The carbon sequestration potential of *Commidendrum robustum* Roxb. (DC.) within the Millennium Forest restoration site, St Helena Island.

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Abstract

The drastic increase in anthropogenic greenhouse gas emissions (GHGs) (particularly carbon dioxide CO_2) into the atmosphere is causing climate change around the world. Tropical forests are considered to be significant sinks of carbon, but are subject to widespread degradation and deforestation. Restoring and conserving tropical forests as a form of climate change mitigation, through the creation of off-setting schemes, can increase rates of carbon sequestration.

Islands are particularly vulnerable to climate change, though they contribute relatively little to the world's GHG emissions. St Helena Island, a UK Territory with a high rate of endemism in the South Atlantic Ocean, produces an estimated 11,000 tonnes of CO_2 annually. St Helena's native forests were decimated following the island's discovery in 1502 and only fragments remain. A restoration project, 'the Millennium Forest', restoring endemic *Commidendrum robustum* Roxb. (DC.) woodland to the degraded Crown Wastes area is managed by the St Helena National Trust (SHNT). SHNT hope to use the site as the basis for a carbon off-setting scheme to mitigate CO_2 emissions from the island's new airport (expected to open in early 2016).

This study found that *C. robustum* biomass and its associated carbon pools increased carbon stocks within the Crown Wastes area by approximately 52.5 ± 12.20 tonnes over 15 years. pH was found to be highly correlated with the carbon estimates. Estimated carbon stocks within five terrestrial carbon pools within the Millennium Forest restoration site were: aboveground live carbon 52.15 ± 12.25 tonnes; litter carbon 4.9 ± 2.45 kg carbon; deadwood carbon 397.95 ± 42 kg; belowground carbon 37.8 ± 2.1 kg; and soil organic carbon 297.5 ± 23.1 tonnes. These results and the level of monitoring, reporting and verifying required by international carbon off-setting schemes make a locally established- and run- scheme more financially viable for the island.

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Author’s declaration

I, Shayla J M Ellick, declare that this thesis is a result of my own research and has not been previously submitted to the University of York or any other institution for examination. Sources of information other than my own have been acknowledged within the text and in the reference list provided.

1.0 Background

1.1 Anthropogenic global warming and climate change

The onset of the Industrial Revolution and the subsequent human population and economic growth has led to the dramatic increase of emissions of key greenhouse gases (GHGs) (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)) into the atmosphere. Global emissions since the late 18th Century have driven atmospheric concentrations of GHGs to unprecedented levels for at least 800,000 years, in a relatively short timeframe [fig. 1] (IPCC, 2014). Recent GHG emissions originate from a wide range of anthropogenic activities including the use of fossil fuels in industrial processes, vehicular emissions and land use change including global deforestation, and habitat degradation (IPCC, 2014).

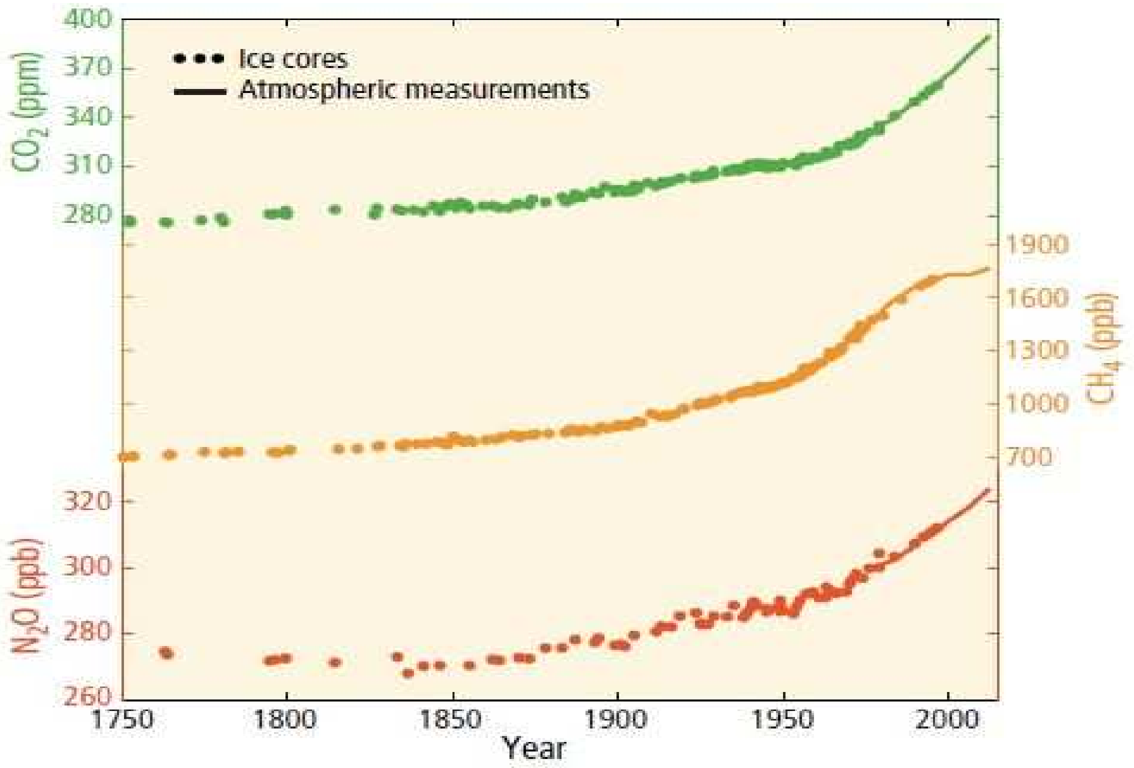

Fig. 1. Global key GHG emissions since the start of the Industrial Revolution. © IPCC, 2014

The considerable increase in GHGs due to human activities over the past few centuries has resulted in positive radiative forcing within the earth's atmosphere (IPCC, 2013); the outcome of this is a phenomenon known as global warming (GW) (IPCC, 2014). There is a wealth of evidence to demonstrate the negative effects of GW including: a warming trend in global land and ocean surface temperatures since 1880; ocean acidification due to increased CO_2 uptake; a global mean sea level rise; and the shrinking of the majority of glaciers worldwide (IPCC, 2014). Arguably the most significant and worrying effect of GW is climate change. Failure to reduce GHG emission levels in order to reduce the effects of GW will result in devastating global climate change in the future; there is already significant evidence that climate change has had global impacts in recent decades, such as changes in precipitation; changes in terrestrial, freshwater and marine species phenology; negative effects on crop yields; and extreme weather events (IPCC, 2014). Climate change is also a major driver of contemporary species and biodiversity loss, which is currently occurring at rates significantly higher than those detailed in fossils records. This will negatively impact ecosystem processes and services at both global and local levels, for example projected reductions in net primary productivity (NPP) and biomass (Hooper et al., 2012).

Predictions of the future effects of climate change include a projected increase in global land and ocean temperatures; a significant increase in sea level in certain regions, particularly vulnerable coastlines; an increase in the frequency of extreme weather events; adverse impacts to human health and livelihoods due to extreme weather events; negative impacts on food and water security; and catastrophic ecosystem and biodiversity losses, and associated functions (IPCC, 2014). Without a major reduction in the emission of GHGs, and thus a reduction in the rate of GW, some of these impacts are highly likely to be irreversible (IPCC, 2014).

Although CH_4 and N_2O are much more powerful GHGs, the IPCC considers CO_2 to have made the dominant contribution to radiative forcing since 1750 (IPCC, 2013; IPCC, 2014). Therefore, the majority of the research into reducing the effects of climate change, particularly on ecosystems and biodiversity, tends to focus on CO_2.

1.1.1 Forest ecosystems and carbon

Global forests function as both sinks and sources of GHGs, particularly CO_2 (Lindner and Karjalainen, 2007). Tropical forests account for approximately 17 - 25% of carbon stocks within the global biosphere (Bonan, 2008; IPCC, 2000), with a recent study estimating the aboveground carbon stock in tropical forests to be 228.7 petagrams (Pg) of carbon (Baccini et al., 2012). The majority of tropical forest carbon though, is contained in soils (Baccini et al., 2012; IPCC, 2000). Thus, tropical forests can be important carbon sinks, but they are also subject to widespread deforestation and degradation, and are vulnerable to the warming impacts of climate change, which can result in them becoming sources of GHGs due to CO_2 being released to the atmosphere (Bonan, 2008; Brown, 2002; Ebeling and Yasué, 2008; Harris et al., 2012). Tropical deforestation and the resulting CO_2 emissions are a growing concern; a study by Harris et al. (2012) estimated emissions of 0.81 Pg of carbon per year (between 2000 – 2005) from tropical forests due to deforestation. Thus restoring and conserving tropical forests has great potential to significantly reduce annual global CO_2 emissions (Ebeling and Yasué, 2008). Consequently, in recent years there has been an increase in interest and research in the carbon sequestration potential of tropical forests (Chave et al., 2005; Ebeling & Yasué, 2008; Usuga et al., 2010).

1.1.2 Climate change and islands

Islands make up approximately only 5% of the global land surface area, but hold an incredible amount of the earth's biodiversity, for example approximately 25% of all endemic vascular plant species (Caujapé-Castells et al., 2010). Their unique and sensitive ecosystems have developed from sustained evolutionary isolation, and are characterised by small populations and ranges; yet, anthropogenic pressure has, and will continue to heavily affect islands (Caujapé-Castells et al., 2010; Harter et al., 2015). Though they produce a relatively small amount of greenhouse gases (Brown, 2008), climate change is expected to inflict severe impacts on islands, and is considered to be one of the main drivers of island biodiversity decline, along with habitat change, invasive alien species, over-exploitation and pollution (Brown, 2008; Caujapé-Castells et al., 2010). Changing temperatures and shifts in climatic conditions will lead to changes in species ranges, both in latitude and altitude – a state that most island ecosystems will not be able to adapt to, thus leading to more extinctions (Brown, 2008; Caujapé-Castells et al., 2010; Harter et al., 2015; Walther et al., 2002).

1.2 St Helena Island

St Helena Island, a tiny UK Overseas Territory in the South Atlantic Ocean (15^{o}56’S, 5^{o}42’W) is one of the most isolated inhabited places on earth [fig. 2]. Measuring 121.7km^{2} in area, the island is located 1300km from the nearest land mass- Ascension Island to the north- and 1800km from the nearest continental landmass –Angola to the east (Ashmole and Ashmole, 2000; Lambdon, 2012; Smith, 1997). The island was discovered in 1502 by the Portuguese and settled in 1659 by the English East India Company (Ashmole and Ashmole, 2000). Today the island’s native population, a melting pot of different cultural influences, numbers approximately 4,170 people descended from English soldiers, African slaves, Chinese and Indian labourers, with an overall resident population of 4,802 (St Helena Statistics Office, 2015).

St Helena is a volcanic island of physical extremes. The coast is almost entirely lined with over 300m high sea cliffs, except in areas where streams have eroded them down to sea level, creating steep-sided ravines [plate 1]. The terrain rises steadily from the coasts creating a mountainous topography, culminating in a Central crescent-shaped ridge at the centre of the island, and the highest point Diana’s Peak at 827m (Lambdon, 2012).

Although tropical in latitude, the island’s warm climate is tempered by the south-east trade winds, and the Benguella current, with annual temperatures seldom exceeding extremes of 14-32^{o}C, and annual rainfall of 175mm in the coastal areas and 1050mm over the Central Peaks (Cronk, 2000; Lambdon, 2012; DFID, 2012). The local climate is modified by altitude, with the majority of the rainfall occurring over the higher ground and the result is a markedly lusher, green interior, with the drier, barren areas around the coasts - known as the Crown Wastes - a harsher, brown landscape (Cronk, 2000; Lambdon, 2012).

