **Net Primary Production (NPP)** denotes the net production of organic matter by plants in an ecosystem. NPP is about half of GPP as plants respire the other half in building up and maintaining plant tissues. NPP can be measured as the increase in plant biomass on a daily or weekly timescale. For all terrestrial ecosystems combined, it is estimated to be about 60 Gt C yr-1.

- Units and Conversions:
  - 1 megagram = 1000 kg
  - Tg = Teragrams or 1 trillion grams = a million tons
  - 1 gC m^{-2} = 0.01 tC ha^{-1}
  - tC yr^{-1} = tons of carbon per year
  - tC ha^{-1} $year^{-1}$ = tons of carbon per ha per year
  - The working units for stock estimates are gC/m^2 (1 gm^{-2} = 0.01 t/ha, where t is a metric ton = 10^6g, which is properly denoted Mg). For national sums we use TgC (10^{12}g), which is a million tons (teragrams).
  - Biomass to carbon = 50%
  - m^2 to ha (1 m^2 = 0.0001 ha)

1. Summary

Carbon sequestration offers some opportunities to offset emissions from hard to mitigate sectors, such as industry and transport. Tree planting and habitat restoration are deliberate carbon dioxide removal activities which may provide opportunities to increase the overall rate of carbon sequestration. A preliminary high level assessment was carried out to quantify the potential carbon benefits of these actions for the City of Cape Town. Presented is a summary of the key outcomes addressing the opportunities, challenges and risks associated with tree planting in a biodiversity hotspot, such as Cape Town.

Four key outcomes that emerged from the study:

1) The Carbon Sinks Atlas highlights that while total carbon stock has remained relatively stable over the three time periods of available data (1990, 2014 and 2018), at approximately ~29 million tons, above-ground biomass accumulation can offset factors driving carbon loss such as such as droughts, fire and land use change.
2) Active tree planting and habitat restoration in green spaces across the city (including the BioNet, urban areas and green belts) is estimated to marginally increase bio-genic sequestration by 0.2%, raising the vegetation's capacity to offset ~1.3% (compared to the current estimate of 1.1%) of the City's estimated total annual greenhouse gas emissions (~228 024 tCO_{2}-eq y^{-1}).
3) Increasing the above-ground biomass through tree planting alone is not able to significantly increase the ability to offset the emissions generated by the city, but these activities can provide additional benefits if adhering to the guidelines.
4) Planting Spekboom in Cape Town does not provide additional carbon sequestration benefits. It is unlikely that urban environments will provide the conditions needed to realise the high carbon sequestration rates published for restoration projects in the Thicket Biome.

This study focused solely on the carbon benefits of active habitat restoration and afforestation. Active interventions are encouraged as they do have a positive impact on the carbon sequestration potential with the city. However the magnitude of the positive benefit is low and is unlikely to significantly offset the City's carbon emissions. The study highlighted several gaps which could be addressed by future research which would reduce uncertainties and improve on the estimate provided. Recommendations for how to improve the results and the implications of the findings are outlined in more detail in the report below. The benefits of active habitat restoration and tree planting extend beyond mitigation measures and incorporate a wider range of ecosystem services which should be further investigated.

2. Introduction

2.1. Purpose

The City of Cape Town (CCT) is developing a Climate Action Plan that will aim for carbon neutrality by 2050. This study provides supporting information on the potential benefits of increasing carbon dioxide removal by bio-genic carbon sequestration resulting from active restoration of degraded land and tree planting. The options are recognized as a low technology and readily available solution to offset emissions from hard to mitigate sectors like industry and transport. Globally, deliberate actions of increasing carbon dioxide removal activities are required as the natural processes of carbon sequestration are insufficient to offset the accelerating pace of global emissions.

However, for the city, the ability to sequester carbon from wide-scale planting of trees or other high carbon dioxide removal species, such as Spekboom, which has been popularized by recent media and the scientific literature, are limited by the occurrence of the globally significant and predominantly treeless species rich fynbos vegetation. A sixth of South Africa's flowering plants grow in Cape Town (occupying 0.1% of South Africa's land surface area)[1] – where roughly 3, 350 plant species are indigenous to South Africa, and 190 of these species are found solely within the city boundaries. Therefore, the availability of suitable land is a key restriction for large scale tree planting activities. The land cover within the city consists of a mosaic of natural vegetation (i.e. conservation sites containing several fynbos vegetation types), transformed urban areas and its associated vegetation (mainly a mixture of indigenous and non-indigenous species located in parks and gardens) and open managed landscapes (e.g. road side verges). In addition to these ecological limitations, the City of Cape Town is prone to periodic water stress and the soils are generally nutritionally poor. This report provides high level estimate of the benefits derived from restoration and tree planting to assist the carbon mitigation strategy within the city and to recommend areas of future research.

2.2. **Project aims:** Objectives and Deliverables:

The objective of this study was to conduct a high-level assessment of the Greenhouse Gas Mitigation options provided by habitat restoration and afforestation in the City of Cape Town. To achieve this goal, it was necessary to determine the following:

- a baseline understanding of the current carbon stocks and its change over time,
- an estimate of the sequestration potential of existing vegetation,
- an estimate of the mitigation benefits of active habitat restoration and tree planting activities.

The approach followed a desktop study and relied on existing and published information. This report describes the rationale for the approach taken, the methods and the results. A brief discussion is provided on the implications of the results, its limitations, assumptions and recommendations for future research.

The next section provides a brief background to the key concepts used in the report followed by a short literature review.

[1] City of Cape Town Biodiversity Report 2018

2.3. Background

Cities are responsible for a large proportion of national greenhouse gas (GHG) emissions. The demand for energy, fuel and land contribute to the rapid increase GHGs, particularly carbon dioxide (CO_2). Rising CO_2 concentrations have led to changing climate patterns, warmer temperatures and altered rainfall regimes, with many regions (e.g. the Western Cape) expected to experience hotter and drier conditions in the future (Engelbrecht et al., 2019). Significant action is needed to reduce the impacts of climate change by reversing the trend of increasing CO_2 emissions. Of the several possible approaches to reduce CO_2 emissions, the sequestration of carbon via natural processes is considered a viable and cheap alternative to several industrial and technologically challenging options (Lal, 2009). As a result, cities are faced with assessing the best mitigation options to reduce emissions and to improve methods to remove CO_2 from the atmosphere.

Trees and plants act as sinks for CO_2 through the process of photosynthesis and underpin several large-scale global strategies of nature-based carbon removal programs[2]. This biological process is primarily responsible for the removal of CO_2 from the atmosphere and diverting it into terrestrial carbon stocks (Figure 1). As a result, captured carbon is stored in the living and dead biomass occurring both above and below the ground in soils. The carbon stored in soil is a significantly large pool, which is capable of removing and locking away carbon for many years (Lal, 2004), provided it is not disturbed. The ecosystem service of climate regulation provided by natural ecosystems, is recognized as an important mitigation option to reduce the concentration of atmospheric CO_2 (Smith et al., 2013). However, there is large uncertainty associated with estimating the carbon budgets, especially in the absence of adequate data records. The available approaches and data sources to account for carbon are continually evolving and improving. The availability of this information, is important to support governments in their planning for actions to reduce emissions.

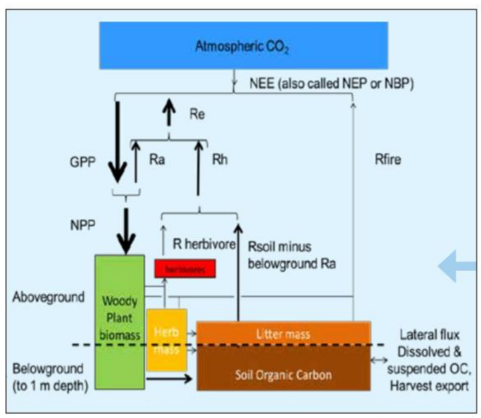

Figure 1: Components of a generalized terrestrial carbon cycle: *The size of the boxes and the arrows, which represent stocks and fluxes respectively, is only roughly indicative of their relative size. Terminology: NEE – Net Ecosystem Exchange, NEP – Net Ecosystem Productivity, NBP – Net Biome Productivity, GPP – Gross Primary Production, NPP – Net Primary Production, Ra – autotrophic respiration (respiration by plants), Rh – heterotrophic respiration (herbivores, carnivores and microbes), Re – ecosystem respiration (the combined respiration from all sources), Rfire – fire emissions. (Figure and explanation extracted from Department of Environment Affairs, 2015)*

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[2] https://trilliontrees.org/home

2.4. Literature review

This section provides a brief overview of the approaches and data available for assessing carbon sequestration. The main unknown factor is the role of the natural environment in carbon sequestration. There are several approaches to estimate carbon uptake by plants which include field measurements (Mills et al., 2012), statistical models and biogeochemical models (Zhu and Geological Survey U.S., 2010) and remotely sensed data (Castro-Magnani et al., 2021; Deng, 2011). Below we discuss several available data sources and concepts which form the rationale for the methods used to assess habitat restoration and afforestation.

The South African National Terrestrial Carbon Sinks Assessment (NTCSA), first completed in 2015 and updated in 2020 (NTCSA, 2020, 2015), provides a detailed assessment of the carbon pools over three time periods (1990, 2014, 2018). Nationally, the total terrestrial carbon stock stored within South Africa's ecosystems is estimated at 9 258 million Tons of Carbon (or TgC, teragrams of Carbon) (up from an earlier estimate of 7170 (±6693-1675 TgC) in 2015). The majority of this can be found across the Savanna and Grassland Biomes with ~89% of all carbon occurring in the soils (Figure 2). The assessment concluded, that at the national scale, drier biomes (e.g. Karoo and Fynbos) in South Africa offer limited potential to sequester carbon. Yet, the fynbos biome, which occupies ~4% of the country's land surface area, accounts for 11% of the national carbon stocks. It is therefore reasonable to assume that the biome plays an important role in climate regulation.

The assessment follows guidelines set by the Intergovernmental Panel on Climate Change (IPCC) to determine carbon stocks and pools (IPCC, 2019) (See Appendix 1). However, it not does provide estimates for rates of carbon accumulation over time, which may be useful to assess the potential for habitat restoration.

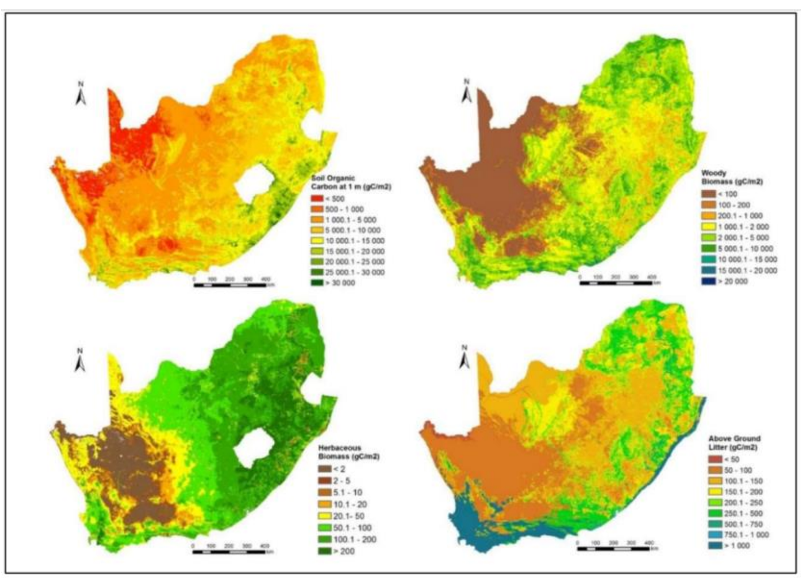

*Figure 2**: Summary figures of the distribution of Carbon Stocks across the different carbon pools in South Africa. Top left: soil organic carbon to 1m depth. Top right: the above- and below- ground woody plant biomass pool. Lower left: above- and below- ground herbaceous biomass pool. Lower right: above-ground litter.** The data is available via an online web-platform (https://ccis.environment.gov.za/carbon-sinks/#/) at a resolution **of 1km x 1km**. **(Figure extracted from NTCSA 2020)***

Globally, the terrestrial biosphere is a net carbon sink of 2 gigatons per year (IGBP Terrestrial Carbon Working Group, 1998). These estimates are derived from satellite products and provide a robust estimate of carbon sequestration over large scales. The carbon budget (see Figure 1) is calculated by accounting for Gross Primary Productivity (GPP), which is a measure of the total CO_2 uptake during photosynthesis. Half of this is respired (due to autotrophic respiration) back to the atmosphere with the remainder referred to as Net Primary Productivity (NPP). NPP quantifies the conversion of atmospheric CO_2 into plant biomass (Running et al., 2004) and is an indication of short-term carbon storage. NPP therefore provides a measure of carbon *available* for storage and is not entirely equivalent to the *amount* of carbon stored, since most of the NPP is ultimately respired, or decomposed. The remaining carbon after these emissions is termed net ecosystem production (NEP). Finally, losses due to non-respiratory processes such as fire, exports or harvesting is referred to as net biome production (NBP). These estimates are seldom taken into account in carbon sequestration studies (Lovett et al., 2006), but can influence whether vegetation is a source or a sink of CO_2 (Velasco et al., 2016).

While NPP has been widely used to determine the average annual rate of carbon uptake by vegetation within a single growth period (Caldwell et al., 2007; Castro-Magnani et al., 2021; Deng, 2011; Yu et al., 2019), it overestimates the amount of carbon sequestered in the long-term (Lovett et al., 2006). Soil carbon, lost to the atmosphere by the process of soil heterotrophic respiration (SHR), accounts for a large proportion of carbon released back to the atmosphere (Ciais et al., 2020). The mean SHR rate for African ecosystems indicates that 30% of NPP is available for sequestration over long periods of time (i.e. 70% is lost back to the atmosphere) Ciais et al. (2020). The IPCC previously assumed a retention value of 10% (Prentice et al., 2001). A global study of forests revealed that soil respiration can be as high as 85% of NPP under normal conditions and as low as 65% of NPP under nitrogen limited conditions (Kracher, 2017). Therefore, including an estimate of SHR provides a conservative estimate of the long-term carbon sequestration potential (Valentini et al., 2000).

In South Africa, few studies have assessed the potential carbon benefits of fynbos (Chisholm, 2010; Mills et al., 2012), with the majority of studies focusing on thicket restoration (Mills et al., 2015; Mills and Cowling, 2006). Estimate of NPP can be derived from the Carbon Sinks Atlas. In absence of adequate data, we assume that fynbos ecosystems respire between 70% and 90% of the carbon sequestered. The values are likely skewed to the lower rate as the dominant woody vegetation occurs soils where both P and N are limited, likely decreasing microbial activity (Chapin and Eviner, 2014; Kracher, 2017).

The fynbos is considered to be a low biomass biome compared to the forests or savannas in South Africa, yet it accounts for 11% of the national carbon stock (NTCSA 2020). It has the potential to accumulate relatively high above-ground biomass in between fire cycles, which is dependent on rainfall and soil nutrients (Kruger, 1977). Fynbos communities can also have a high soil organic matter content which can reach up to 88% in 11 year old fynbos, (Cowling, 1992). The two distinct fire adaptation guilds in the Fynbos namely resprouters and reseeders, adopt different carbon allocation strategies. Resprouters regenerate from underground storage organs such as bulbs, corms and roots, which add to the below-ground carbon content. The allocation of carbon to these storage organs in between fire intervals is important for the survival of many species. Reseeders (e.g. Proteas) accumulate carbon above-ground as woody litter and invest in the production of woody cones to protect seeds. These seeds are released after fire into an environment free of competition and predation. Fynbos communities degraded by alien plants, inappropriate fire regimes, disturbance and urbanization disrupt the carbon and nutrient cycling processes within these ecosystems, potentially having large impacts on climate regulation.

Urban trees have significant potential to act as carbon sinks. However, to quantify these benefits requires an understanding of the relationships between tree age, height and volume often from obtained from sampling, resulting in species-specific growth models (McPherson and Peper, 2012; Stoffberg et al., 2010). These equations allow for easily obtainable measurements such as tree diameter (diameter at breast height) or tree height to determine standing biomass (dry mass) to estimate carbon accumulation and consequently carbon sequestration potential (McPherson et al., 2016).

In South Africa, there are no comprehensive databases for urban trees. However, notable examples of urban tree studies are provided by (Stoffberg et al., 2010) for the City of Tshwane, Glenday (2007) for eThekwini and De Lacy and Shackelton (2014) for urban trees in Grahamstown. These studies have included field measurements of tree dimensions, soil carbon to provide reliable estimates for the carbon benefits or in developing allometric models to determine growth rates, biomass and carbon stocks. However, in the absence of data, several generic methods exist. These include standards provided by the US Environmental Protection Agency[3], or rates of sequestration based on the urban tree canopy cover (Nowak et al., 2013). These values have been used to estimate carbon sequestration in other cities such as Spain (Baró et al., 2015) and Canada (McGovern and Pasher, 2016) in the absence of available local data.

Carbon dioxide removal activities through, habitat restoration and active tree planting have received significant scientific and media attention in recent years. The United Nations (UN) has declared the coming decade as one to focus on ecosystem restoration[4]. An important message being driven by the UN is that appropriate restoration techniques are required to suite the worlds' diverse range of ecosystems. Similarly, in urban and heavily modified landscapes the concept of urban forestry, which, relates to the establishment, promotion, maintenance and management of trees, is another strategy to green urban and peri-urban areas (Shackleton, 2012). Globally, the widespread promotion of tree planting should be focused on areas experiencing large rates of deforestation. However, ecosystems such as grasslands and shrublands (e.g. the fynbos) should be excluded from tree planting scenarios as non-forest environments are rich in biodiversity and contribute to climate regulation in different ways (Bond et al., 2019).

[3] https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references
[4] https://www.decadeonrestoration.org/

Box 1: A note on SPEKBOOM:

Spekboom plants have been popularized by their ability to sequester significant amounts of carbon, which is normally obtained under intact and undisturbed habitats in higher rainfall areas (Mills and Cowling, 2006; van der Vyver and Cowling, 2019). Spekboom is a drought hardy, succulent plant common to the subtropical thicket biome occurring the Eastern Cape. These landscapes have been severely impacted by overgrazing and several restoration projects have been set up to achieve multiple benefits of job creation, improving biodiversity and climate regulation. While the use of Spekboom for the revegetation of degraded thicket is ecologically appropriate, it is not recommended for use in the restoration of degraded areas in other biomes (NTSCA 2020). It is likely to show limited or no success, with biome-appropriate species providing a better approach. The photosynthetic pathway of Spekboom, Crassulacean acid metabolism or (CAM), allows it to fix CO_2 during the night reducing the rate at which CO_2 is lost to the atmosphere during respiration. As a result, more CO_2 is maintained allowing for the development of complex carbohydrates and plant materials. The ability to form a dense canopy and protect the soil from rainfall, and disturbance provides the conditions needed for soil carbon to increase significantly (Mills and Fey, 2004). Carbon sequestration rates of between 1 and 2 tC/ha/y can be achieved, with higher rates of up to 4tC per hectare per year is possible. To achieve, this planting densities at restoration sites typically range between 2000 and 2500 with some sites receiving up to 5000 cuttings per hectare (Mills et al., 2015). This is not likely to occur in an urban setting where plants will remain in pots or in maintained gardens (Figure 3).

In 2020, the City of Cape Town celebrated the Spekboom challenge by handing out 5000 Spekboom plants[5]. While Spekboom is suitable for water wise gardens, road medians or roadside verges the City strongly recommends that it is not to be planted in nature reserves, natural areas, or sites of conservation importance in the city. In an urban context, the carbon benefits of Spekboom are not likely to be realized, especially since dense leaf litter mats and canopy cover are not able to develop. Spekboom is included in the analysis below for illustrative purposes.

a) 
Photo credit: Ryan Blanchard

b) 
Photo credit: Anthony Mills

Figure 3: a) Spekboom cuttings prepared in a nursery b) Example of the scale of Thicket restoration projects to realized climate benefits.

3. Methods

3.1. Study site

The City of Cape Town occupies an area of 2, 461 km^2 and is considered the economic hub of the Western Cape Province, contributing approximately 9,9% of the South Africa's gross domestic product (City of Cape Town, 2018). As a result, it is estimated that 21 million tons of CO_2 is emitted each year.

This growth has placed tremendous pressure on the natural environment through the transformation of habitat, the introduction and spread of invasive alien species and has resulted in several threatened vegetation types existing within the City. There is a significant opportunity for restoration to improve the biodiversity, structure and function in degraded habitats. Cape Town has a rich biodiversity, characterized by diverse landscapes, species which are range-restricted and occur nowhere else on earth (Figure 4). It lies within the fynbos region and has a Mediterranean climate which adds to the character of this globally important tourism destination. The City is also prone to drought and water stress conditions.

Figure 4: Fynbos communities across the Cape peninsula. Photo Credits: Ryan Blanchard

[5] https://resource.capetown.gov.za/documentcentre/Documents/Graphics%20and%20educational%20material/Spekboom_Information_Booklets.pdf

3.1.1. Land cover classification

The approach used in this study relies on the identification of distinct land cover classes and an estimation of its area. We selected the 2013-14 National Land Cover map which was localized to the Western Cape, as described by Pool-Stanvliet et al. (2017). To accurately account for the natural vegetation within the city, the Biodiversity Network (BioNet) (Holmes and Pugnalin, 2016) and the Natural Vegetation Remnants layers for the City of Cape Town (CapeNature, 2016) were merged into the Western Cape land cover raster layer and clipped to the Cape Town Municipal boundary. This combined Fynbos class is approximately 90 000 ha (900km^2) in size and comprises of 20 national vegetation types consisting of several Fynbos, Renosterveld and Strandveld vegetation types (collectively referred to in this report as Fynbos), as well as indigenous Afrotemperate forest (referred to as Forest). Following the method of O'Farrell et al. (2019), the 122 land cover classes were resampled to eight classes for the purposes of this study (see Appendix 2 for a detailed description). The eight classes are: *Cultivated, Forest, Fynbos, Natural and other open space (NOOS), Plantations, Sport and school, Urban, Water/wetlands* (Figure 5). This step created an enhanced layer where we could be sure that the indigenous vegetation types were both present and accurately located within the broader land cover. The attributes of the BioNet provided information on habitat condition and an indication of land suitable for habitat restoration (Table 1).

Table 1: Summary table indicating the distribution and extent (km^2) of the BioNet Areas and the overlap with the eight land cover classes used in this study.