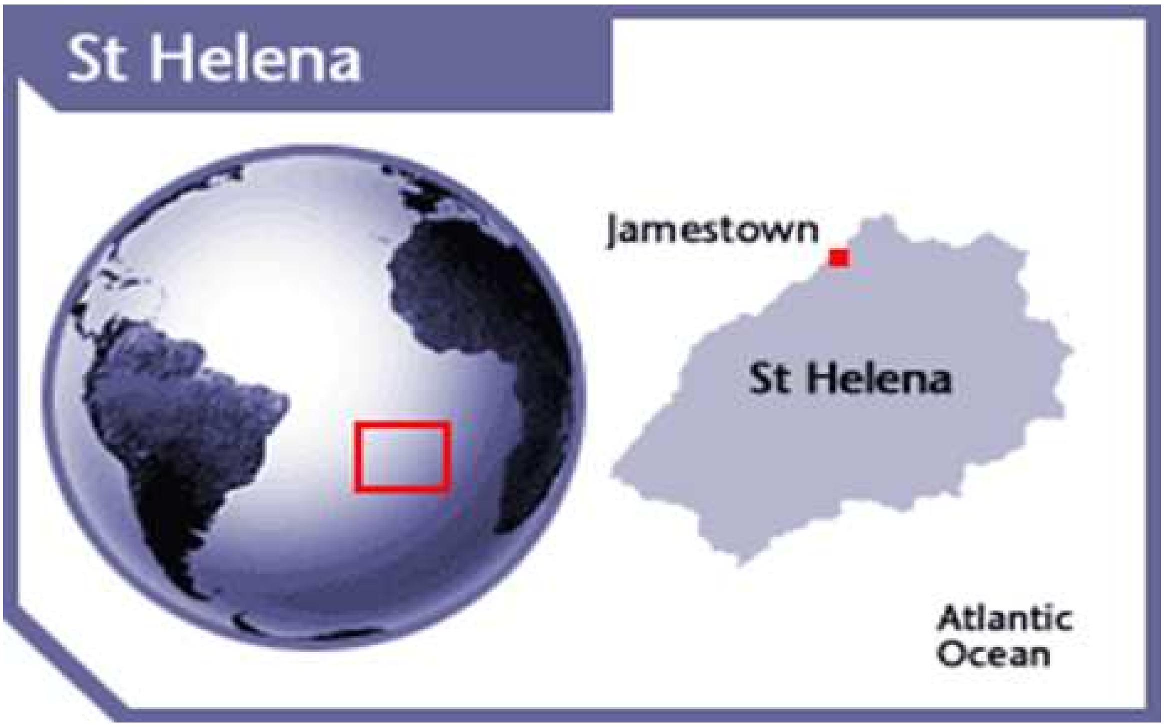

Fig. 2. Location of St Helena Island in a world context. © Foreign and Commonwealth Office, 2011

Plate 1. An aerial view of the island displaying the mountainous terrain. Part of the capital, Jamestown can be seen in the lower left-hand corner. © Marc Lavaud, 2007

1.2.1 Past and present vegetation

Although there are no accurate records of the island's flora when it was first discovered, some accounts tell of a lush, plentiful island; however, the vegetation today has been heavily influenced by human interference (Cronk, 1989; Smith, 1997). The introduction of livestock (goats, pigs and cattle) for fresh meat by sailors using the island as a mid-Atlantic stopover led to extensive overgrazing of the native forests; historical accounts tell of flocks of goats over a mile long (Lambdon, 2012). Exploitation of the abundant forests, particularly after settlement, for timber and fuel also led to widespread deforestation (Cronk, 1989; Lambdon, 2012). These activities resulted in devastating soil erosion across the island, with the loss of an estimated $20km^3$ of humic clay topsoil over the centuries, particularly from the Crown Wastes; most plants are unable to colonise the subsequent poor soils (Ashmole and Ashmole, 2000). There is an account by Governor Janisch from 1885 (as cited in Cronk, 1989, p.58) which tells of the appearance of the sea around the island resembling black mud after a catastrophic rainfall event, as large quantities of topsoil were swept away following a freak thunderstorm. In the present day, after particularly heavy rainfall, there is still a noticeable sediment load washed into the ocean from the mouths of the ravines.

The island has a high rate of endemism, with 45 endemic flora species (Lambdon, 2012), 456 endemic invertebrate species (Pryce, 2015), 23 endemic bryophytes (Wigginton, 2015) and one remaining endemic bird found on the island (Ashmole and Ashmole, 2000). Several species have become extinct since the island's discovery and it is likely that some species endemic to the island passed into extinction long before accurate records of the island's natural history were made (Cronk, 1989; Lambdon, 2012; DFID, 2012). However, it is also extremely likely that with more targeted research, particularly on the bryophytes and invertebrates, more endemic species could be discovered (Gray, 2015).

There must have once been extensive endemic dominated plant communities across the island; however, the widespread overgrazing and deforestation, the land clearance for cultivation and pastureland, and the later mass introduction of exotic species, has resulted today in relict populations of native vegetation restricted to tiny fragments around the island (Cronk, 1989; Lambdon, 2012). These fragments are concentrated in endemic cloud forest along the Central Ridge and also in dryland species particularly along the cliffs, where they were previously inaccessible to both human and grazing pressure (Cronk, 1989; Lambdon, 2012). The remaining vegetation is dominated by non-native species, with 82-88% of the total island species list having been introduced by humans (Lambdon, 2012). A recent 2013 – 2014 census of all endemic and several native flowering plants and ferns revealed that endemic species cover approximately 13% of the island land mass. However, removing the three most widespread endemic species from this figure results in a drop to just 1.3% of the island land mass i.e. 42 endemic taxa are reliant on only 1.6km^2 of fragmented habitat. Provisional assessments using IUCN Red List methodology suggest that 22 endemic plant species fall under the Critically Endangered category - the highest threat category (Lambdon and Ellick, 2014).

1.2.2 Transport links and economy

The Royal Mail Ship (RMS) St Helena [plate 2], a passenger and cargo ship and one of only two RMS's left in operation, is currently the island's only regular transportation link to the outside world (Ashmole and Ashmole, 2000). The ship calls at St Helena, Ascension Island and Cape Town with travel taking five nights to Cape Town and up to three to Ascension Island from St Helena (Andrew Weir Ship Management Ltd., 2015).

Plate 2. Jamestown, the capital of the island, located within a steep valley, with the RMS St Helena anchored in the harbour. © Marc Lavaud, 2007.

St Helena's economy is largely dependent on UK aid with 61% of the St Helena Government's £32.1 million 2015/16 recurrent budget funded by the Department for International Development (DFID) (SHG, 2015a); tourism, fisheries and agriculture also generate some income. The island has seen high levels of outward migration, 'brain drain' and economic decline (DFID, 2012), with the annual median salary coming to just £6,670 (St Helena Statistics Office, 2014). In 2011, after many years of political delays, the UK government announced that it would provide up to £246.6 million for the construction and limited operation of an airport on St Helena (DFID, 2012; SHG, 2015b). The airport is currently under construction and due to be completed in February 2016, with the phasing out of the RMS St Helena later that year (SHG, 2015c). It is hoped that the provision of air access and the island's increased connectivity to the outside world will reverse the trend of outward migration, and help stimulate economic growth and financial stability so that the island is no longer reliant on British aid (DFID, 2012; SHG, 2015b).

1.2.3 Contribution to GHG emissions and mitigation efforts

Relative to global emission levels, St Helena is thought to contribute negligible amounts of GHGs to the atmosphere, with an estimated production of 11,000 metric tonnes of CO_2 in 2008 (UN Statistics Division, 2012 cited in DFID, 2012, pg.8). It was estimated that air access would contribute to less CO_2 emissions than continuing with sea access, at least in the early years of operation; estimations (based on 70 flights per year from Cape Town on a B737-700W aircraft) suggest emissions of 30.7 tonnes of CO_2 per trip, which equate to approximately 0.31 tonnes of CO_2 emitted per passenger (AECOM Ltd., 2011). Updated projections of emissions are needed; however, regardless of the low numbers estimated, the island is still vulnerable to climate change, specifically natural resources such as biodiversity and ecosystems; economic resources such as tourism, fisheries, forestry and energy supply; and local livelihoods (DFID, 2012). Thus, mainstreaming of climate change adaptation and mitigation into national policies should be encouraged (Brown, 2008).

St Helena currently obtains 22% of its energy needs from renewables in the form of wind power and a small percentage of solar power; the remainder is provided by diesel generators. However, a new solar farm is currently under construction and will increase the amount of renewable energy provision on the island to approximately 30% upon operation (Connect St Helena Ltd., 2015; SHG, 2015d). Household solar water heaters are also commonly used on the island, in addition to solar powered street lighting (DFID, 2012).

A climate change policy is currently being developed by the St Helena Government's Environmental Management Division. There have also been some initial discussions between island stakeholders towards the establishment of a 'green tax' to fund conservation activities on the island in particular, and more recently these have been extended to include climate change adaptation and mitigation activities; although thus far this concept has yet to move beyond the discussion stage (Peters and Sansom, 2015). Some form of 'green tax' though, could have great potential for funding carbon mitigation programmes on St Helena; a similar concept has been proposed in the Virgin Islands, where up to $15.6 million annually could be raised through levies on tourists and foreign companies to fund the implementation of their climate change policy (Penn, 2011).

1.3 Global climate change mitigation

Increased awareness of the threats posed by climate change has yielded more consideration of, and research into, practical applications of adaptation and mitigation activities at both national and global levels, in order to combat these threats. While adaptation focuses on adjusting to the effects of climate change, mitigation aims to reduce the amount of GHGs being emitted in order to reduce the effects of climate change in the future (IPCC, 2014). Mitigation activities can include supporting the use of fossil fuel alternatives such as renewable energies for example, wind power, solar power, tidal power, and the use of biofuels. New technologies also focus on capturing CO_2 from the atmosphere and storing it underground. Additionally, efforts have also been centred on global forests in recent years; through afforestation, and reducing deforestation and degradation. However, even with more emphasis placed on climate change mitigation, anthropogenic GHG emissions continue to rise (IPCC, 2014).

Climate change mitigation activities can also provide a wealth of varied co-benefits in addition to reducing GHG emissions, such as a reduction in local air pollution and consequent benefits to human health, the development of cheaper energy sources through renewable energies, and improved productivity and quality of life (Jochem and Madlener, 2003). Perhaps the most valuable co-benefit of climate change mitigation activities for this study is the gain in ecosystem services and biodiversity through landscape-scale restoration and conservation projects (Galatowitsch, 2009; Gillroy et al., 2014).

1.3.1 Carbon off-setting

In recent years, the concept of carbon off-setting in order to mitigate the effects of climate change has emerged. Initially, this occurred at a grass-roots level, through the planting of trees by individuals and organisations concerned by their GHG emissions (Grace, 2004). The Kyoto Protocol then provided a framework for national-level off-setting mechanisms, such as the Clean Development Mechanism (CDM); the Kyoto Protocol allowed developed countries the opportunity to off-set their GHG emissions by purchasing carbon credits (equivalent to one tonne of carbon) from less developed countries (Grace, 2004; SEI and GHG Management Institute, 2011a; SEI and GHG Management Institute, 2011b). There are two markets for carbon credits: the compliance market and the voluntary market; projects wishing to enter the markets as a provider of carbon credits must pay a fee to join a program or standard. The compliance market for which standards and programs such as CDM require stricter monitoring and reporting; and the voluntary market for which offsetting programs such as Gold Standard and Verified Carbon Standards allow more flexibility for businesses or individuals wishing to offset their carbon emissions (SEI and GHG Management Institute, 2011a; SEI and GHG Management Institute, 2011b). Both markets, however, require accurate accounting of carbon stocks, and some form of monitoring, reporting, and verifying these; thus, in order for developing countries to access these markets a consistent process of measuring, reporting and verifying actual quantities of, and reductions in, CO_2 is needed (Gupta et al., 2012; Wertz-Kanounnikoff et al., 2008).

Each established standard or offsetting program within a carbon market will have its own preferred scope, for example, Gold Standard focuses on renewable energy and energy efficiency projects, while Verified Carbon Standard projects focus on GHG emissions reductions; each of these will also have an established methodology (SEI and GHG Management Institute, 2011a). There are several methodologies available for measuring carbon in tropical forests, which have varying levels of complexity; for example, the IPCC provides a Tiered system, where the higher Tiers generally use more accurate techniques – such as high-resolution remote sensing and intensive ground-truthing - which reduce uncertainty in the carbon estimates (Morris and Riddle, 2011; Wertz-Kanounnikoff et al., 2008). In more developed countries there is greater access to high quality data for quantifying carbon stocks, including frequently updated forest inventories and high-resolution remote sensing imagery; whilst in less developed countries these options are less accessible due to low resources. Thus, in recent years a great deal of research has been carried out in tropical forests in order to establish reliable standards to monitor, report, and verify both carbon stocks and reductions, in order to authenticate evidence of a reduction in CO_2 emissions resulting from the country's off-setting activities.

Co-benefits of carbon off-setting schemes include mitigation of GHG emissions through tropical forest conservation, reforestation and protection; alternative livelihoods for local people; and sustainable development of developing countries (Grace, 2004; Ebeling & Yasué, 2008; Petrokofsky et al., 2012, Willcock et al., 2012). Carbon offsetting schemes can facilitate economic and social development in less developed countries, by providing areas with little resources the opportunity to generate carbon finance, while also helping to reduce loss of biodiversity to deforestation and land use change (Marshall et al., 2012).

The conception of programmes such as the United Nations Framework Convention on Climate Change (UNFCCC) Reducing Emissions from Deforestation and Forest Degradation (REDD+) scheme, provide potential for less developed countries with little resources to create new income streams through carbon finance (Ebeling & Yasué, 2008).

1.3.2 St Helena and carbon off-setting

Although there are no carbon off-setting schemes currently operating on St Helena, the potential advantages of setting up a scheme are significant. As discussed previously, the island's soils and native flora have been subjected to centuries of degradation and the co-benefits of carbon off-setting could help to counteract this. A carbon off-setting scheme would have substantial benefits for the island such as a new income stream for landscape-scale restoration and conservation projects on the island, which would help to halt and reverse habitat degradation and fragmentation, lessen biodiversity losses and the spread of invasive species, and reduce changes to ecosystem processes.

A recent Darwin Initiative funded project (‘Creating Community Forests to Enhance Biodiversity and Provide Educational Activities’ (Project: 20005) (http://www.nationaltrust.org.sh/shnt-conservation-programmes/natural-heritage/community-forests-project/)) awarded to the St Helena National Trust (SHNT) in 2013, aspires to set up a carbon off-setting scheme for the island in preparation for the opening of the airport, using endemic species that are planted throughout three Community Forest sites (Darwin Initiative, 2015; SHNT, 2015a).

The timing of the fieldwork for this study meant that only one of the Community Forest sites, the Millennium Forest, was suitable for sampling at this time. It is expected that the Millennium Forest, which is presently a restoration site managed by the SHNT, can become financially and ecologically sustainable through contributions from the local community and tourists wishing to offset their carbon emissions by paying for the planting of trees within the Community Forest sites. Currently, the Forest is dependent on grant funding and contributions from awareness-raising.

1.4 Terrestrial carbon pools

Typically, in comprehensive assessments of forest carbon stocks there are five major terrestrial carbon pools that are generally measured: (1) aboveground live biomass, which is the most easily measurable and consists of all woody stems, branches and leaves; (2) litter, which comprises all fallen litter up to a certain size threshold; (3) deadwood, which includes all standing and fallen coarse woody debris above a certain size threshold; (4) belowground biomass, which consists of living and dead roots; soil carbon (roots living and dead); and (5) soil carbon. Generally, in national assessments of forest carbon stock, large stratified networks of permanent sampling plots are set up and trees within the plot are tagged with a unique number (Brown, 2002). Plots can range in size depending on the precision required; however, most studies typically establish plots of $1ha^2$, subdivided into $20m^2$ sub-plots for ease of fieldwork. Transects can also be used over large areas, with measurements being taken at selected intervals (Brown, 2002).

1.4.1 Aboveground live biomass (AGB)

Aboveground live biomass (AGB) is a major carbon pool in tropical forests, and being by far the most accessible, it is the most studied; forest degradation and deforestation directly impacts this pool (Gibbs et al., 2007; Pfeifer et al., 2013). There are several established methods for the assessment of AGB: the non-destructive methods which typically use forest inventory data, either gathered from remote sensing or through direct field measurements, or destructive methods which involve careful measurement of trees that have been cut down (Brown, 2002; Gibbs., et al 2007; Qureshi et al., 2012). Remote sensing options, such as Lidar and satellite imagery, can be expensive and depend on good weather conditions for cloud-free images. Ground truthing is also required to calibrate and verify results (Asner et al., 2010; Marshall et al., 2012; Wertz-Kanounnikoff et al., 2008). Forest inventory data or field measurements, importantly diameter at breast height (DBH) and height (Brown, 2002; Chave et al., 2005), can be converted to estimations of aboveground live biomass through the use of biomass expansion factors or allometric regression equations (Brown, 2002). Several global allometric equations have been developed e.g. Chave et al.'s (2005; 2014) equations using detailed data from numerous studies, however, it is always desirable to develop national/site-specific equations where possible to do so (Wertz-Kanounnikoff et al., 2008).

DBH is a standard measurement taken at 1.3m (Chave et al., 2014) and recorded for all trees, usually over 10cm in diameter; each tree over 10cm diameter is then tagged, in order to track changes in carbon stock over time (Brown, 2002; Gray, 2014). It is often assumed that trees under 10cm in diameter contribute minimal amounts to the total forest biomass, though this can depend on the successional phase of the trees. Thus trees smaller than 10cm in diameter are not usually measured; 5cm, though, is typically the lowest threshold used (Brown, 2002; Chave et al., 2014).

Height data is not always used in the estimation of AGB, because there is generally a lack of data; however, many studies show that, when available, the use of height data within the allometric equations can help to improve the precision of the estimated biomass (Brown, 2002; Marshall et al., 2012; Chave et al., 2014; Feldpausch et al., 2012). Carbon content is then estimated from this figure using a conversion factor of 0.5; generally in carbon assessment carbon content is assumed to be 50% of biomass (Brown, 2002). However, in actuality carbon content of trees can vary among species and according to various factors, such as age and environmental stressors (Lamlom and Savidge, 2003), therefore, this assumption should be tested where possible in individual studies.

Wood specific gravity (WSG) is also an important predictor in allometric equations estimating AGB as including this variable reduces error in estimating the tree biomass. Where species level WSG is not available, most studies use a genus or family level average (Chave et al., 2005; Marshall et al., 2012); Chave et al. (2014), found that although using a WSG average sometimes introduced random errors, the analyses were not biased by these values. Where species-specific WSG is not available, WSG can be calculated by obtaining pith to bark cores from multiple trees per sample plot with a sharp increment borer (Chave et al., 2006; Muller-Landau, 2004). The range of these cores is important as wood density can be up to 20% higher in the inner wood than the outer (Chave et al., 2006). Basic WSG is calculated as:

Oven dry mass (g) / green volume (cm^3) / density of water (1.000 g cm^{-3}) (Williamson and Wiemann, 2010).

Ideally, when estimating AGB, a small sample of trees would also be destructively sampled to verify the accuracy of the equations used to convert the field measurements to biomass (Brown, 2002; Gibbs et al., 2007; Qureshi et al., 2012). However, destructive sampling is very expensive, time-consuming and damaging to the overall forest health (Gibbs et al., 2007; Qureshi et al., 2012).

1.4.2 Litter

Fine litter biomass typically contributes to a small portion of the total carbon pool in forests (Brown, 2002) as only a fraction of the carbon within litter is decomposed and incorporated into the forest soils; much of it is instead released into the atmosphere as CO_2 (Raich and Nadelhoffer, 1989). It is because of this that leaf and woody litter is overlooked when estimating carbon storage within forests (Brown, 2002).

Methods for estimating carbon in litter biomass include the use of fine litter fall traps, which evaluate litter accumulation through the use of litter traps. These are square frames resting on four legs that are 1m high with a mesh bag resting on top of the frame. The litter traps are placed in suitable areas (ideally wind-free) and checked every fortnight to reduce decomposition within the traps. All material including woody debris less than 2cm in diameter are collected, dried and weighed (Gray, 2014). Quadrats can also be a useful way of measuring fallen litter stock; for example, a random 0.5m^2 quadrat can be taken from each sub-plot and all the organic litter including woody debris under 2cm in diameter collected, dried and weighed. Ideally, quadrat sampling would be repeated seasonally (Gray, 2014).

Additionally, Gibbs et al. (2007) conducted extensive literature reviews and established a predictive relationship which estimates litter carbon stocks to be ~10-20% in mature forests; in studies where it is challenging to undertake intensive fieldwork, this predictive value could be used to estimate litter carbon stocks in forests.

1.4.3 Deadwood

Deadwood or coarse woody debris, like litter, tends to be under-researched in forest carbon estimation projects, despite making up a significant amount of aboveground biomass. It includes all dead woody material typically over 10cm in diameter and can include standing deadwood or fallen debris; usually separated into two classes: fine or coarse deadwood (Brown, 2002; Baker and Chao, 2011).

Based on extensive literature reviews, Gibbs et al. (2007) suggest that deadwood can be assumed to be approximately 10-20% of the total aboveground carbon biomass in mature forests, which can be used when field measurements cannot be carried out.

Field measurements of deadwood are the most common methods of measuring this carbon store. There are several methods to deadwood sampling; a conventional method is the use of line transects, which provides rapid estimates of landscape-level deadwood stock (Gray, 2014; Baker and Chao, 2011). All pieces of deadwood above a certain threshold are measured and the category of decomposition is recorded [table 1]. Density of decomposition classes is site-specific but in some situations can be related to wood density in living biomass, thus, these values can be used to calculate total deadwood biomass (Baker and Chao, 2011). Alternatively, several smaller pieces from each decomposition class should be collected and the green volume and dry weight determined, in order to calculate density for each decomposition class. Deadwood biomass can then be calculated using the deadwood measurements collected in the field and the calculated density (Gray, 2014).

Table 1. Classes of deadwood decomposition and their characteristics (Baker and Chao, 2011).

Decomposition class	Characteristics
1	Solid wood, recently fallen, with intact bark and fine branches still attached.
1.5	Solid wood, but with no fine branches, and bark starting to fall off.
2	Non-solid wood, in poorer condition, but where it is still difficult to push a nail into the wood by hand.
2.5	Soft, rotten wood, where a nail can be pushed into the wood easily.
3	Soft, rotten wood, which collapses easily when stepped on.

Standing deadwood (dead trees) should also be measured (DBH & height), where the diameter is above a specified threshold- usually 10cm. The density for the decomposition class should be used in the calculation of biomass of standing deadwood (Baker and Chao, 2011).

1.4.4 Belowground biomass (BGB)

Belowground biomass or BGB is a major sequesterer of carbon in forests; it has been suggested that in many forests root production contributes up to 50% of annual carbon cycling (Vogt et al., 1998), and up to 33% of global annual NPP occurs in fine root production (Madji et al., 2005). Thus, it is important that belowground biomass is accurately estimated in any carbon estimation project. Roots, however, can be very difficult to measure and estimate biomass of, and though there is no agreed upon method for estimating belowground biomass, there is a range of methods available; however, some of these are often expensive and/or time-consuming, and are not always able to be utilised over large areas (Petrokofsky et al., 2012).

An estimation of root biomass can be calculated using root:shoot ratios, for which AGB and BGB needs to be known (Brown, 2002; Cairns et al., 1997). Sequential soil cores or pits can also be employed to excavate and analyse fine, medium, and coarse root biomass (Brown, 2002; Cairns et al,. 1997; Qureshi et al., 2012; Vogt et al., 1998). Generally, soil cores or pits are good for estimations of standing biomass.

In growth cores are a method used for measuring fine root growth and are relatively cheap and easy to construct (Madji et al., 2005). Essentially, an area of soil is removed from the ground and is carefully sampled for roots, the root-free soil or an equivalent amount of sand is then put back into the ground within a plastic mesh core, which has been constructed to a given diameter and height. After a period of several months, the core is re-sampled to ascertain root production over that period (Vogt et al., 1998; Gray, 2014).

The methods described above are destructive and have several limitations; for example, with soil cores it can be difficult to re-sample the same root section. These methods can also alter soil and nutrient structure and it can often be difficult to establish the mortality status of the root sampled and timescale of root re-growth (Madji et al., 2005; Vogt et al., 1998).