		Reclassified land cover classes (km^2)								
	Habitat Condition*	**Cultivated**	**Forest**	**Fynbos**	**Natural and other open space**	**Plantations**	**Sport and school**	**Urban**	**Water/ wetlands**	**Total**
BioNet	Good	0.20	3.52	680.70	10.57	0.21	0.41	2.79	25.12	723.53
	Poor	0.01	0.02	157.57	7.21	0.00	0.00	0.73	0.87	166.42
	Bad	51.33	0.03	60.77	127.81	4.04	5.00	48.00	10.40	307.36
Area outside of the BioNet		339.73	0.18	0.00	305.22	4.74	43.71	528.02	33.88	1255.47
Total area km^2		**391.27**	**3.75**	**899.04**	**450.81**	**8.99**	**49.12**	**579.54**	**70.27**	**2452.79**

*BioNet CBA classes highlighted in Appendix 3

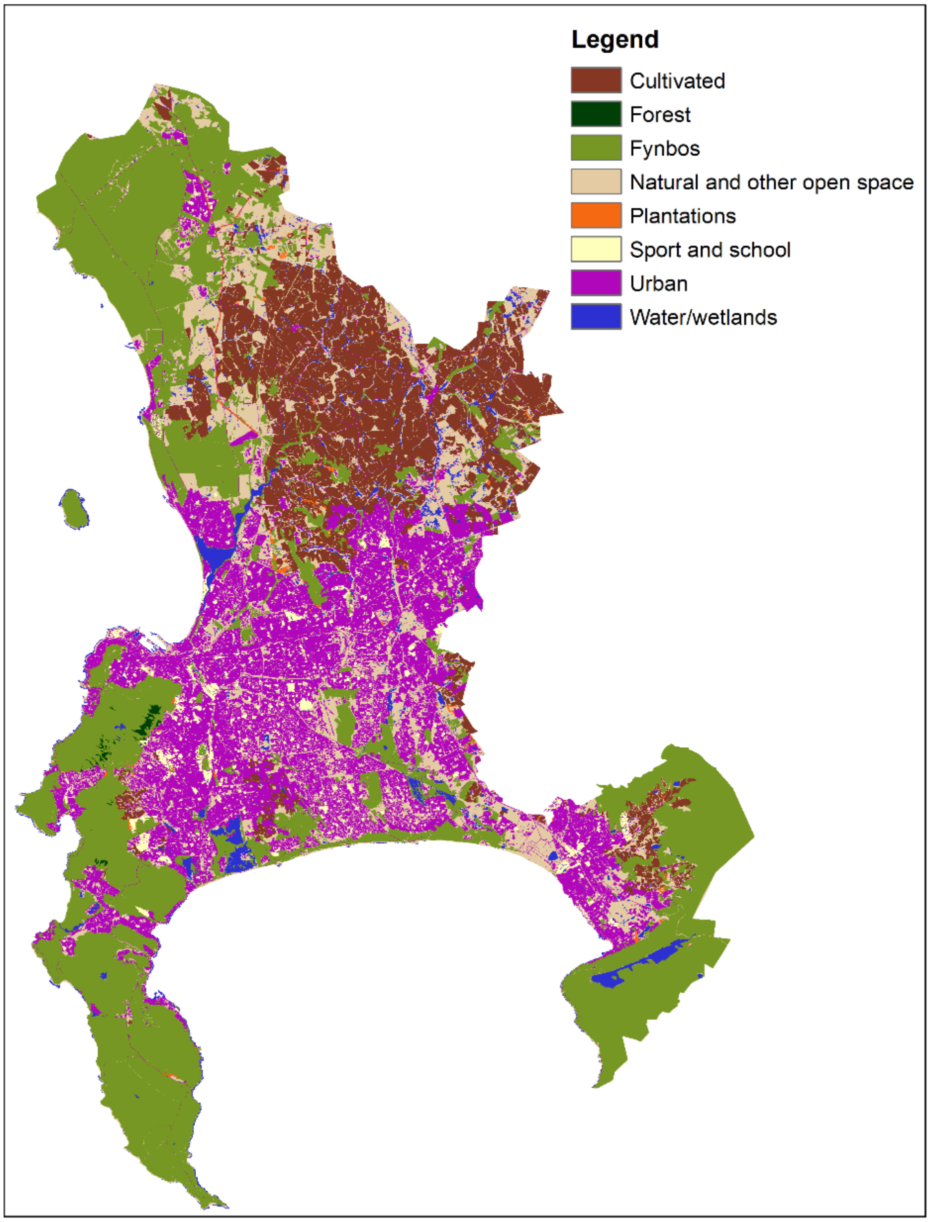

Figure 5: The distribution of eight reclassified land cover classes within the City of Cape Town. Note the Fynbos class is denoted by the coverage of the BioNet.

3.2. Data Analysis:

3.2.1. *Carbon storage and distribution across the city*

Carbon stock data was downloaded using the Carbon Sinks Atlas online portal[6]. For the purposes of this study only Total Organic Carbon (TOC) and Soil Organic Carbon (SOC) for 1990, 2014 and 2018 were downloaded. In ARCGIS, the zonal statistics tool was used to summarize the carbon values across the eight selected land cover classes. To calculate carbon gains and carbon losses over time, the difference between the 1990, 2014 and 2018 TOC layers was calculated. This is an indication of the change in carbon stock and sequestration potential over time, with the maximum period being 28 years. It was not possible to extract an annual rate of change as required by the IPCC (see equation 2.4 in the Appendix 1).

Two additional data layers, provided by the CSIR, are included for background information on the vegetation dynamics. The first is an *above-ground biomass map* for 2018[7] at 100m resolution. This was map was used to better visualize the distribution of above-ground biomass across the city. Above-ground biomass measures include the mineral and water content of the vegetation and is not equal to the carbon content. To obtain this value, biomass values were multiplied by a factor of 0.5. The second additional layer was a *veld age* map derived from MODIS[8] satellites indicating the number of days since the last recorded fire. Veld age highlights the potential duration of above-ground carbon storage within the fynbos. The resolution of this product is 500m and provided a satellite record of approximately 18 years. Veld age was characterized to indicate vegetation age as five classes (<5 years, <10 years, <14 years, <18years and no fire record). Vegetation classed as 'no fire record' indicates pixels where a fire has not been detected by satellites and are likely to be older than 18 years.

3.2.2. *Carbon Sequestration*

3.2.2.1. *Estimates per land cover class*

In the absence of detailed information for the City of Cape Town, we use vegetation productivity indices and estimates of soil heterotrophic respiration to provide an estimate of carbon sequestration rates for the various land cover classes. Data for both GPP and NPP (resolution 1km^2) were downloaded from the Carbon Sinks Atlas through the South Africa Spatial Data Infrastructure Portal (Department of Environmental Affairs, 2015). Firstly, estimates of vegetation productivity were summarized across all eight land cover classes based on the NPP data derived from the Carbon Sinks Atlas (NTSCA 2015). This was carried out in ARCGIS using the zonal statistics tool to determine the mean rate of carbon uptake per year (tC ha^{-1} year^{-1}). As described in the literature review, most of the carbon captured via photosynthesis is respired back to the atmosphere due to soil heterotrophic respiration. We assume that between 10-30% of NPP is available for sequestration over long periods of time (i.e. 90-70% is lost back to the atmosphere). The estimate of SHR was applied to all land cover classes except the cultivated and wetland class. These two land cover classes were assumed to have a net Zero effect due to land management (e.g. Tillage or outgassing) practices following IPCC Tier 1 approaches (IPCC, 2019).

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[6] https://ccis.environment.gov.za/carbon-sinks/

[7] Input layer into the Carbon Sinks Atlas. CSIR Biomass map v1.1 2018

[8] Data obtained from the Advanced Fire Information System hosted at the CSIR. www.afis.co.za

3.2.2.2. Mitigation Action: Habitat restoration

The BioNet was reclassified into three habitat condition classes. Based on the methodology described above, the zonal statistics tool in ARCGIS was used to determine the mean NPP for each class. The difference in NPP between habitat in a good condition and habitat in a poor condition was used to determine the potential carbon gained by habitat restoration. This difference was multiplied by the area of potentially restorable habitat. According to Holmes and Pugnalin (2016) approximately 11.6% of habitat in the BioNet is in a poor condition. These include the classes CBA1d, CBA2, ESA and Other natural vegetation (Table 2). This results in approximately 166km^2 suitable for habitat restoration across the city.

Table 2: The CBA categories in the Biodiversity Network Conservation Plan containing habitat in poor condition.

Name	**Description**	**Area km^2**
CBA1d	Critically Endangered vegetation of low/ restorable condition. Essential for management consolidation & viability of CBA 1a, CBA 1b & protected sites	18.1
CBA2	Critically endangered vegetation of restorable condition. Needed for national targets but not for management consolidation, connectivity or viability of priority Biodiversity network sites.	35.4
CESA	Unselected areas that are in natural vegetation. Essential ecological support for CBA 1, CBA 2 & protected sites.	50.6
Other natural areas	Natural vegetation in Endangered, Vulnerable and Least Concern in good or restorable condition.	62.3
Total		**166 km^2**

3.2.3. Urban trees and mitigation actions

3.2.3.1. Existing Urban Tree canopy

A recent study by the City of Cape Town found that trees over 2.75 m in height, cover approximately 7% the city area (~171 km^2). We multiply this tree cover estimate by the average net carbon sequestration rate of urban trees derived from a study in the United States (Nowak et al., 2013). The average net sequestration rate of 0.164 kg C m^{-2} year^{-1} (SE =0.0305) was used for this study and is based on climatically similar cities (based on Koppen-Geigger climate zones) such as the City of Los Angeles (0.107 kg C m^{-2} year^{-1}, SE=0.015) and the City of San Francisco (0.221 kg C m^{-2} year^{-1}, SE=0.046). These cities occur within a Mediterranean climate and contain the Chaparral biome, which is similar to that of fynbos (Van Wilgen, 1992). Nowak et al., (2013) highlights the average carbon sequestration of urban trees across 28 major cities in the US is 0.205 kg C m^{-2} year^{-1} (SE = 0.041).

3.2.3.2. Mitigation Action: Expanding the urban tree canopy

The approach by Nowak et al. (2013) was used to estimate the impact of increasing the tree canopy cover from 7% to 10% in urban areas. The net sequestration rate of 0.164 kg C m^{-2} year^{-1} (SE =0.0305) was applied to an additional 74km^2 of tree canopy cover.

3.2.3.3. Mitigation Action: Urban tree planting

The City of Cape Town Nursery is responsible for supplying trees of a suitable size, on request, to the city regions for planting. These regions request trees for new developments, to replace dead trees or improving the tree cover in public spaces (pers com Jan Botes). Table 3 shows that ~20 000 trees left the nursery between 2012 and 2021 (data supplied by Jan Botes of Cape Town Nursery).

We apply the standard US Environmental Protection Agency (EPA) approach for estimating tree carbon accumulation to data from new trees. This rapid assessment method has been calibrated by the (EPA) to calculate the weighted average of carbon sequestered by coniferous or deciduous (including evergreen) trees. According to the EPA, a medium growth coniferous or deciduous tree, planted in an urban setting and allowed to grow for 10 years, sequesters 10.5 and 17.2 kg of carbon, respectively. A weighted average is calculated based on the proportion of each tree class planted over a given time period. In the absence of species-specific data for the trees planted by the City, we use the estimated sequestration rates provided by the EPA. This equates to 16.56kg per ten years based on 10% conifers and 90% deciduous trees planted.