Rhizotrons can be used to observe in situ root growth and are not destructive; these are chambers made of transparent Perspex which are supported by a wooden or metal frame. The rhizotrons are inserted into the ground and checked over appropriate intervals of time and permanent markers are used to trace diameters of roots onto the perspex. The perspex sheets are then scanned and the root biomass analysed and estimated using specific software (Gray, 2014). Mini-rhizotrons are another non-destructive method which allows long-term measurement of the same roots. Transparent tubes are inserted into the ground and tiny cameras can be inserted into these to take photos of the roots at different depths over a period of time; the images are analysed by specific software (Vogt et al., 1998; Madji et al., 2005). However, this method also requires some destructive sampling in order to convert the image data to root biomass (Vogt et al., 1998).

Finally, where it is difficult to gain an estimate of root biomass using field methods, Gibbs et al. (2007) have carried out extensive literature reviews which suggest a predictive relationship for root biomass of approximately 20% of the amount of aboveground carbon forest stock.

1.4.5 Soil

Soils are an important component in forest carbon storage, and are considered to hold the majority of carbon stock in the terrestrial pool - even more than living biomass (Adolfo Campos, 2010; Post and Kwon, 1999; Usuga et al., 2010; Lal, 2004); the bulk of this is situated in forests, with an estimated 20% of the world's carbon stock being held in forest soils (Qureshi et al., 2012). Thus, large scale land use change such as deforestation could have major implications for this carbon store; projects to negate such changes and enhance soil carbon sequestration will be highly beneficial for the degraded soils (Lal, 2004). More consequence is placed on soil organic carbon (SOC) over inorganic carbon, as it is SOC which is not locked into the soil as carbonates and can be released as CO2 through respiration (Chapman, 2009).

Methods to estimate carbon content in soil include the use of soil cores or soil pits to obtain soil samples for carbon analysis. If possible, each layer of the soil should be sampled until the bedrock has been reached (Gray, 2014). Where the collection of soil samples is not feasible, existing inventory data and/or data obtained from the literature of other studies can be used to estimate carbon stock in soil (Willcock et al., 2012).

There are several documented methods for determining soil carbon from soil samples: the most common can be categorised as wet digestion and dry combustion (Adolfo Campos, 2010; Rodeghiero et al., 2010). Wet combustion, for example the Walkley-Black method established in

1934, is widely used; it uses chemicals to oxidise SOC during heating. This method is quick and easy to carry out, and does not require a lot of equipment, but has a major limitation in that it produces waste that contains strong acids and chromium (Adolfo Campos, 2010; Rodeghiero et al., 2010). Dry combustion methods use elemental analysers which oxidise the soil organic carbon using thermal combustion at high temperatures; this method is considered to be the most reliable and precise, but the main limitations with this method are the high cost and time-consuming maintenance of the analysing instruments (Adolfo Campos, 2010; Rodeghiero et al., 2010; Sutherland, 1998).

Loss on ignition (LOI) tests are considered to be a useful alternative to these methods, whereby dried soil samples are ignited at high temperatures, usually 360 – 600^{o}C and the weight lost is considered to be indicative of the soil organic matter (SOM) in the sample ((Adolfo Campos, 2010; Rodeghiero et al., 2010). SOC is considered to be approximately 58% of SOM (Chapman, 2009). LOI is an inexpensive method due to the relatively low cost of equipment used and is labour efficient as it allows the analysis of large sample sizes at the same time (Adolfo Campos, 2010; Rodeghiero et al., 2010; De Vos and Vandecasteele, 2005). However, there is some debate on using LOI to estimate SOM- which is thought to be over-estimated with this method; thus, some studies recommend either using LOI as an estimate of SOC rather than SOM, or using the Van Bremmerlen factor (1.724) to correct the over-estimation (Adolfo Campos, 2010; Rodeghiero et al., 2010; De Vos and Vandecasteele, 2005). Ideally, a few samples would also be sent for laboratory analysis using a precise method such as dry combustion, in order to verify the results of the LOI tests (Rodeghiero et al., 2010).

Bulk density (BD) should also be calculated for the samples taken, as it is an essential variable in converting estimates of SOC in the soil sample to an estimate of the sampling area (Gray, 2014).

2.0 Aims and objectives

The preliminary intention for any potential carbon off-setting scheme on St Helena was to access an international offsetting programme; however, recently the idea has been proposed to set up a local scheme backed by evidence-based research. Therefore, the main goal of this study is to investigate the quantity of carbon stocks in this under-researched restoration site. This can then provide the data necessary to inform any future offsetting scheme.

Aims:

- To investigate the carbon sequestration potential of the St Helena Gumwood, *Commidendrum robustum* (Roxb.) DC. at the Millennium Forest restoration site, St Helena
- To explore the success of the rehabilitation of Crown Waste land through ecological restoration of endemic *C. robustum*

Objectives:

- Gather baseline measurements of the five key terrestrial carbon pools: aboveground live biomass, litter, deadwood, belowground biomass, and soil within the Millennium Forest site in order to determine carbon content of each pool
- Collect basic soil nutrient data in order to establish whether these affect the carbon sequestration potential of the site
- Analyse the field measurements to estimate carbon content of each carbon pool and the relationship of the soil data to these
- Employ the results of the analyses to investigate the potential of an island carbon off-setting scheme
- Consider the potential of the Millennium Forest as a viable ecological restoration site

2.1 Hypotheses

The main priority of the study was to explore the effectiveness of *C. robustum* as a sequesterer of carbon at the Millennium Forest restoration site, thus, the main question asked by the study is:

1. Does the planting of *C. robustum* increase carbon stocks within the Crown Wastes?

A lesser priority of the study was to determine the influence of soil nutrients on the effectiveness of *C. robustum* to sequester carbon within the Millennium Forest restoration site, thus, the second question asked by the study is:

2. Is there a relationship between soil nutrient levels and the quantity of carbon stored within the restoration site?

3.0 Study species

The island’s habitats can be classified broadly into coastal fringe, ridges and deserts, scrub and woodland, and finally the cloud forest which, although fragmented, represents the last remaining truly native habitat on the island (Lambdon, 2012). Originally identified for study were five endemic species which encompass a range of the habitats, ecologies, and growth forms found on the island. They are species which all occur or are planted within the Community Forest sites and would have offered a broad range of options for any potential off-setting scheme. In addition to *C. robustum, Melanodendron integrifolium* D.C. (Black Cabbage) [plate 3] and *Lachanodes arborea* (Roxb.) B.Nord. (She Cabbage) [plate 4] which are both cloud forest species; and *Commidendrum rugosum* (Aiton) DC. (Scrubwood) [plate 5] and *Trochetiopsis ebenus* Cronk (Dwarf Ebony) [plate 6] which are dryland species occurring mainly along the coastal fringe, were selected for study. They are all well-known, iconic species on the island, and are used by the conservation community in habitat restoration work and seed orchard programmes.

Plate 3. *Melanodendron integrifolium* D.C. (Black Cabbage) tree within the Diana’s Peak area. © Shayla Ellick, 2014

Plate 4. *Lachanodes arborea (Roxb.) B.Nord. (She Cabbage)* within a government seed orchard. © Shayla Ellick,

Plate 5. Wild *Commidendrum rugosum* (Aiton) DC. (Scrubwood) at Man & Horse cliffs © Shayla Ellick, 2014

Plate 6: *Trochetiopsis ebenus* Cronk (Dwarf ebony) © David Stanley, 2014

However, a pilot study conducted from July to early September 2014 revealed that in order to make the data more robust and repeatable the number of species and sites to be studied had to be reduced, due to time limitations. The methodology developed for this project though, can be used in the future to research the carbon storage potential of other St Helena endemic tree species and sites. The species chosen for this study was the most iconic and well-known on the island, the island's national tree *Commidendrum robustum*, the St Helena Gumwood.

3.1 *Commidendrum robustum* (Roxb.) DC; the St Helena Gumwood

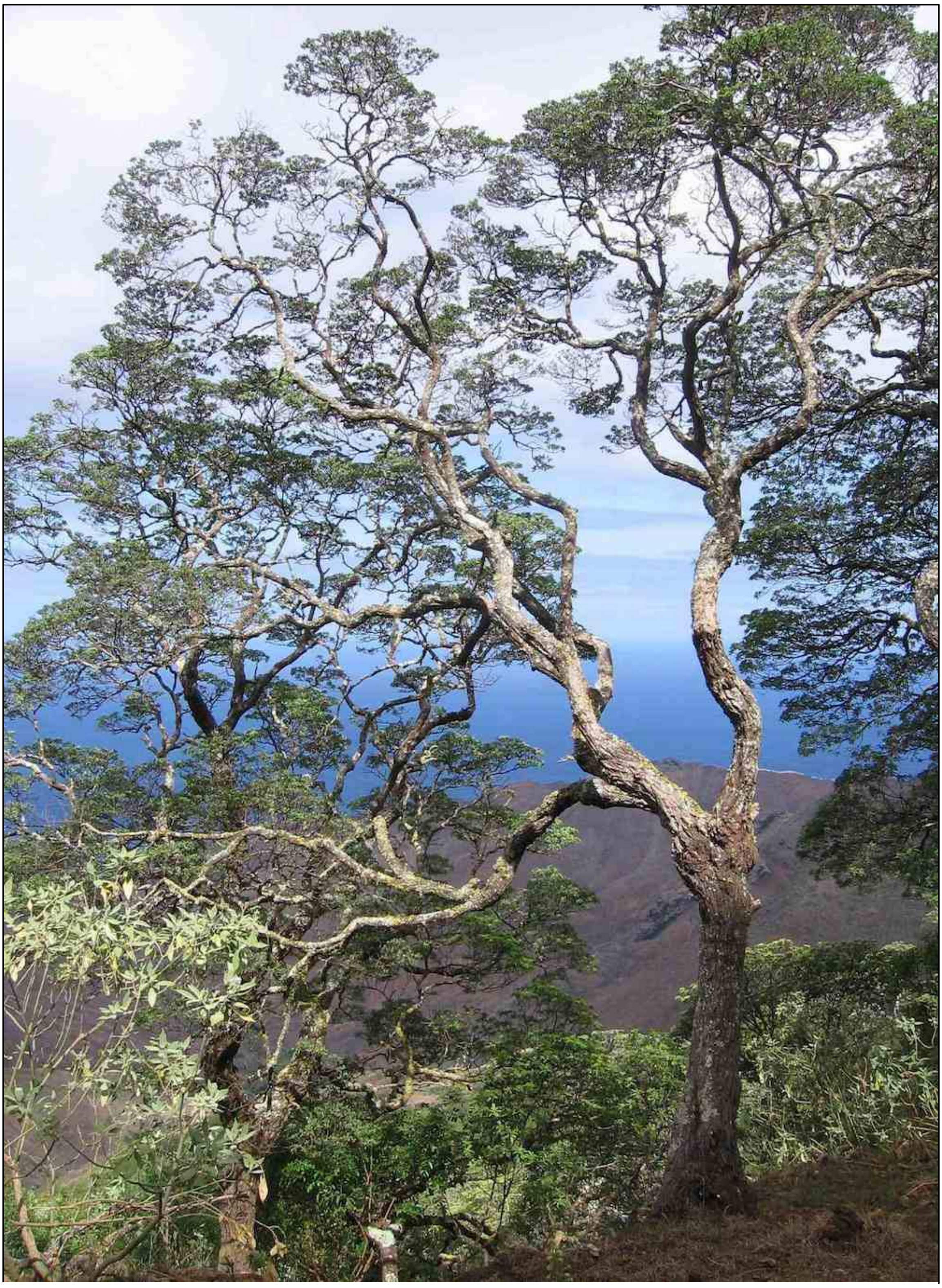

Plate 7. A mature *C. robustum* at Peak Dale © Jason Courtis, 2013

The St Helena gumwood is one of four endemic species within an endemic genus and is one of the more drought resistant *Commidendrum* (Cronk, 1986; Eastwood et al., 2004). It is a gnarled, relatively small tree, although it has been known to grow up to 9m in height (Lambdon, 2012). The species is very variable at different sites across the island, particularly in leaf shape and colour (Courtis, 2015), but typically form domed canopies as adults, with seedlings usually growing fast and straight and with much bigger leaves than the adults (Cronk, 1986; Cairns-Wicks, 2003). The bark is a dark brown and rugged, covered with lichens in older specimens [see mature specimen in plate 7]; the leaves are clustered in a short, terminal spiral (Lambdon, 2012). Flowering occurs occasionally throughout the year, but mainly in winter (Cronk, 1986); the species regenerates well when there is restricted grazing pressure (Cairns-Wicks, 2003; Eastwood et al., 2004).