To provide insight on the carbon benefits of Spekboom planting use the estimate that a single *Spekboom* tree sequester between 0.4kg and 2 kg of C per year[9] (Mills and Cowling, 2006; NTCSA 2020). Spekboom is included in this calculation as 5000 Spekboom plants were handed out to the public during an awareness campaign[10].

Table 3: City of Cape Town nursery tree planting figures:

Year	Total trees	Species	Spekboom*
2012 - 2013	4484	Mixed	
2013 - 2014	3605	Mixed	
2014 - 2015	2858	Mixed	
2015- 2016	3591	Mixed	
2016 - 2017	268[11]	Mixed	
2017 - 2018	924	Mixed	
2018 - 2019	1584	Mixed	
2019 - 2020	1758	Mixed	5000
2020 - 2021	1296	Mixed	

*in response to the educational campaign of the Spekboom challenge

[9] Mills and Cowling 2006 estimate that 15.4 t CO_2 ha^{-1} yr^{-1} is possible. The NTSCA indicates 1-2tC ha^{-1} yr^{-1}. This equates to 1000-4196 kgC/ha. When divided by the planting density of 2500 trees per ha, this equates to roughly 0.4kg - and 2kg per cutting per year. Survivorship can range between 0 and 80% depending on the initial planting conditions (Mills et al 2015).

[10] https://resource.capetown.gov.za/documentcentre/Documents/Graphics%20and%20educational%20material/Spekboom_Information_Booklets.pdf

[11] A drought had restricted the planting activities during this period.

4. Results

4.1. Carbon Storage and veld age:

The distribution of Total Organic Carbon (TOC) and Soil Organic Carbon (SOC) across the city highlights areas of high and low carbon (Figure 6). For all three periods of available data (1990, 2014, 2018), TOC remained within the range of ~29 million tons of carbon, with SOC accounting for ~81% of the TOC (Table 4). The remainder of the organic biomass (TOC minus SOC) comprises the remaining carbon pools which includes above- and below-ground biomass, above- and below-ground herbaceous biomass and litter. On average, these pools remained fairly constant across all three time periods. However, a positive net change in carbon stocks is observed between 1990 and 2014 (40 600 tC), while a decrease is observed between 2014 and 2018 (-165 800 tC) resulting in less carbon stocks than the baseline year of 1990 (Table 4). Figure 7 shows the difference in carbon stocks between year's highlighting that carbon stocks are not static and that the factors driving carbon storage require further detailed investigation.

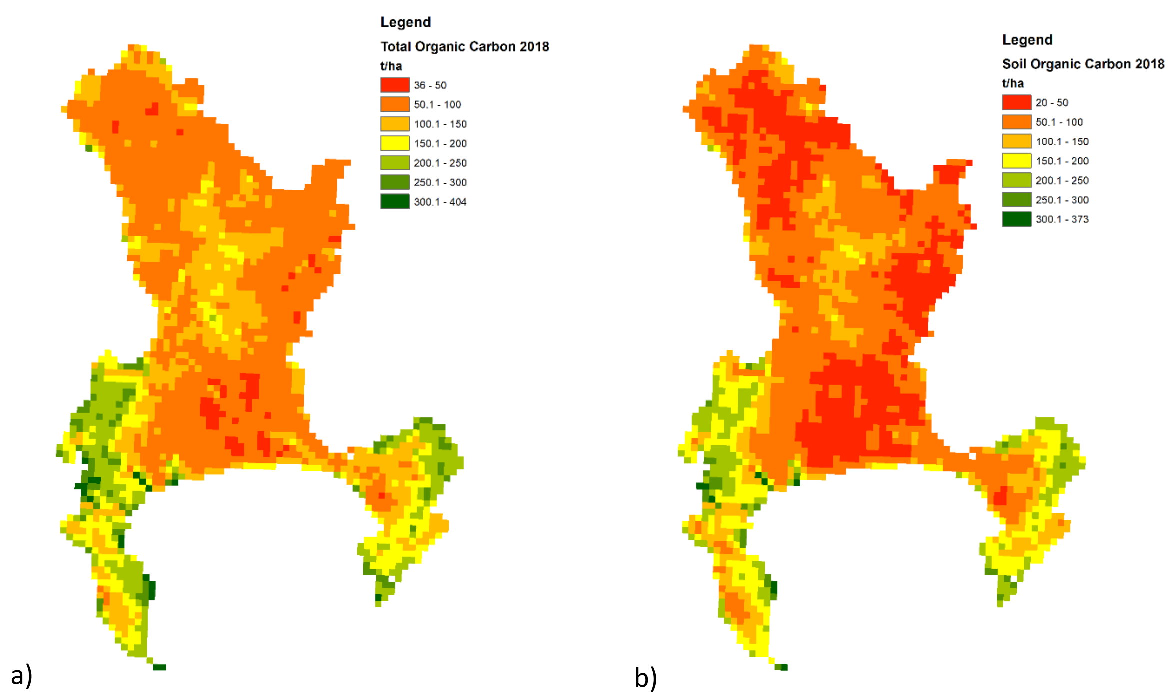


Figure 6: Total organic Carbon and Soil organic Carbon in 2018 for the City of Cape Town. On average Soil Organic Carbon accounts for ~80% or Total Organic Carbon (Date derived from the NTCSA 2020).

Table 4: Summary of Total Organic Carbon (TOC) and Soil Organic Carbon (SOC) values for three available dates. Data sourced from the Carbon Sinks Atlas.

Description	1990 (tC)	2014 (tC)	2018 (tC)
Total organic carbon (TOC)	28 862 600	28 903 200	28 737 400
Soil organic carbon (SOC)	23 329 500	23 370 800	23 204 500
% SOC	81%	81%	81%
TOC minus SOC	5 533 100	5 532 300	5 532 900

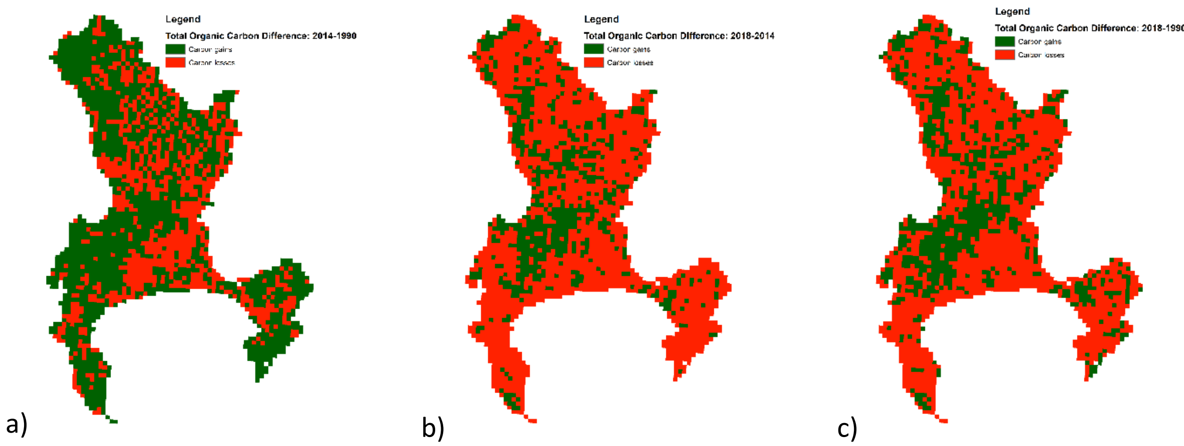
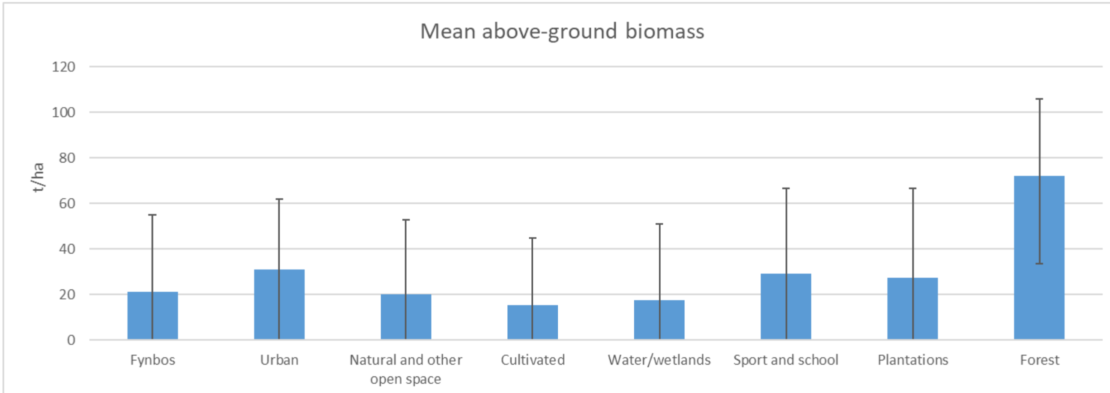


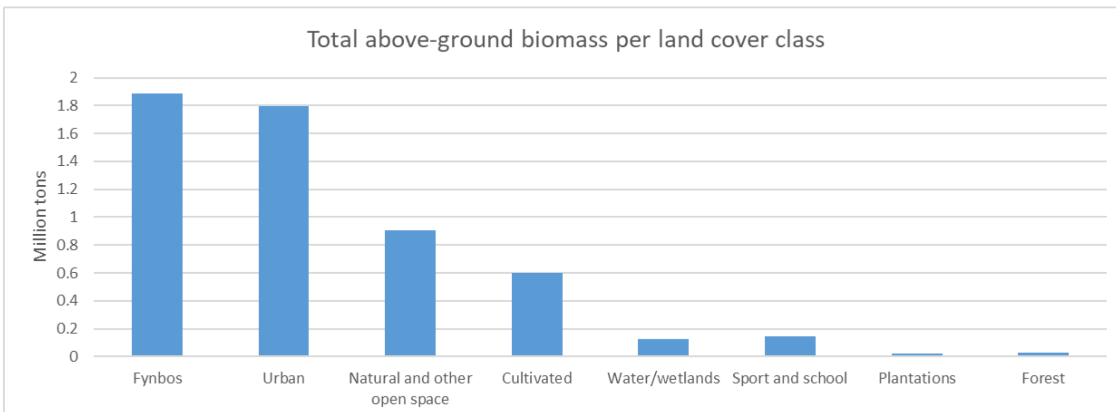
Figure 7: Difference in carbon pools between years a) difference between 2014 and 1990, b) difference between 2018 and 2014 and c) difference between 2018 and 1990.

4.1.1. Above-ground biomass and land cover

Mean above-ground biomass for 2018 ranges between 15 and 72 t/ha, across the 8 selected land cover classes (Figure 8a), based on the fine scale above-ground biomass data layer from the CSIR (100m resolution). Indigenous forests had the greatest carbon density across all classes (72 t/ha), followed by the urban class (31 t/ha), sports fields (29 t/ha), plantations (27 t/ha) and fynbos (21 t/ha). However, the net biomass within the fynbos class is proportionately greater on an area basis than that of forests (Figure 8b). The majority of the above-ground biomass stock is located within the Biodiversity Network (34%), urban areas (32%) and the natural and other open spaces (16%) land cover classes.



a)



b)

*Figure 8: The distribution of above-ground biomass across 8 land cover classes. a) The mean (±1.96*SD) biomass in tons per hectare for each land cover class, b) the sum of all biomass within each land cover class. Data shown for the above-ground biomass carbon pool only.*

4.1.2. Fire history and vegetation age

The fire history illustrates that approximately 51% of the natural land cover classes (i.e. Forests, Fynbos and the Natural and other open space class) have not burnt in the last 18 years (Figure 9 and Table 5). In these areas, fires were either too small to be detected by satellites or a fire had occurred prior to the start of the satellite record. Approximately 25% of the Fynbos vegetation class is younger than 5 years old. The most recent fires occurred on the Cape Peninsula, City Bowl and the Helderberg mountains in the last five years. The remainder of vegetation has burnt at varying intervals within the 18 years of the fire record.