Currently, the gumwood is limited to isolated relict wild populations within its believed mid-altitudinal range, where previously [fig. 3] it was thought to have dominated enormous woodlands across the island (relict gumwoods can be seen in many old paintings). These large woodlands declined after the island was colonised due to the introduction of grazing animals and the use of the wood for fuel and timber (Cronk, 1986; Lambdon, 2012).

The largest and most significant of the relict gumwood populations is the woodland at Peak Dale [fig. 3; plates 8 and 9], which is the only substantial natural gumwood woodland left on the island (Cronk, 1986; Lambdon, 2012), with approximately 663 mature trees (population estimated from a census in 2013 - 2014) (Lambdon and Ellick, 2015). The other relict population is at Deep Valley [fig. 3], which is split into 2 sub-populations, containing a total of just 16 trees. Thus, approximately 98% of the global population of *C. robustum* is found at the Peak Dale site (Lambdon and Ellick, 2015). All other occurrences of *C. robustum* on the island have been planted, with some large specimens found around the island.

In 1986, Cronk (1986) recorded a trend of centuries of regeneration failure in the gumwood, caused by grazing stock. A recent IUCN Red List assessment (not yet published) places *C. robustum* in the Critically Endangered category, due to the lack of regeneration in wild populations and a decline in mature trees and sub-populations. The main cause of this has been grazing and trampling of juveniles by feral cattle, rabbits and rodents (Lambdon and Ellick, 2015).

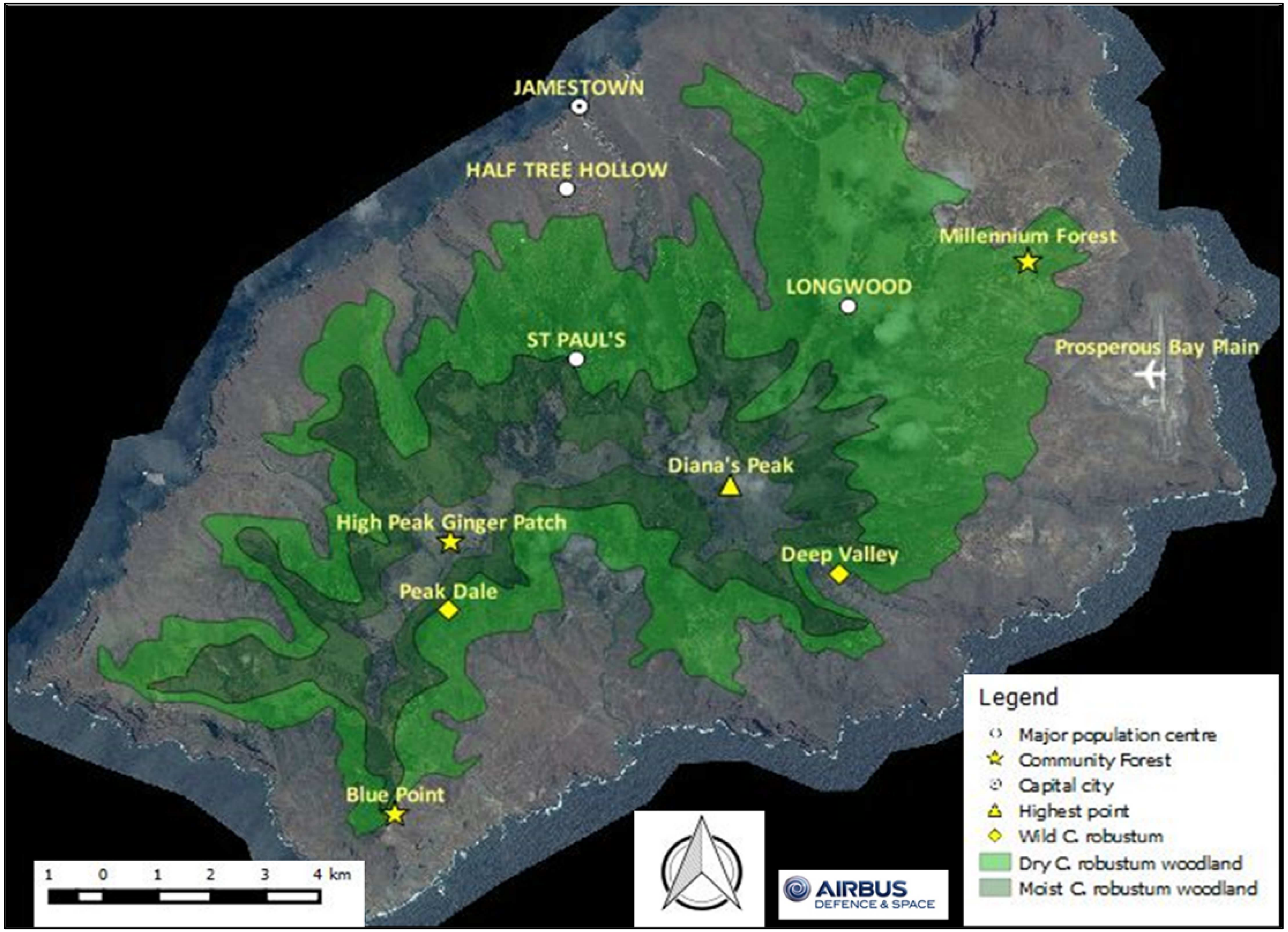

Fig. 3. Map showing the locations of wild populations of *C. robustum* in the context of Cronk's 1989 historical estimations of *C. robustum* dry (light green) and moist (dark green) woodland extent. © CNES 2014, Distribution Airbus DS / Spot Image.

Plate 8. A managed stand of *C. robustum* at Peak Dale © Jason Courtis, 2013

Plate 9. *C. robustum* canopy at Peak Dale © Jason Courtis, 2013

4.0 Study site: the Millennium Forest

The Millennium Forest is located approximately 400m above sea level on the eastern side of the island, near the outer limits of the lost 'Great Wood', a *C. robustum* woodland that once covered large parts of the island (Lambdon, 2012). The site became a part of the designated National Conservation Area network in 2012 (through the Millennium Forest Nature Reserve) (SHG, 2012); however, the Millennium Forest site itself only covers around 10% of the area of the nature reserve [fig. 4] (SHG, 2015e).

The Millennium Forest is situated within the Crown Wastes – a saline, semi-desert area inhospitable to most vegetation, barring some non-native species [table 2] which appear to thrive, such as *Carpobrotus edulis* (L.) N. E. Br. (Cronk, 2000). The site receives a significant amount of wind, sweeping across Prosperous Bay Plain (the area where the airport is being constructed [fig 3] towards the forest; this is reflected in the low-lying, windswept position of some of the gumwood trees. Cronk (2015) recorded the dominant vegetation at the site in 1980 to be almost entirely *C. edulis*, with sporadic occurrences of *Opuntia ficus-indica* (L.) Mill, *Diospyros dichrophylla* (Gand.) De Winter and *Chrysanthemum monilifera* (L.) Norlindh [see table 4.1]. The soils are heavy clays (Ashmole and Ashmole, 2000) and fairly impermeable, with low nutrient content due to the catastrophic loss of large quantities of topsoil to substantial soil erosion since the island was settled.

Table 2. Non-native species found within the Millennium Forest restoration site

Scientific name	St Helena common name
Atriplex nummularia	Old man saltbush
Atriplex semibaccata	Saltbush
Carpobrotus edulis	Creeper
Chrysanthemum monilifera	Wild coffee
Diospyros dichrophylla	Poison peach
Lantana camara	Lantana; wild currant
Mesembryanthemum crystallinum	Ice plant
Opuntia elatior	Red tungi
Opuntia ficus-indica	White tungi
Phormium tenax	New Zealand flax

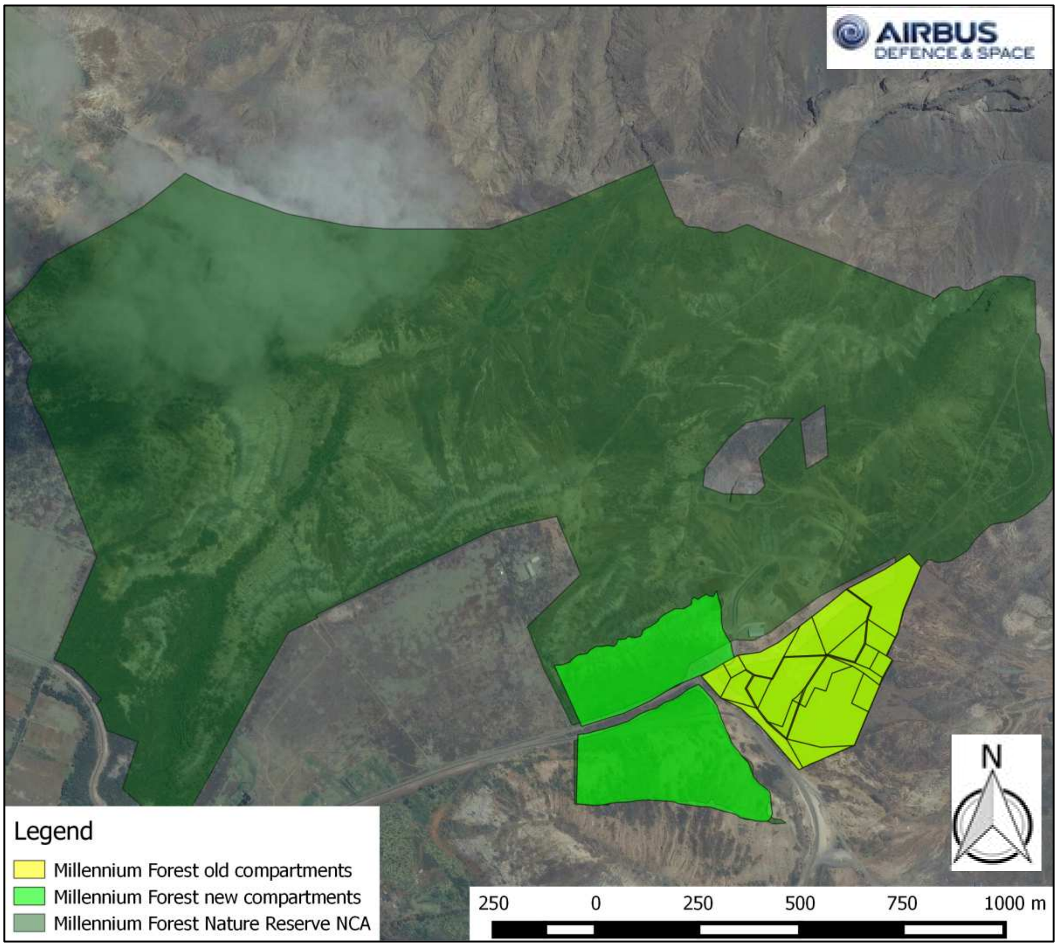

Fig 4. Map showing the location of the Millennium Forest restoration site old compartments (yellow) and new compartments (light green) in the context of the Millennium Forest Nature Reserve NCA. © CNES 2014, Distribution Airbus DS / Spot Image.

Plate 10. Millennium Forest in December 2000 looking toward the gatehouse © Dr Rebecca Cairns-Wicks, 2000.

Plate 11. Millennium Forest in April 2015 looking toward the gatehouse © Jason Courtis, 2015.

Plate 12. Millennium Forest April 2002 looking towards Prosperous Bay Plain and the Central Basin © Dr Rebecca Cairns-Wicks, 2002.

Plate 13. Millennium Forest May 2015 looking toward the Central Basin (far left-hand side) © Jason Courtis, 2015

The Millennium Forest project aims to develop a programme of staged planting blocks expanding the current planted area, and extending to other parts of the nature reserve when possible (SHG, 2015e). Restoration efforts at the current Millennium Forest site began in 1998, building on some trial plantings that were carried out at the site in the late 1980s. The restoration project aims to restore 250ha of gumwood woodland across the whole nature reserve; to date, well over 10,000 trees have been planted over approximately 35ha [plates 10, 11, 12 and 13] (SHNT, 2015b) and there is some evidence of regeneration within the site (JNCC 2015a). Eight other dryland endemic species are also being incorporated into the planted area, to develop the understory and diversity of the forest (SHG, 2015e). Some areas of the current Forest are being irrigated with waste water as the amount of rainfall is not sufficient at this time to sustain the trees. Some areas are also being fenced off to avoid grazing of seedlings and ring-barking of young tree by rabbits, which are a major problem affecting regeneration and juvenile survival rates within the site.

The current expanse of the Millennium Forest is the result of a long-term community conservation endeavour, managed by the St Helena National Trust. Since intensive plantings began in 2000, the local community has been heavily involved, with every islander planting a tree and the local community participating in monthly restoration days. Funds are also raised through plantings e.g. people can pay to have a tree planted for them. In addition to being an active restoration site, the Millennium Forest is also used for recreation; visitors can follow a nature trail through the forest and use the viewing platform for panoramas across the island, particularly the view of the airport site (SHG, 2015e). The Millennium Forest Project was the recipient of the JNCC Blue Turtle Award in 2010 (JNCC, 2015a), an award which recognises a valuable contribution by a group or individual to nature conservation within a UK Overseas Territory or Crown Dependency (JNCC, 2015b).

The SHNT relies on donations and grant funding to continue the restoration work at the Millennium Forest; both are sources which are unlikely to sustain high levels of restoration work over the long-term. Ideally, a carbon offsetting scheme would provide a more reliable income stream for the restoration site.

5.0 Methodology

To enable St Helena to become part of an established international carbon offsetting scheme, or for a local evidence-based scheme to be set up, a baseline assessment for the Millennium Forest of all five terrestrial carbon pools the IPCC requires to be monitored in carbon assessment, needs to be established. All fieldwork was conducted from late January – early April 2015, with the exception of the aboveground live biomass measurements and soil samples for Plot 1, which were carried out in early August 2014.

5.1 Establishing plots to estimate carbon stocks within the Millennium Forest

20m^2 plots were chosen for the study as these were considered to be more manageable for fieldwork, and a number could be studied within the time period available; the intention was to complete as many of these plots as possible within the available timeframe. Study plots were selected from inside the original compartments of the Millennium Forest [fig. 5]. These trees are older and the majority do not receive any management in the form of irrigation with wastewater and rabbit control (fencing, trapping and trunk protection), unlike the newer compartments. When the study plots were selected, they were carefully checked to make sure little to no management had occurred, as it is unlikely that there will be any large-scale continuation of these major management inputs on a long-term basis.

QGIS 2.4.0 (Chugiak Version: http://www.qgis.org/en/site/) was used to generate random points within the original Millennium Forest compartments. These random points were used as the south-east corners for each study plot. Upon arrival at these co-ordinates the south-east corner was marked with a rock or wooden post and biodegradable tape. Then, using a compass for direction, a 20 x 20 m plot was paced out (north from the south-east corner, then west and then again to the south and each corner point was marked).

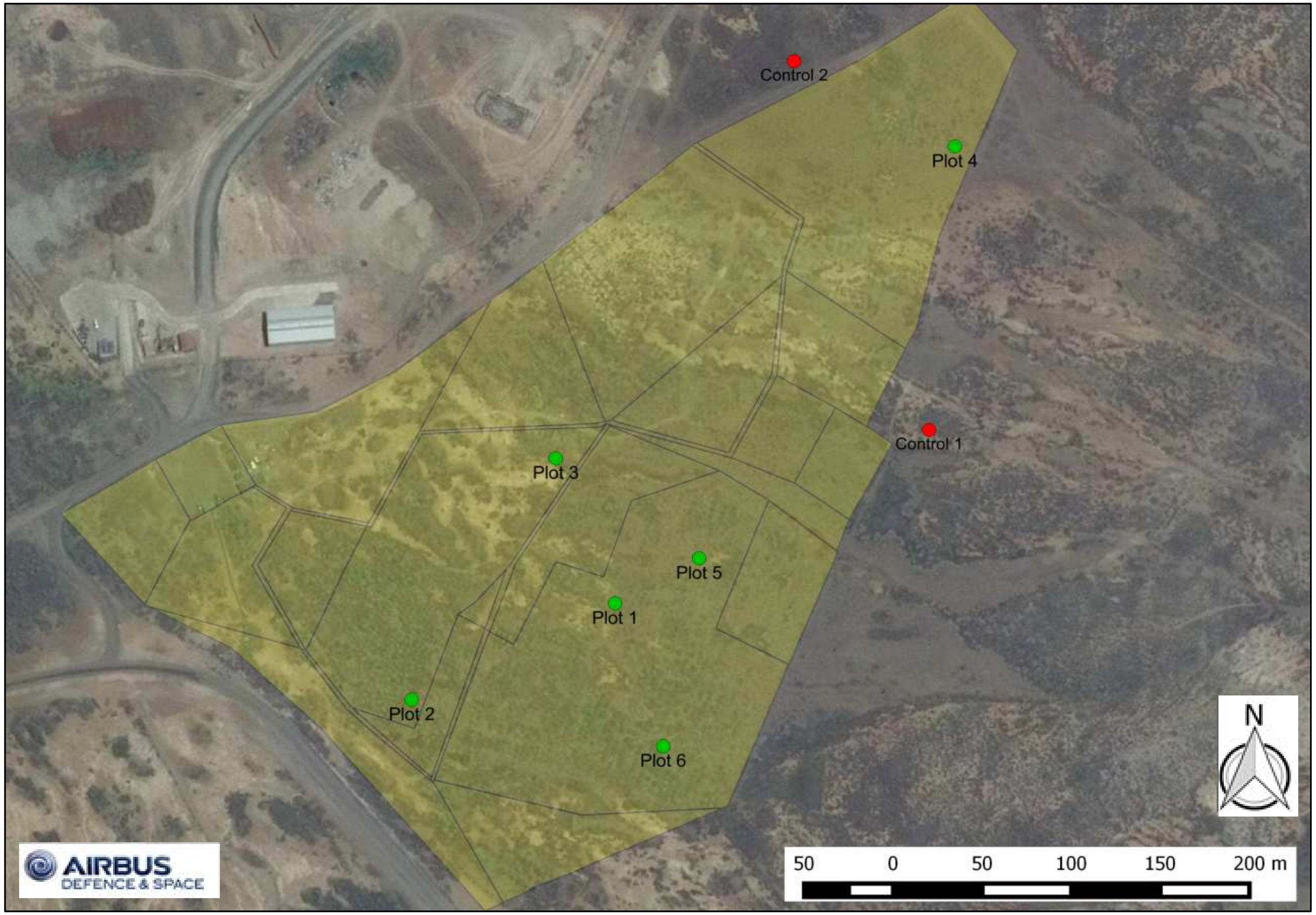

Fig 5. Locations of study plots (green circles) within the original compartments of the Millennium Forest, and control plots (red circles) outside of the Millennium Forest boundary. © CNES 2014, Distribution Airbus DS / Spot Image.

A record of other species present within the plots was also taken; a list of these species and their common names can be found in table 2.

5.1.1 Plot 1

Plot 1 consisted of small, sparsely planted *C. robustum* trees [plate 14], with patches of *C. edulis*, *Atriplex semibaccata* R.Br. and *Mesembryanthemum crystallinum* L., in addition to swathes of bare ground. Plot 1 (as well as plots 3, 4 and 5) is considered by some local conservationists to be just out of the boundary of the natural range of gumwoods.

Plate 14. View of Plot 1 from the south-east corner. © Shayla Ellick, 2015

5.1.2 Plot 2

Plot 2 consisted of small *C. robustum* trees [plate 15], much more densely planted than in Plot 1, with *C. edulis, A. semibaccata*, and small patches of *Phormium tenax* J.R.Forst. & G.Forst. and *D. dichrophylla*, with the occasional patch of bare ground.

Plate 15. View of Plot 2 from the south-east corner. © Shayla Ellick, 2015

5.1.3 Plot 3

Plot 3 contained *C. robustum*, again sparsely planted, but slightly taller than in the previous two plots [plates 16 and 17]- this could be because the majority were sheltered by a small hill in the middle of the plot (which can be seen on the bottom left of plate 17). Also present was *P. tenax*, *C. edulis*, *Lantana camara* L., *A. semibaccata* and *Atriplex nummularia* Lindl.

Plate 16. Plot 3 (left side of plot, on top of hill) © Shayla Ellick, 2015

Plate 17. Plot 3 (right side of plot) © Shayla Ellick, 2015

5.1.4 Plot 4

Plot 4 is located at the extreme eastern end of the Millennium Forest. The *C. robustum* trees present are small and sparsely planted [plate 18]. Also found at the site are *C. edulis, A. semibaccata, M. crystallinum* and *Opuntia elatior* Mill., as well as patches of bare ground.

Plate 18. View of Plot 4 from the south-east corner. © Shayla Ellick, 2015

5.1.5 Plot 5

Plot 5 consisted of large patches of bare ground, with small *C. robustum* trees [plate 19], *C. edulis, O. ficus-indica, A. semibaccata, A. nummularia , L. camara* and *D. dichrophylla*.

Plate 19. View of Plot 5 from the south-east corner. © Shayla Ellick, 2015

5.1.6 Plot 6

Visually, Plot 6 held the biggest *C. robustum* trees of all the study plots [plate 20]; the trees were much taller than the other plots, with larger stem diameters and canopies. Other species present within Plot 6 were *C. edulis, A. semibaccata*, A. *nummularia*, *O. ficus-indica*, *P. tenax*, and *L. camara*.

Plate 20. View of Plot 6 from the south-east corner. © Shayla Ellick, 2015.

5.1.7 Control plots

Two control plots were also included in the study. These fall outside of the Millennium Forest boundary and were selected from two representative areas in the Crown Wastes near the Millennium Forest, which represented the pre-restoration condition of the site before tree plantings were started. Once within the representative areas, a random number table and compass were used to select a random direction and random number of steps. The resultant point became the south-east corner of the plot and both control plots were marked out in the same manner as the study plots, as described above.

Control plot 1 (C1) [plate 21] had only *C. edulis* and *A. semibaccata*, with occasional large patches of bare ground.

Plate 21. Control plot 1 (C1) from the south-east corner. © Shayla Ellick, 2015.

Control plot 2 (C2) [plate 22] consisted mainly of *C. edulis*, with some large patches of *A. semibaccata* and one occurrence of *D. dichrophylla*.

Plate 22. Control plot 2 (C2) from the south-east corner. © Shayla Ellick, 2015

5.2 Aboveground live biomass

Remote sensing options to estimate the living biomass of trees in the Millennium Forest were not feasible for this study, as there were no recent high-resolution images available for assessment. These images would have been fairly expensive to obtain, and would also have been subject to weather conditions i.e. there was no guarantee that the portions showing Millennium Forest would be cloud free. Thus, direct field measurements were the best method of collecting inventory data for the Millennium Forest. ABG was estimated using allometric equations developed by Chave et al. (2005) and subsequently improved in 2014 (Chave et al., 2014) [see data analysis section 5.9]. Chave et al. (2014) use three variables which are important predictors of aboveground biomass: trunk diameter (cm), wood specific gravity (WSG) (g cm^{-3}), and height (m). A correction factor of 0.5 is used to convert the biomass estimate to a carbon estimate.

No destructive sampling was possible to verify the accuracy of the equations used, due to the status of the Millennium Forest as a restoration site for a critically endangered species. There were also no instances of recently fallen trees, which could have been used as an alternative to destructive sampling.