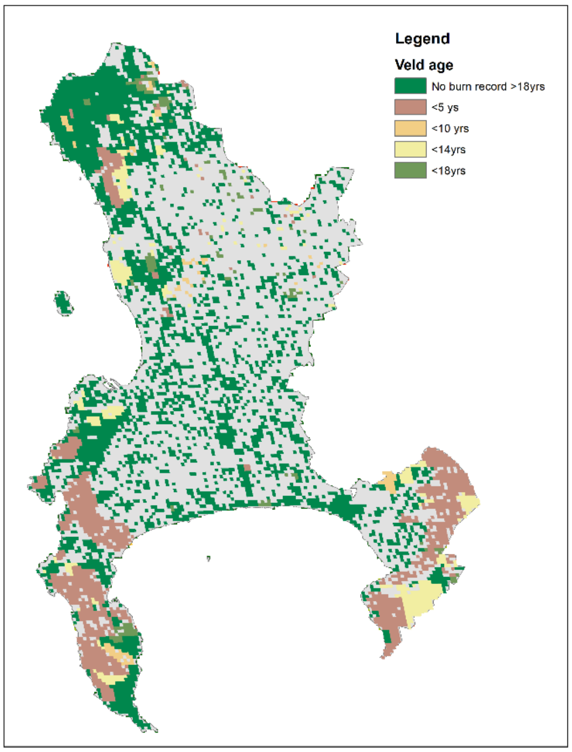


Figure 9: Vegetation age in relation to fire history. Main drivers of carbon loss urbanization, fires, land use change. Potentially the role of conservation and urban trees have resulted in increased carbon stocks. Urban and cultivated areas have been masked out.

Table 5: Percentage veld age for indigenous remnants

Veld Age	Percentage of Natural Remnants
<5yrs	25
<10yrs	10
<14yrs	8
<18yrs	6
>18 or no record	51

4.2. Carbon Sequestration by existing vegetation

The average NPP value for each land cover class ranges between 0.91 and 2.38 tC ha^{-1} $year^{-1}$ (Table 6). The largest area-weighted value occurs within the *Fynbos* land cover class followed by the *Urban*, *Natural and other open space* and *Cultivated* areas. It is estimated that 211 297 (±42 316) tons C per year is captured by the vegetation across the city. This equates to approximately 3.7% (±2.4%) of Cape Towns' annual emission rate. However, these values represent the upper limit estimates and are likely to overestimate the actual long-term carbon sequestration. By including an estimate of respiration, where approximately 70-90% of carbon is released back into the atmosphere, a mean estimate of between 24 112 and 61 236 tC per year can be expected (Table 6). This equates to 0.3 - 1.07% of the total annual emissions.

4.3. Mitigation benefits of habitat restoration and afforestation

4.3.1. Habitat Restoration

The difference between the mean of NPP values between *habitat in good condition* and *habitat in poor condition*, suggested that on average, vegetation productivity could be improved by 0.18 tC/ha^{-1} $year^{-1}$ (Table 7). While this might seem minimal this represents an increase in woody above-ground vegetation, improved soil carbon potential and reduced soil loss. This equates to an increase of approximately 300-900 (±398) tC per year inclusive of soil respiration factors SHR90 and SHR70 respectively. Including the restoration of *habitat in bad condition* increases the potential rate to 572 - 1715 tC per year. On average this equates to <0.2% in relation the annual GHG emissions. The spatial distribution of habitat in a poor condition is shown for the BioNet regions to indicate where restoration activities could take place (Figure 10).

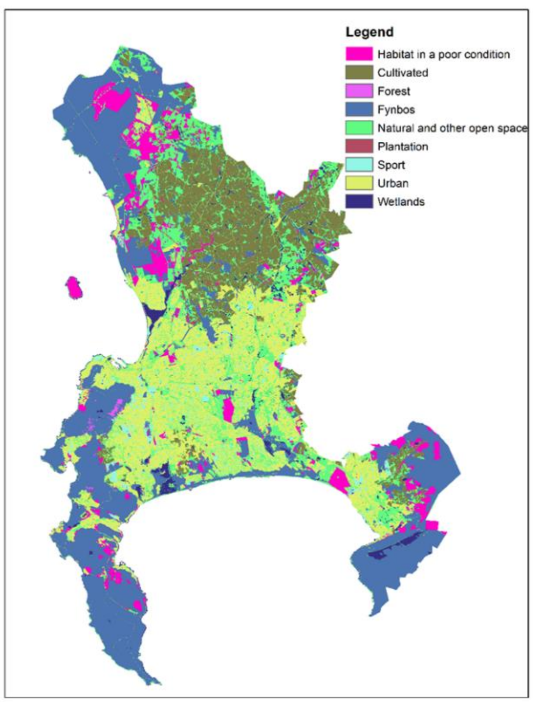


Figure 10: Areas within the Biodiversity Network (BioNet) identified as having habitat in a poor condition.

Table 6: Carbon sequestration per land cover class based on indicators of vegetation productivity such as Net Primary Productivity. Two estimates of Soil Heterotrophic Respiration (SHR) are included to illustrate potential uncertainty of long term carbon storage.

Land cover class	**Area (%) km^2 (A)**	**Mean NPP (SD) tC/ha/y (B)**	**Carbon (SD) tC/y (C=A*B)**	**Mean Carbon sequestered less SHR70 (D_{70}) tC/y (E_{70}=C*D_{70})**	**Mean Carbon sequestered less SHR90 (D_{90}) tC/y (E_{90}=C*D_{90})**
Cultivated*	391 (16%)	1.14 (±21)	44 763 (±8 235)	-	-
Forest	4 (0.1%)	2.38 (±47)	866 (±171)	256	87
Fynbos	900 (36%)	1.11 (±47)	100 014 (±42 146)	30 004	10 001
Natural and other open space	452 (18%)	0.98 (±32)	44 482 (±14 452)	13 344	4 448
Plantations	9 (0.3%)	1.14 (±36)	1 067 (±339)	320	107
Sport	49 (2%)	1.02 (±46)	5 003 (±2 238)	1 501	500
Urban	578 (24%)	0.91(±36)	52 686 (±20 633)	15 806	5 269
Water/wetlands*	70 (3%)	1.02 (±26)	7 179(±1 833)	-	-
		-			
Total	**2451***	**-**	**256 060 (±90 045)**	**61 236 (±23 993)**	**20 411 (±7998)**
City of Cape Town annual emissions	**CO_2 equivalents (tC)**	21 000 000 (5 727 273)	939 740	224 736	74 908
% of CCT annual emissions sequestered			4.5% (2.9-6)	1.1% (0.65-1.49)	0.36% (0.22-0.5)

Conversion: 1m^2=0.000001km^2; 1g = Mg; NPP = Net Primary Productivity; SD = Standard deviation; NPP data extracted from NTCSA (2015); *excluded due to insufficient data or assumed net zero carbon; **Area based on raster datasets and may differ from actual area.

Table 7: Carbon sequestration gains resulting from active habitat restoration based on indicators of vegetation productivity such as Net Primary Productivity. Two estimates of Soil Heterotrophic Respiration (SHR) are included to illustrate potential uncertainty of long term carbon storage. The Habitat condition classes are derived from the BioNet.

		Current situation		**Change**	**Restoration potential**		
Habitat condition	**Area km²**	**Mean NPP (SD)* tC/ha/y (B)**	**Current Total tC/y**	**Increase/ change tC/ha/y**	**Total carbon tC**	**Mean Carbon sequestered less SHR70 (D_{70})**	**Mean Carbon sequestered less SHR90 (D_{90}) tC/y**
Good to fair	898	1.16 (21.1)	104 175	-	-		
Fair to poor	166	0.98 (47)	16 311	0.18	2995.84	898	300
Bad	136	0.96 (46.8)	13 067	0.20	2722.23	817	272
Total	**1200**		**133 552**		**35096**	**1715**	**571**
City of Cape Town annual emissions	**CO_2 equivalents (tC)**	21 000 000 (5 727 273)			**128 801**	**6 296**	**2 098**
% of CCT annual emissions sequestered			**2%**		**0.61%**	**0.03%**	**0.01%**

4.3.2. Urban Tree planting and afforestation

The spatial distribution of above-ground biomass in urban suburbs is shown to highlight areas where the biomass is above or below one standard deviation of the mean across all suburbs (Figure 11) and additional greening programs may be required.

The City of Cape Town nursery grows a variety of species of which 15 main tree species are preferred (See Appendix 4). These are mainly deciduous or evergreen trees and palms. While it was not possible to extract the proportion of each trees dispatched or planted, our estimates are in line with the tree stock available in the nursery. Calculations show that should 60% of trees survive to 2030, then approximately 327tC could potentially be sequestered by the trees planted in the last 8 years based on the nursery records (Figure 11). This equates to approximately 20tC per year over a 15 year period. However if 100% of trees survived to 2030 then 547tC would be sequestered. If an average of 1500 trees continue to be planted per annum between 2021 and 2030, then an additional 82tC can potentially be sequestered.

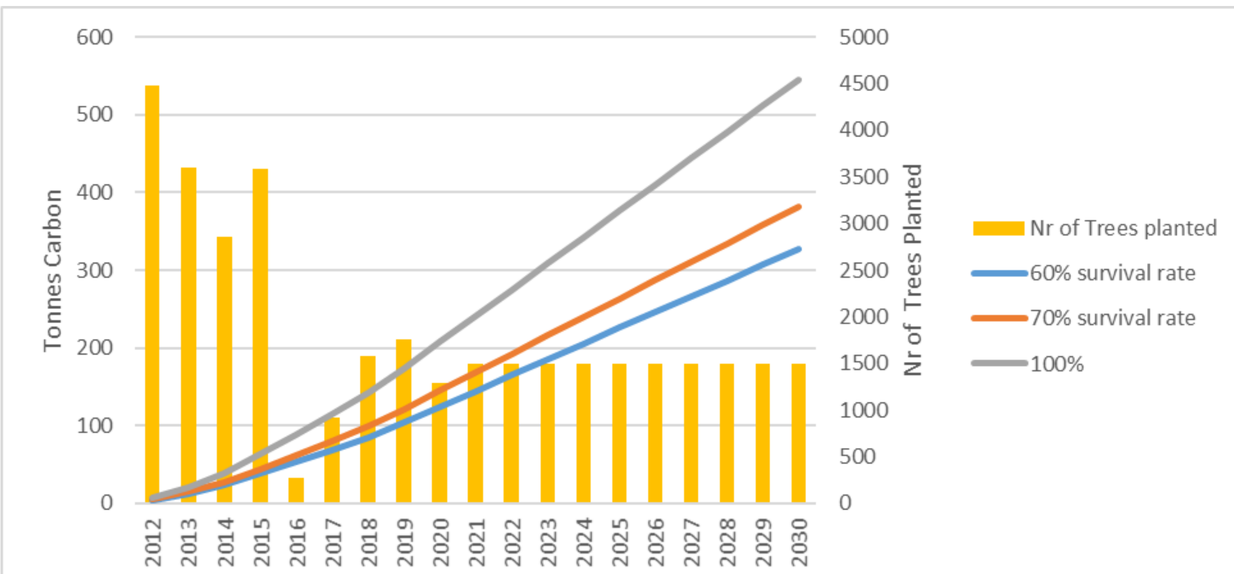


Figure 11: Estimated accumulation of Carbon from tree planting activities conducted by the City of Cape Town Nursery. The left axis is associated with line graphs and the right axis is associated with bar graphs.