5.2.1 Measuring trunk diameter

The *C. robustum* trees within the Millennium Forest are small in stature (compared to the wild population at Peak Dale) and very few were found to be over 10cm in diameter, thus a threshold of 5cm was used. The trees across this restoration site also have very short trunks, and it was not possible to measure diameter at the standardised 1.3m DBH. The diameter measurement was therefore taken at the highest point on the trunk before the tree started to branch. It was assumed that the height measurement used in the equation will offset any error caused by the use of the shorter diameter.

For all trees over 5cm within the plots, diameter was recorded using diameter tape (Lufkin W606PM 2m length). These were then tagged with biodegradable tape to distinguish which trees had already been measured.

5.2.2 Measuring wood specific gravity

The Global Wood Density Database (Zanne et al., 2009) was searched for *C. robustum* but no WSG values were available for this species at either genus or species level. As this is an endemic genus, it was decided that it would be more valuable to calculate WSG for this species than use proxy, family level values.

Pith to bark cores were obtained with a sharp increment borer (Mattson: 4331, 5.15, diameter) (Chave et al., 2006; Muller-Landau, 2004) from three random trees per plot and immediately placed into sealed bags to stop them from drying out. Green volume was measured using the water displacement method as described by Chave et al. (2006), whereby a container of water was placed on a digital scale (Acculab VIC412 VICON) (precision to 0.01g) which was then zeroed. The core was placed into the water and then carefully forced under without touching the bottom or sides of the container. The cores were then placed into a drying oven (Gallenkamp Hotbox Oven Size 3) at 100^{o}C for at least 48 hours until they had achieved a constant weight, which was recorded.

5.2.3 Measuring height

The nature of the trees at the Millennium Forest (relatively short of stature) made it possible to measure tree height with the use of a 5m tape measure, as none of the trees measured were over 2.5m.

5.3 Litter

Quadrats were used to estimate litter biomass within the study plots; this was because the Millennium Forest is an unsheltered, usually fairly windy site and litter traps would not have worked well.

A 0.5m^{2} quadrat was placed randomly within each plot and all fine organic litter within the quadrat was collected (including twigs with less than 2cm diameter). These samples were weighed (precision to 0.01g), and then dried at 80 ^{o}C for at least 48 hours until they achieved constant weight.

5.4 Deadwood

One metre wide transects were carried out along the study plot boundaries. Any large pieces of coarse woody debris over 2 cm in diameter were measured. This low threshold was used due to the small stature of the trees within the Millennium Forest; it was felt that using this lower threshold would capture more of the deadwood biomass. The length and diameter of each large piece was recorded and the green volume was later calculated from this. Smaller pieces from each represented decomposition class [see table 1] were collected and stored in sealed bags. The green volume of these samples was measured back in the lab using the water displacement method described earlier. The samples were then dried as per the method for measuring WSG described earlier, and weighed to 0.01g accuracy.

It was anticipated that all pieces of deadwood would be sampled for invertebrates before any drying occurred, as many endemic invertebrates are dependent on *C. robustum* deadwood for habitat. Examination of the deadwood did not reveal much invertebrate activity, except ants and cockroaches, none of which are endemic.

5.5 Belowground biomass

Rhizotrons, while a good method for more accessible sites and a good resource for educational activities, would not have been practical within the timeframe of this study. Other methods such as mini-rhizotrons, although non-destructive, were too costly at this time. Thus, in growth cores were determined to be the most suitable method for this study due to the low cost, simple design, and repeatability across the Millennium Forest site.

Five in growth cores were placed in each study plot, one near each of the corners and one in the centre of the plot. Mesh cores measuring 14cm in diameter and 20cm in height were constructed- this depth could be consistently reached across all the plots within this site (the soils are so poor in this area that in some places bedrock can be reached at just over 20cm). A trowel was used to remove the soil where the samples were to be taken. The soil removed from the ground was then sampled in 10 minute sampling periods for roots; each sampling period was placed into a sealable plastic bag. The soil was not sieved in order to avoid much change to the soil structure. The sampled soil was then placed back into the mesh core; this was not root-free, however, using the time sampling method can allow for later estimation of the amount of roots left in the soil.

The root samples were stored in a sealed box in a darkened room until they were placed into the drying oven. The root samples were dried at 80^{o}C for at least 48 hours until at constant weight, and then the weight was recorded (precision to 0.01g). It was intended to revisit the cores after a period of two months to then estimate root production over this period of time.

5.6 Soil

At least 15 soil cores to a depth of 20cm were taken from across each plot using a soil auger (inner diameter 14mm); because of the nature of the soils within the Millennium Forest and surrounding Crown Wastes, this was the maximum depth that could be achieved before hitting the bedrock. Where possible, the soil cores were taken in a ‘W’ formation across each plot, to be as representative of the whole site as possible.

The soil samples were kept in sealed bags, and stored in a sealed box in a dark room. The wet weight was recorded (precision to 0.01g), and the samples were then dried in a standard drying oven at 80^{o}C for at least 48 hours to drive off all moisture in the soil until they had achieved a constant dry weight, which was also recorded.

LOI tests were used to estimate the organic carbon content of the soil; the SOM within the soil sample is ignited and released as carbon dioxide and ash. Each oven dried soil sample was thoroughly mixed and a sub-sample was taken from this and crushed to a fine powder in a ball mill (sub-samples for plot 2 were crushed with a pestle and mortar). Porcelain crucibles were weighed (precision to 0.01g) and 2g sub-samples (5g sub-samples were used from Plot 2) were then measured into each crucible. The crucibles were then placed into a muffle furnace (Gallenkamp Muffle Furnace Size 2 for samples from Plot 2 and Carbolite CWF 1200 for the remaining samples) where the samples were ignited at 550°C for 4 hours. Following ignition the samples were placed into a dessicator where they were allowed to cool to room temperature with no moisture retention before being weighed again.

5.7 Control plots

Soil samples were also obtained and processed from the control plots as per the methods discussed in section 5.6, so that carbon content of soils in the control plots could be compared to carbon content in the study plots.

5.8 Soil nutrients

Random soil samples were also taken across all the plots (study and control) and tested in the field for basic levels of nitrate, sodium and potassium using LAQUA Twin Meters by Spectrum Technologies Inc., and ph and EC using a Hanna H1 9811-5 pH and EC probe. Samples of rainwater were also collected from SHNT's rainwater tank at the forest, to act as a control value for the nutrient data within the plots.

5.9 Data analysis and calculations

Data analysis was mainly carried out using the 'R' statistical package (version 3.1.1 http://cran.r-project.org/) and Microsoft Excel 2010. To explore the major question of the study – 'does the planting of *C. robustum* increase carbon stocks within the Crown Wastes?' - carbon stocks were calculated for each carbon pool (described below). The data was presented using boxplots to show the average (median), variation and range of carbon values within and between plots. Bar-charts and tables were also used to present total carbon values per plot with 1 SE for comparison purposes.

Aboveground biomass

The allometric equation [see Appendix 1] used to estimate AGB was Chave et al.'s 2014 Model 4, which was considered their best-fit pantropical model due to it performing well across different forest types and climatic conditions (2014, pp.3182):

$$AGB_{est} = 0.0673 \times (WSG \times D^2 \times H)^{0.976}$$

The results were then multiplied by 0.5 to estimate carbon within the biomass, and then divided by plot area. The AGC estimate was then converted into carbon in tonnes per hectare ($t\ ha^{-1}$) and totalled for each plot [see fig. 10].

Litter

To estimate carbon stored in litter the results of the quadrats were converted into plot level estimates (mass / plot area). As the biomass collected was so small these plot level estimates were converted into a kg ha^{-1} figure instead of t ha^{-1} [table 4].

Deadwood

For the pieces of deadwood, the volume was calculated using "π x r^2 x length" and multiplied by the calculated WSG, this was then multiplied by 0.5 to get an estimate of carbon per piece of deadwood. Again, as the biomass was relatively small the carbon was estimated in kilograms instead of tonnes. The total values per plot were totalled and can be found in table 5.

Belowground biomass

To calculate carbon in belowground biomass, the root biomass obtained from each sampling period (10 minute period over a total time of 40 minutes) was totalled for each core; as these values were relatively small they were calculated in kilograms. This was then multiplied by 0.5 to give an estimate of belowground carbon (BGC) and divided by plot area; the average amount of BGC per plot can be seen in fig. 12.

Soil

In determining SOC, bulk density (BD) was first calculated by dividing the dry weight of each sample by its known volume (Gray, 2014). The volume was calculated using π x r^2 x h (diameter of the soil auger was 1.4 cm and height of the soil samples was 20 cm and was 30.78760801 cm^3.

Weight loss percentage following LOI was then calculated as:

LOI% = (dry weight – weight after muffle furnace/dry weight) * 100 (Adolfo Campos, 2010; Sutherland, 1998).

This equation calculated the percentage of SOM lost to the combustion process; the average LOI percentage for each plot was determined and applied to each soil sample within the plot. The resulting mass (g) of each soil sample was then considered to be the mass of SOM within the sample. The Van Bremmerlen conversion factor (1.724) was then applied to this mass to give an estimate of SOC within the soil sample. An average (mean) of the SOC in the samples collected for each plot was calculated. The total SOC content within each plot was then estimated as below:

average SOC per plot (g) * average dry BD (g cm^{-3}) * volume of plot (20m x 20m x 0.20m = 80,000 cm^3 (800 m^3)).

The resulting values were then converted into a t ha^{-1} value for each plot, to a depth of 20 cm, which is shown in fig. 15.

Soil nutrients

The basic soil nutrient levels collected were plotted on bar-charts for comparison across plots and between control and study plots. The value used for the rainwater control was the average of the two rainwater values taken.

Multi-variate analysis

To explore the second question of the study – ‘Is there a relationship between soil nutrient levels and the quantity of carbon stored within the restoration site?’ – principal components analysis (PCA) was employed. PCA reduces the dimensionality of the variation in a dataset, and is particularly useful where the variables have different units and different variances (Coghlan, 2014). ‘Past’ version 3.06 (http://folk.uio.no/ohammer/past/) was used to run Principal Components Analysis (PCA) on the total carbon values per plot and the soil nutrient data to observe the relationships between these variables. PCA was run three times, first using just the carbon data to look at relationships within this, second using just the soil nutrient data to look at relationships within this and third using all of the data to look at relationships between the two. Bi-plots were used to present the results of the PCAs.

6.0 Results

6.1 Aboveground live biomass

Total number of trees per plot is shown in table 3 below:

Table 3. Total *C. robustum* trees recorded in each study plot.

Plot	Number of trees
1	18
2	31
3	19
4	25
5	12
6	21

The average WSG per study plot is shown in fig. 6; the majority of the plots average between 0.6 and 0.7g cm^{-3}, with only plots 1 and 2 showing higher values. Plots 1 and 2 though, also show greater variation in values than the other plots, with particularly high variability in plot 2.

Fig. 7 shows average diameter of the trees in each plot. The majority of the study plots contain *C. robustum* which average less than 10 cm in trunk diameter; the smallest trunks on average were found in plot 4. The only plot that contained trees with an average of more than 10 cm diameter was plot 6, which also held one outlier tree with a diameter of over 20cm. Plots 5 and 6 also had the largest variability in trunk diameter.

The average height of trees in each study plot is shown in fig. 8; the smallest trees were found in plot 4 where the trees averaged heights less than 1.5 m. The remaining plots held trees with average heights ranging from 1.5 – 2m, with the tallest trees found in plot 6. Plot 4 had the smallest trees, but plot 6 also had larger variation in both. The tree heights were most variable in plot 3.