The analysis of the existing urban tree canopy of trees above 2.75m in height shows that approximately 28 139 tC per year is sequestered, based on the net sequestration rates adopted from Nowak et al., (2013) (Table 8). This accounts for 0.49% of annual emissions generated by the city. Assuming that the estimate of carbon sequestration for all vegetation derived from NPP, as described above, are comparable with this one method, then based on the mean estimate, the urban tree canopy cover accounts for approximately 45% of the total amount of carbon sequestered by vegetation in Cape Town. This is similar to the findings illustrated by the NPP as shown above. Note that the distribution of urban trees and biomass is not equal throughout the City (Figure 12).

Should the urban tree canopy be increased by 3%, then this would contribute to an additional 12 059 tC sequestered per annum (Table 8).

Table 8: Estimate of Urban Tree carbon sequestration based data extracted from Nowak et al. (2013).

Tree Canopy Cover	Area (km^2) (A)	Average Net sequestration (SE) (kg C m^{-2} $year^{-1}$) (B)	tC $year^{-1}$ (C=A*B)	% of annual emissions	Number of trees*
7% of Cape Town Area occupied by trees >2.75m)	172	0.164 (0.34)	28 140 (±11 505)	0.49%	1.7-14 million trees
3%	73.5	0.164 (0.34)	12 059 (±4 931)	0.21%	735k to 6 million trees

*An assumption is that if the tree canopy for mature ranges between $12m^2$ and $100m^2$ (Note this is speculation)

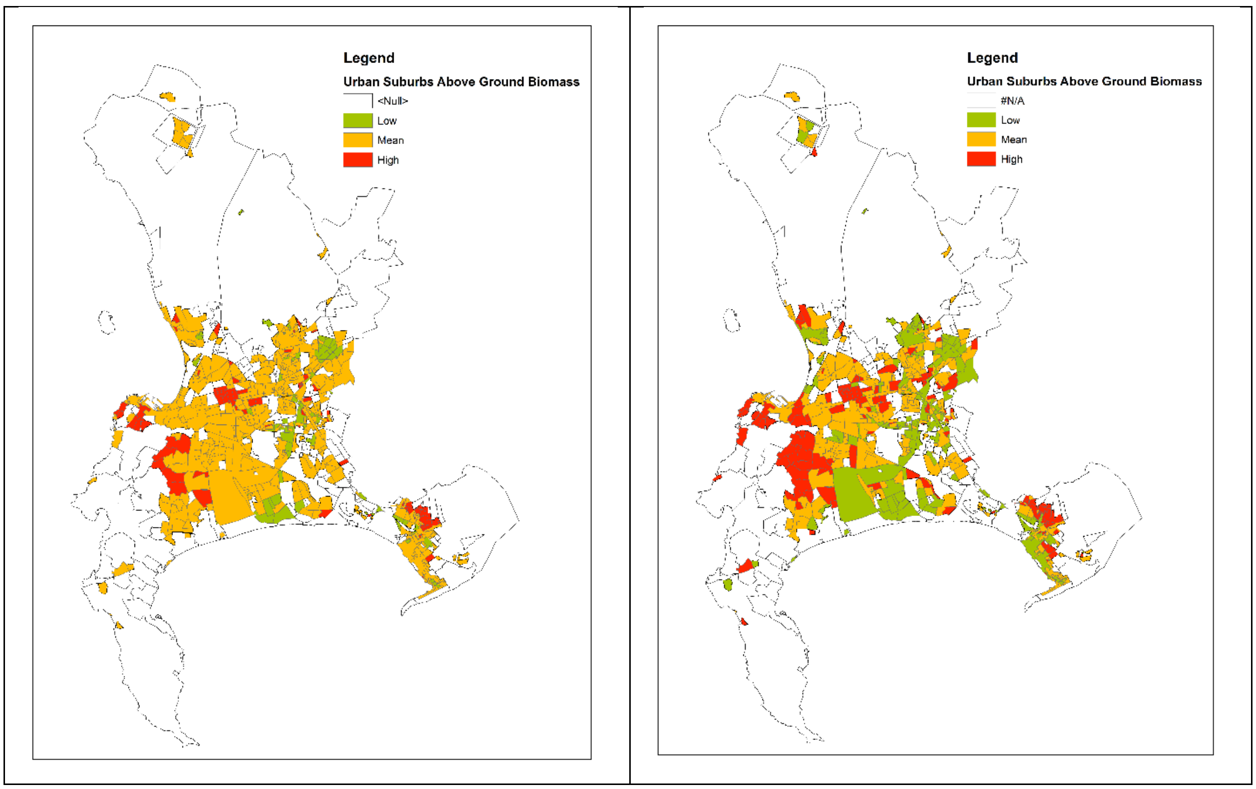


Figure 12: Distribution of the above-ground biomass in suburbs dominated by the urban land cover class. Mean and 1 standard deviation to indicate high and low areas. B) Mean and 1/2 standard deviation to indicate high and low areas

4.3.3. Spekboom planting

Calculations show that in ten years till 2030, between 11 and 46tC could potentially be sequestered by the 5000 the Spekboom trees handed out by the nursery in 2020. These assumptions are based on the sequestration rate of 1tC/ha and 4tC/ha achieved under good conditions. These figures apply to a planting strategy of 2500 cuttings per hectare of undisturbed veld and 100% survival. The realistic figure is probably less than 11tC if we assume the mortality rate to be 60% and that single plants will be kept in pots which could limit the growth potential of the plant.

5. Discussion

Habitat restoration and urban tree planting offer minimal benefits to significantly mitigate the GHG emissions at the scale of the metro. These results reflect the high-level approach adopted in this study and it is certain that future research will improve on the estimates provided here. This study relied on previously published information and existing data as proxies for estimating carbon stocks and carbon sequestration and supplemented these with existing data from both the published literature on fynbos ecology and international literature on tree carbon sequestration. The approach highlights the complexity of estimating carbon fluxes and the gaps in knowledge needed to support decision making.

The implications of the results are discussed in more detail below.

5.1. Implications of the results for understanding carbon stocks and carbon sequestration

The calculations show that the existing vegetation cover across all land cover classes in the city sequesters between 0.36-1.1% of the annual emissions total. However, the total organic carbon stock between 1990 and 2018, derived from the NTSCA, remained relatively stable ranging between 28 737 400 MtC and 28 862 600 MtC (~106 $MtCO_2eq$). The relative stability of the carbon stocks between 1990 and 2018 indicates that the long-term sequestration carbon is influenced by a number of factors. These include, land use and land cover change, the relationship between plant productivity and climatic factors (e.g. rainfall and drought) and fire. These factors have varying impacts on the different carbon pools (Zhu and Reed, 2012). Little is known about the saturation points or maximum storage potential for these pools and whether a limits have been reached. More detailed assessments are needed to improve the understanding between areas of high carbon storage and uptake and areas shown to have lost carbon over time. Terrestrial carbon stocks have always been considered vulnerable due to the rapid rate at which these stocks can be depleted (IGBP Terrestrial Carbon Working Group, 1998). For example, the city has undergone large urban growth in recent years resulting in habitat loss and habitat fragmentation (O' Farrell et al., 2012), which has been shown to impact carbon stocks.

Between 2015 and 2018 the city was impacted by a meteorological drought (Taing et al., 2019) which coincided with the large reduction in TOC. Ecological studies in the fynbos show that climate influences vegetation growth and mortality rates, which could result in the vegetation becoming a source rather than a sink of carbon (Dawson et al., 2012; Subedi et al., 2021). Recent experiments have shown that some fynbos species can control their stomata to limit photosynthesis to reduce water loss and thus reducing the rate at which carbon is fixed. However, studies also indicate that warmer temperatures may increase the speed at which microbes consume plant debris and other organic matter thereby raising the amount of carbon dioxide released into the atmosphere (Fang, 2010). Climate projections for the City of Cape Town point to hotter and drier conditions, which could impact carbon sequestration rates. More research is needed to understand the impacts of drought on carbon stocks and vegetation mortality in both natural and urban areas.

The fynbos is a fire prone vegetation type and approximately 35% of the vegetation is younger than 10 years old and a further 8% is less than 14yrs. Fires can result in stand replacing events leading to additional loss in soil carbon due to runoff and erosion. The fire ecology is quite different for Fynbos, Strandveld and Renosterveld and the vegetation responds differently to fire (van Blerk et al., 2021). The natural fire return interval on the Cape Peninsula has shortened over time due increased human pressures such as ignitions (e.g. cigarettes, braai fires), urbanization and invasive alien plants. An analysis of the fire history of Table

Mountain between 1970 and 2007 shows that mean fire return intervals decreased from 31 years (due to fire suppression policies) to 13 years, and some areas burning within six years of a fire (Forsyth and Van Wilgen, 2008). Increasing fire frequency is likely to impact the carbon cycle within fynbos by shortening the time for biomass to accumulate both above- and below- ground. It is possible for sites to fully recover in a relatively short space of time. More research is needed to understand the role of fire and to determine the vulnerability of carbon stocks within the city. An important research question emerging is the time needed to ensure that a fire event is carbon neutral. It was not possible to fully account for these factors in this study.

5.2. Implications of results for understanding the mitigation benefits provided by habitat restoration

Active habitat restoration can lead to a marginal increases in the rate at which is carbon sequestered. These values are based on the restoration of the entire available area, which in practice could require decades. Despite this, there are significant additional benefits that habitat restoration can provide throughout the BioNet. Further analysis is needed to assess the viability of sites for restoration. Factors to consider include plot size, current species composition, the ability to restore floristic structure and function, connectivity to the BioNet and the security of investment. Restoration activities are likely to be long-term engagements and more research is needed to indicate when these areas are likely to result in net carbon sinks. Despite these limitations, habitat restoration should primarily be undertaken to restore biodiversity and ecosystem function with secondary benefits of ecosystem services such as climate regulation.

As an example, several restoration activities are ongoing across the city which are overseen by different organizations. The objectives of these restoration activities are to improve the biodiversity and the representation of ecosystem types across the city. These include initiatives by South African National Biodiversity Institute (SANBI) at Tokai Park, South African National Parks (SANPARKS) at Devils Peak and The City of Cape Town and its Environmental Management Department and Recreation and Parks Department across various sites. Some examples of active restoration locations can be found at Bracken, Haasendal, Rondevlei, Kenilworth, Joostenbergskloof, Blaauwberg and Rondebosch Common. While soil monitoring is usually carried to determine whether excess nitrogen has successfully been depleted from the soil to facilitate fynbos growth, it might be beneficial to include a carbon monitoring protocol to assess the climate regulation benefits of these projects. Civic led activities to improve urban green spaces has also been shown to have positive effects on biodiversity (Anderson et al., 2014).

Furthermore, this study highlights the importance of conserving undisturbed or fallow areas for protecting the soil carbon stocks. This information should be useful to support climate sensitive land use planning necessary for minimizing GHG emissions and to protect existing carbon stocks. Managing land use and land cover change therefore becomes critical to managing the carbon stocks within the city. This is likely to be challenging as the city is faced with a housing backlog, urban development and infrastructure placing great pressure on the remaining natural and other open space in the city. These areas have been shown to provide significant additional benefits to human health and wellbeing in the provision of several important ecosystem services (O’Farrell et al., 2019).

5.3. Implications of results for understanding the mitigation benefits provided by tree planting

It is likely that trees contribute between a third and a half of the carbon sequestered by vegetation in the city. Urban areas accounts for 25% of the vegetation productivity, thus have large above-ground carbon stocks. However the distribution of these are skewed towards the mountain foothills of Table Mountain and Somerset west with the Cape Flats having lower above-ground biomass. The vegetation within these urban areas comprise a mixture of alien and indigenous species, which are often maintained to some degree.

Trees for planting in open spaces such as roadsides, parks or sports fields are produced by the nursery, which had dispatched approximately 20 000 trees over an 8 year period. Survival of these trees are not adequately tracked and tree mortality remains a concern after planting. The results highlight that reducing tree mortality can lead to higher carbon benefits in the long term. The City of Cape Town, through their Tree Management Policy (City of Cape Town, 2019), outline the requirements and limitations to tree planting throughout the city, indicating that there are limitations to the widespread planting of trees. These include the identification of suitable locations, soil conditions, and access to water. Significant investment is needed to ensure that trees establish adequately to withstand the varying climatic conditions in Cape Town. As such locations are often selected to include highly maintained locations like gardens, schools, parks and sports fields. It was recommended that trees be planted in locations where survival is ensured (pers comm Jan Botes, City of Cape Town nursery). Information on best practice, suitable species options and location criteria can be found in the Best Practice guideline developed for the Green Infrastructure Programme (City of Cape Town, 2020).

While we were only able to use simplified carbon accumulation models, more detailed species-specific models may provide improved estimates of the carbon benefits of tree planting. It is also important to note that the Cape Flats may provide sub-optimal conditions for tree growth, thereby resulting in slower growth rates which maybe more in line with our calculations. The effort and investment in nurturing trees in unfavorable environments may negate the carbon benefits intended to be extracted from tree planting activities and may in fact become a source of carbon.

The scenario of increasing the tree canopy cover by 74km^2 highlighted that at maturity, a 20% increase in net annual carbon sequestration from this land cover class could be expected. However, in relation to the annual GHG emissions of the city the total offset potential of vegetation by rises by 0.2% to 1.3%. These results compare similarly to other countries where the mitigation potential of the urban tree canopy cover is low. For example, only 0.47% of Barcelona's GHG emissions were offset by the urban tree canopy (Baró et al., 2014). Similarly, online calculators indicate that to offset the annual emissions of 21 million $C0_2$ eq you would require a forested area (US based) 45 times the area of Cape Town (see Appendix 6).

The main limitation to tree planting is the availability of suitable land and the likely small scale nature of potential projects. For example, the density of tree planting if limited to new house developments, road side planting or gardens is far from the density achieved under plantations forests. Other places of interest include running trails, parks to increase amenities for local citizens. Adequate consultation is likely necessary as safety concerns are often linked to the densification of trees and shrubs. Trees can provide multiple ecosystem services but they can also provide disservices which should be considered if urban forests are to be planted (Shackleton et al., 2016).

5.4. Data validation and limitations

For each of the components analyzed, secondary approaches were determined to verify the results derived from the vegetation productivity approach. For example, the sequestration rates derived from NPP for fynbos, compares well with previous estimates for biomass accumulation in Mediterranean vegetation of approximately 1-2.5 t/ha per year (Mooney, 1983). Other studies show that fynbos biomass can accumulate between 0.7 and 4.3 t/ha per year depending on the site, with some locations achieving biomass up to 70 t/ha. A previous study in the coastal lowland forests of South Africa found that on average 10.4 tC/ha per year (Smithwick, 2019), whereas the average NPP derived from the NTCSA (2015) for forest areas was approximately 9.7 tC/ha per year. The assessment of soil carbon by Mills et al. (2012) across intact and disturbed soils provides some insight to disturbed land use classes in Cape Town. For example, pastures have high soil organic carbon compared to fynbos or vineyards, despite the low above-ground biomass. This could mean that the open space network within the city could be an important soil carbon store under appropriate management.

The largest uncertainty, relates to the measures of soil respiration used in this study. NPP has been widely used to determine the average annual rate of carbon uptake by vegetation within a single growth period (Caldwell et al., 2007; Castro-Magnani et al., 2021; Deng, 2011; Yu et al., 2019), yet it is known to overestimate the amount of carbon sequestered in the long-term (Lovett et al., 2006). NPP therefore provides an upper limit to carbon sequestration which may be beneficial for the management of carbon landscapes. To account for the release of carbon back into the atmosphere this measure is often detected using bottom-up biogeochemical models or top-down approaches eddy-covariance equipment (Turner et al., 2011). It is uncertain how these processes are likely to respond to climate change as atudies also indicate that warmer temperatures may increase the speed at which microbes consume plant debris thereby raising the amount of carbon dioxide released into the atmosphere (Fang, 2010).

Our literature search found no previous studies on soil respiration in relation to carbon sequestration for fynbos vegetation. However, Kambol (2013) assessed the impact of invasive species on soil respiration rates in fynbos riparian systems. He found that respiration rates increased during the dry summer months, decreased during the cold wet months and was higher in invaded ecosystems than cleared or pristine sites. Unfortunately it was not possible to extract estimates of soil respiration in relation to NPP for use in this study. As such estimated soil respiration remains a large uncertain factor in this study.

To compare the tree carbon results obtained in this study, we modelled the outputs provided by Stoffberg (2006) as comparison (Appendix 5). These rates imply much higher sequestration rates. However the growth rates for trees Pretoria and Cape Town are not likely to be similar. Hence the EPA approach was retained as this applied to new trees planted and adopts a more conservative approach. Due to limited data it was not possible to use several available tools which rely on an inventory of tree species including, size class, diameter at breast height, and height class as example to improve accuracy of assessments (McPherson and Simpson, 1999).

There are several options to improve the estimates derived in this study. These included better understanding of the carbon content across various pools, calibrating ecosystem models such as the Century Ecosystem Program (Parton et al. 1993) to predict carbon dynamics over time and improved species-specific allometric models for calculating tree growth and carbon sequestration under various conditions.

6. Recommendations

This study has been successful in providing a high level assessment and defendable approach for understanding the carbon benefits of active habitat restoration and tree planting activities in the City of Cape Town. However, a number of a factors should be considered when planning for increasing mitigation benefits. Climate regulation is one ecosystem service, of several, which should be addressed in future to determine the wide ranging benefits of these mitigation actions. With this in mind we recommend the following:

Continued investment in the protection and management of the BioNet makes sense for long-term climate benefits

- The highest carbon density and carbon stocks can be found in the land cover classes containing indigenous vegetation. These areas should be protected and managed appropriately to ensure the climate regulation benefits they provide.

The Natural and other open space areas outside of the BioNet presents a unique opportunity to protect undisturbed carbon stocks and improve multi-functional land use planning.

- These sites are still important in the context of the Green Infrastructure Network (O'Farrell et al. 2018) and provide valuable services to residents of Cape Town such as recreation, water infiltration and improved connectivity between pristine vegetation patches. Avoiding degradation in undisturbed areas is recommended. Opportunities to increase tree cover densities may exist in transformed areas such as Sports fields, Sporting complexes, greenbelts within the green infrastructure network. However restoration activities should not be overlooked in these areas.

Prioritisation of habitat restoration projects in degraded areas should include a climate focus to reduce uncertainties.

- Several well documented restoration activities within the Cape Town region have focused on the removal of invasive alien species such as acacias[12] and pines[13] as well as the necessary follow-up restoration activities to improve species recovery. These case studies could include climate regulation benefits by improving the knowledge of soil carbon under indigenous vegetation.

The focus should be on responsible tree planting, rather than afforestation programs, within urban areas while adhering to biodiversity and water limitations.

- Tree planting should rather seek to meet the needs of communities than to focus solely on the GHG benefits. Unfortunately the limitations of space, habitat conditions and water availability are not conducive for wide-scale tree planting to take place across the sandy cape flats regions. While some tree species may cope, these areas are not prone to tree planting. If trees are established, then careful species selection, and nurturing plans are required. However, several urban

[12] https://www.ser-rrc.org/project/the-blaauwberg-large-scale-sand-fynbos-restoration-project-cape-town/

[13] https://restory.co.za/2020/01/13/passive-restoration-of-critically-endangered-cape-flats-sand-fynbos-at-lower-tokai-park-section-of-table-mountain-national-park-cape-town/

neighbourhoods could benefit from increased tree cover which has been shown to provide several beneficial ecosystem services. Here home owners should be encouraged to take responsibility for the trees planted in their neighborhoods.

Appropriate tree species should be identified prior to any planned for tree planting should consider the following:

- The presence of the polyphagous shot hole borer (PSHB) in the City has impacted the tree planting strategy of the nursery. The PSHB beetle is an invasive species from Asia which lives inside the bark of trees, creating tunnels in which it lays its eggs. Certain species such as Plantanus and oaks are suitable hosts which can facilitate the spread of this invasive species. Tree replacement strategies are underway to remove host plants to limit the spread of PSHB.

Identify suitable tree corridor or green belt areas that would benefit from tree cover densification, with ongoing maintenance to assist tree establishment and including a drought and water availability plan.

- Tree mortality should be avoided and maintenance plans should form part of the strategy to ensure tree survival to protect future carbon gains. However these plans should be mindful of overall water limitations and potential impacts to the biodiversity network and reduction in corridors. Increased cover and the radiative cooling with respect to increased albedo is something to consider (Smart 2016). Roadside and scenic route tree planting, sports fields and complexes should only be prioritized if the maintenance is available to ensure that trees establish successfully. The cost of watering, water availability and water sources (boreholes, treated water, etc.) should be considered.

Spekboom planting should be limited to home gardens or landscaping features.

- The use of Spekboom should be carefully considered in accordance with the tree planting guidelines produced by the City. While there might be opportunities to include Spekboom in landscaping projects, the carbon benefits are not likely to be realised. Should these plants grow to the full potential of reaching 3-5m in height they might pose additional unforeseen impacts such as becoming a safety hazard in urban centers.

6.1. Recommendations for researchers

More research is needed to address the data gaps highlighted in this study. Several future research topics are suggested:

- How long is carbon locked away for in the various carbon pools in the fynbos biome?
- When are fynbos fires a carbon neutral event and how does the fire return-interval impact this?
- Verification of the role of carbon sequestration by the urban tree canopy through improved allometric relationships models.
- How beneficial are fruit trees (e.g. olive trees) in urban environments?
- Better understanding the role of soil respiration the fynbos and urban environments.
- Under which conditions does the potential carbon stock reach saturation?
- How can the role of the oceans be included in mitigation efforts for the City?

7. Conclusions

In summary, while there are significant opportunities to increase the restoration and urban tree planting efforts across the city, these actions provide limited benefits for carbon mitigation. It is likely that these activities may boost annual sequestration rates which over time will have a positive net benefit. These findings are in line with other biodiverse cities around the world. The study highlighted there are significant gaps and opportunities to improve the knowledge related to climate regulation of natural and planted vegetation across the city. This would drastically improve on the estimates provided in this study.

Trees are not typical to the fynbos biome except for the occurrence of Afrotemperate Forest patches located in mountain kloofs and in fire and wind protected areas. Expanding tree cover to the Cape Flats is not recommended in the remaining natural areas and should rather be prioritized for transformed land classes such as public parks, sports fields, and urban developments or along streets. However the role of community led projects to restore fynbos communities should remain a priority and be encouraged. Projects designed to increase tree cover in these areas should ensure appropriate maintenance plans and the necessary supporting infrastructure, so that new trees are nurtured to grow and survive. Water security remains at the forefront of city planning and this should be factored in to the plans for maintaining tree cover where appropriate. As shown in other studies, ensuring that trees survive to reach maturity is more beneficial than continual planting of new small trees.

This study focused solely on the carbon benefits of habitat restoration and afforestation. More research is needed to examine the wider range of ecosystem services provided by restoration and urban tree planting beyond that of carbon sequestration only. As an example, benefits such as reduced air and water pollution, altering heating and cooling costs, and increase real estate values should be further investigated.

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9. Appendices

Appendix 1: A Description of carbon pools and IPCC methods

BOX 1: Carbon Pools:

This box illustrates the different carbon "pools" or stocks as defined by the IPCC (IPCC, 2019). These pools are linked and the stocks change over time as carbon enters or leaves at varying rates.

Biomass: all biomass of living vegetation, both woody and herbaceous, where *above-ground biomass* refers to everything occurring above the soil including stems, stumps, branches, bark, flowers, seeds, and foliage and *below-ground biomass* includes the biomass of live roots.

Dead organic matter: comprises *dead wood* which includes all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil larger than 10cm in diameter and *litter* which is all non-living biomass < 10cm but with a size greater than the limit for soil organic matter.

Soils: Includes organic carbon in mineral soils to a specified depth (generally 30 cm) and includes live and dead fine roots and dead organic matter within the soil that are less than the minimum diameter limit (suggested 2 mm).

Carbon enters the soil as plant litter and from dead biomass. This process facilitates the breakdown of litter and dead organic material to be decomposed and enter the soil carbon pool. Decomposition can result in respiration which releases CO_2 to the atmosphere.

Changes in pools:

The IPCC 2006 and its refinement in 2019 provides standardised methods for assessing the changes in carbon pools over time. These are based on the equations outlined below. Herbaceous stocks are estimated to have zero impact due to their ephemeral nature. The emissions from decay are balanced by the regrowth within the same annual period. The greatest attention is paid to the changes in stock based within the woody plants and trees.

EQUATION 2.3
ANNUAL CARBON STOCK CHANGES FOR A STRATUM OF A LAND-USE CATEGORY AS A SUM OF CHANGES IN ALL POOLS

$$\Delta C_{LU_i} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

Where:

ΔC_{LU_i} = carbon stock changes for a stratum of a land-use category

Subscripts denote the following carbon pools:

AB = above-ground biomass
BB = below-ground biomass
DW = deadwood
LI = litter
SO = soils
HWP = harvested wood products

a)

EQUATION 2.4
ANNUAL CARBON STOCK CHANGE IN A GIVEN POOL AS A FUNCTION OF GAINS AND LOSSES (GAIN-LOSS METHOD)

$$\Delta C = \Delta C_G - \Delta C_L$$

Where:

ΔC = annual carbon stock change in the pool, tonnes C yr^{-1}
ΔC_G = annual gain of carbon, tonnes C yr^{-1}
ΔC_L = annual loss of carbon, tonnes C yr^{-1}

b)

Equations extracted from IPCC (2019).

Appendix 2: Land cover classes and data sources and descriptions of reclassification

Land cover class	Data source and corresponding field name		Description
	Indigenous remnants	WC land cover	
Cultivated	-	Cultivated fields Cultivated orchards and vines	All cultivated areas
Forests	Southern Afrotemperate Forest	Indigenous forests	Combined coverage of Indigenous forests from both data layers.
Fynbos	Atlantis Sand Fynbos Boland Granite Fynbos Cape Flats Dune Strandveld - False Bay Cape Flats Dune Strandveld - West Coast Cape Flats Sand Fynbos Cape Winelands Shale Fynbos Elgin Shale Fynbos Hangklip Sand Fynbos Kogelberg Sandstone Fynbos Lourensford Alluvium Fynbos Peninsula Granite Fynbos - North Peninsula Granite Fynbos - South Peninsula Sandstone Fynbos Peninsula Shale Fynbos Peninsula Shale Renosterveld Swartland Alluvium Fynbos Swartland Granite Renosterveld Swartland Shale Renosterveld Swartland Silcrete Renosterveld Western Coastal Shale Band Vegetation		All natural indigenous vegetation types except Southern Afrotemperate Forest are combined under the heading of fynbos. These were extracted from the Indigenous vegetation remnants and merged with the Western Cape Land cover layer. This classification assumes that all fynbos vegetation types have similar biomass properties.
Natural and other open spaces	- Beach		All natural areas in the WC land cover
Plantation	-	Plantation	These include legacy plantations on the slopes of Table Mountain. While no longer actively harvested for timber, they provide recreational activities to the public.
Sport fields	-	Sports fields and schools	All schools and sports fields
Urban		All urban classes	All residential, urban classes and man-made features were combined into one class.
Water and Wetlands	Cape Lowland Freshwater Wetlands Freshwater Lake Cape Estuarine Salt Marshes	Water and wetland features	All wetland and water features were combined into one class

Appendix 3: BioNet Classes

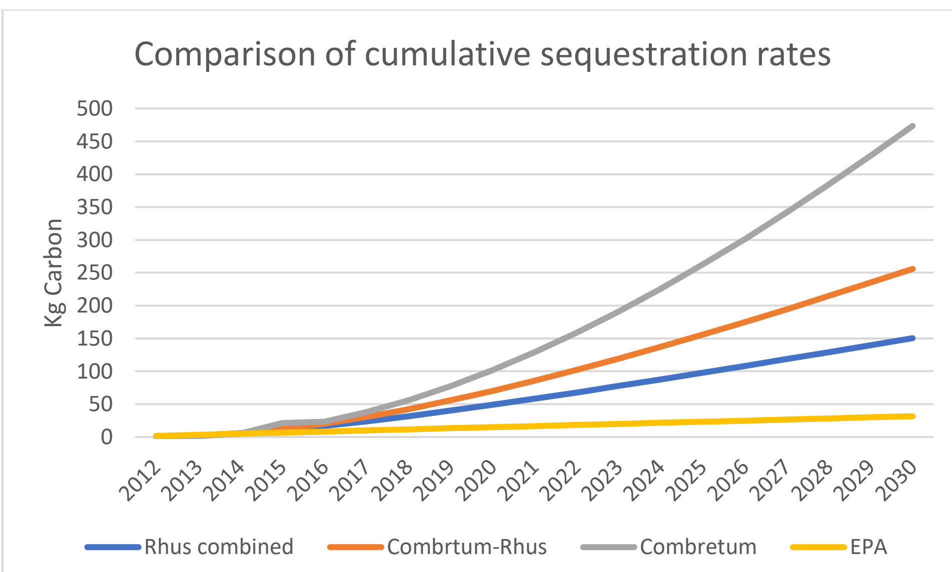
Appendix 4: Tree species: list of fast growing and medium and large trees (City of Cape Town 2020)

Fast growing Large size (7m+)		Fast growing medium size (3-5m)	
Species name	Drought Tolerance	Species name	Drought Tolerance
Ficus natalensis	High	*Brachylaena discolor*	High
Ficus rubignosa	High	*Buddleja saligna*	High
Kiggelaria africana	Medium/High	*Searsia chirindensis*	Medium
*Quercus nigra**	Medium	*Searsia lancea*	High
Rauvolfia caffra	Medium	*Searsia pendulina*	Medium/High
Vachellia karroo	High	*Tarchonanthus camphoratus*	High
Vachellia xanthophloea	Medium/High	*Syzygium guineense*	Medium/High
		Virgilia oroboides	Medium
		Washingtonia robusta	Medium/High

**alien $ top fifteen list of the nursery.*

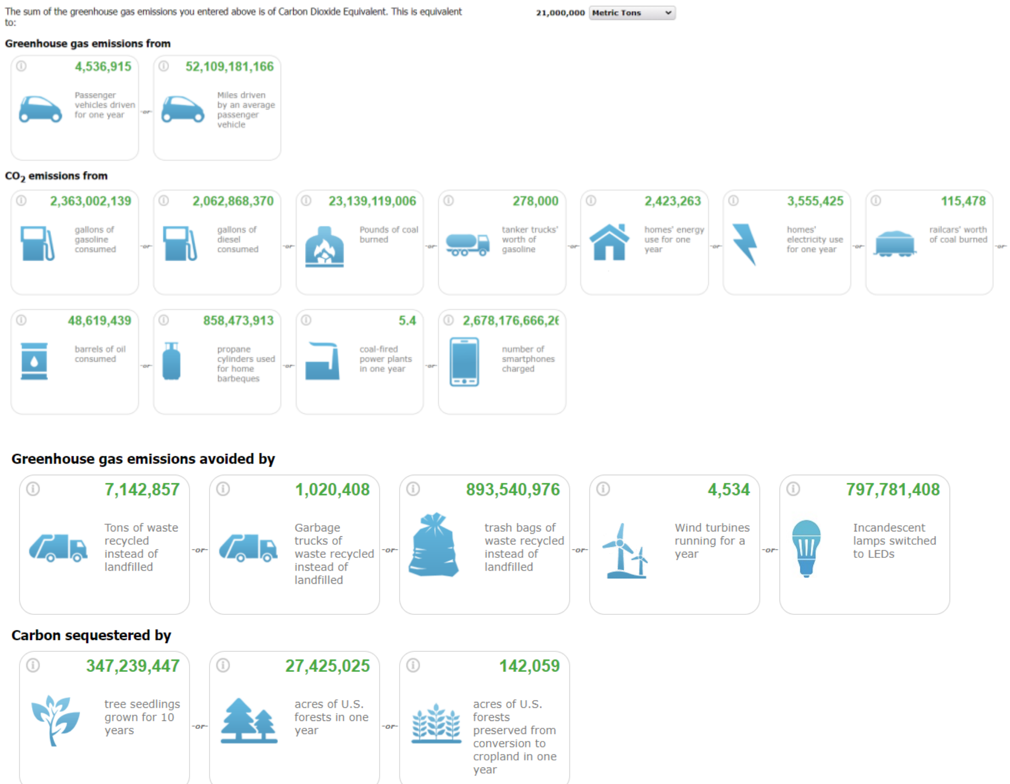
Appendix 5: Comparison of cumulative carbon sequestration rates

The figure illustrates the allometric functions used in the City of Tshwane (Stoffberg 2006). These functions have been calibrated for savanna tree species which may grow faster than trees in Cape Town. The use of the generic sequestration rates may underestimate the potential for new trees.



Appendix 6: Greenhouse gas equivalencies calculator:

https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator



Benefits of habitat restoration