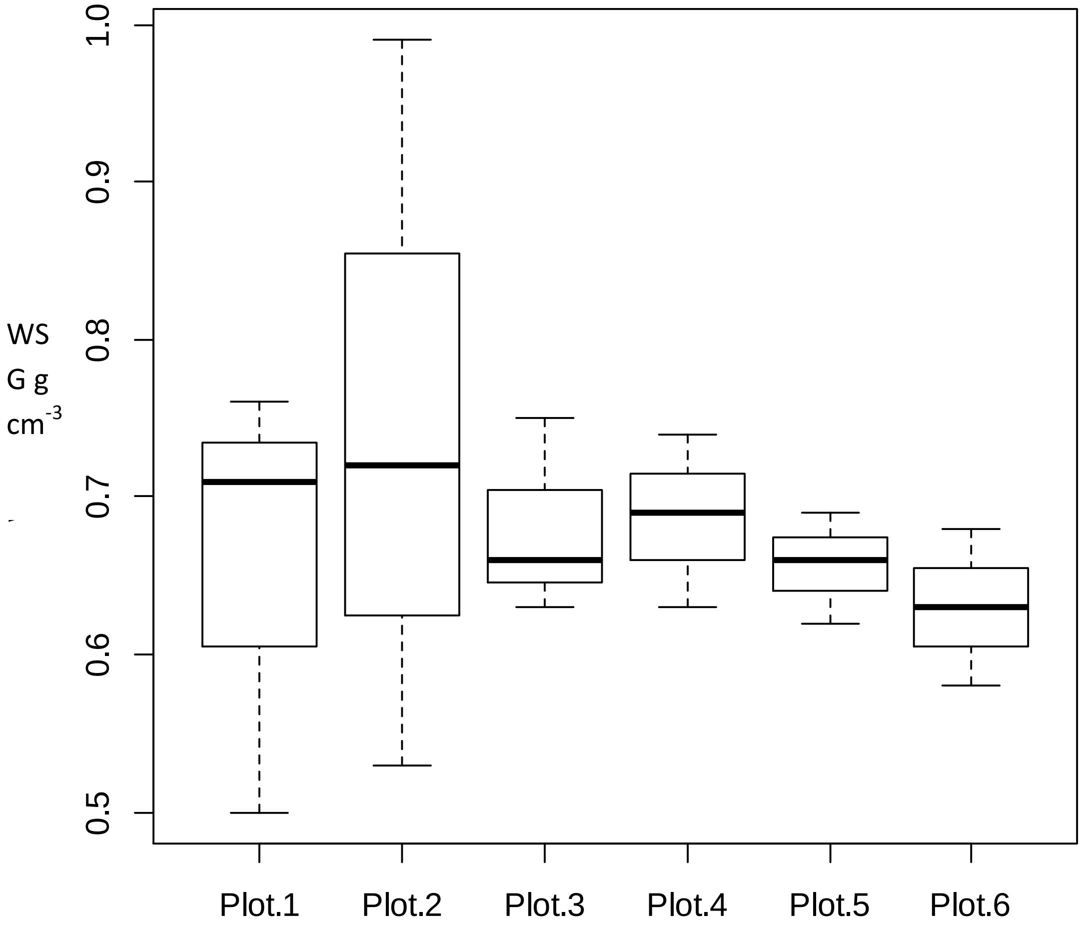

Fig. 6. Boxplots displaying average (median) WSG (g cm^{-3}) and the range of the data for each study plot. The whiskers indicate minimum and maximum values for each plot.

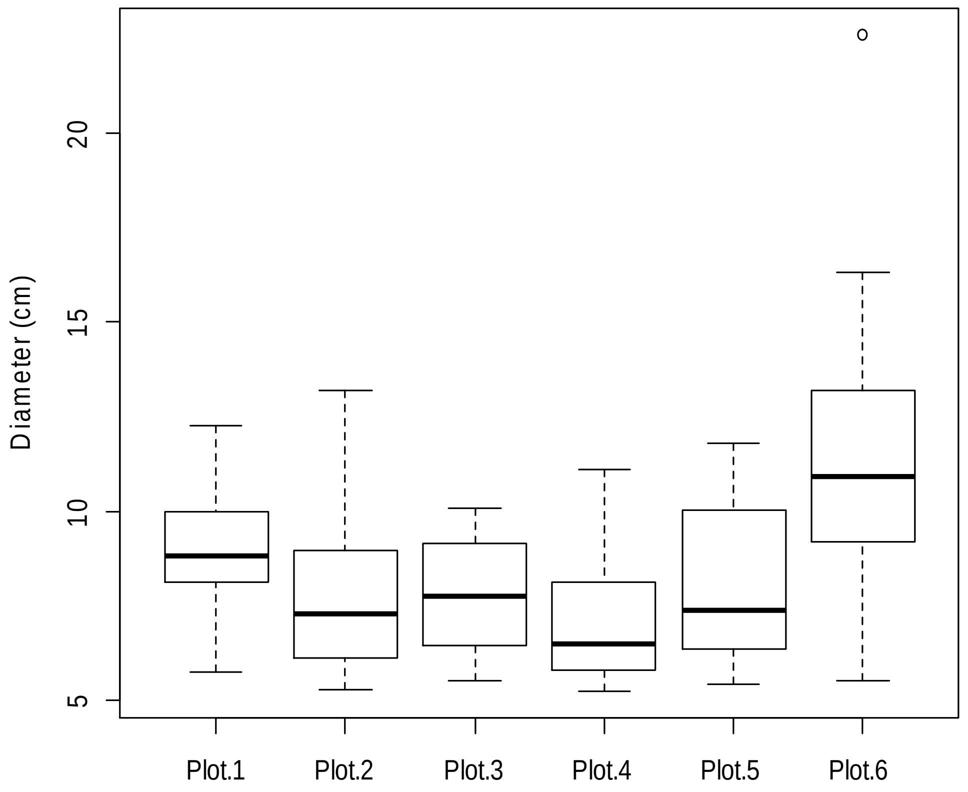

Fig. 7. Boxplots showing average (median) diameter (cm), the range of diameters and minimum and maximum non-outlier values recorded for trees across the study plots. The circle represents an outlier.

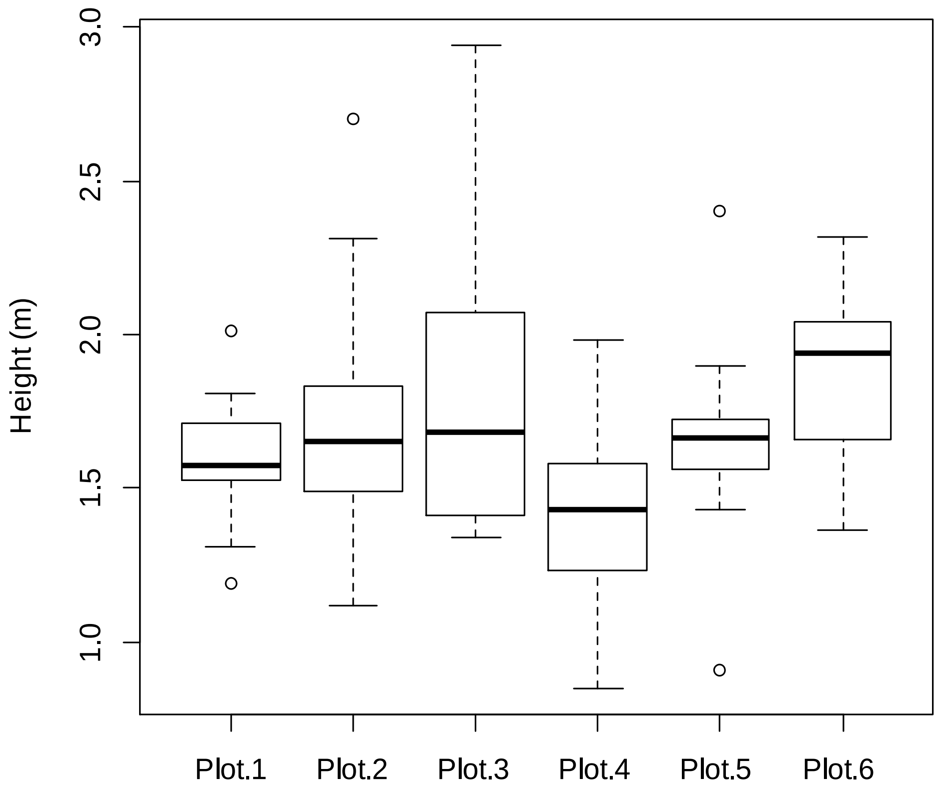

Fig. 8. Boxplots showing average (median) height (m), the range of heights and minimum and maximum non-outlier values recorded for trees across the study plots. The circles represent outliers.

The WSG figure used in this equation was the overall across-plots mean WSG, which was 0.68 ± 0.03 g cm^{-3} (1 SE, n=12). The equation estimated AGB in kilograms, which was multiplied by 0.5 to estimate aboveground carbon (AGC) content and converted into tonnes per tree [fig. 9]. The results show that plot 6 held the highest average of tonnes of carbon held in each tree, with plot 4 averaging the lowest amount of tonnes of carbon per tree. Plot 6 also had the most variability in carbon per tree. These results are consistent compared to the diameter and height results, where plot 6 has the largest trunk diameters and the tallest trees.

Plot 6 held the largest amount of AGC, which was 3.11 tonnes, with plot 2 holding the next largest amount of 1.88 tonnes – over a tonne less than the value held in plot 6. Plot 5 held the least amount of AGC (0.74 tonnes) and was the only plot containing less than one tonne.

AGC per plot was also estimated using plot-specific means of WSG [fig. 10] to see if there were any variations in the AGC results when using these figures instead of the overall across-plots mean WSG. In only two of the study plots (plots 2 and 4) did using the plot-specific means in the AGB calculations result in higher AGC values than when the overall across-plots mean WSG was used. However, in terms of total AGC, using the across-plots mean WSG over-estimated the total AGC amount by 0.1 tonnes (8.82 tonnes using the plot-specific means, vs. 8.92 tonnes using the across-plots mean).

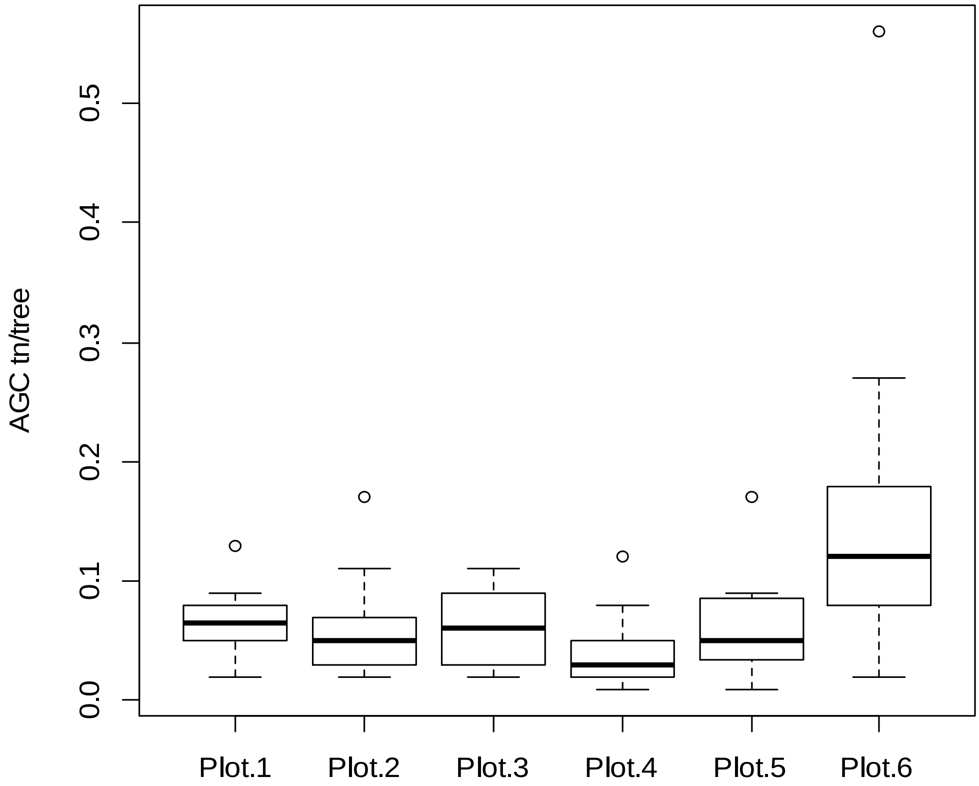

Fig. 9. Boxplots showing average (median) AGC (tonnes), the range of AGC and minimum and maximum non-outlier values in each study plot (using the across-plots mean WSG). The circles represent outliers.

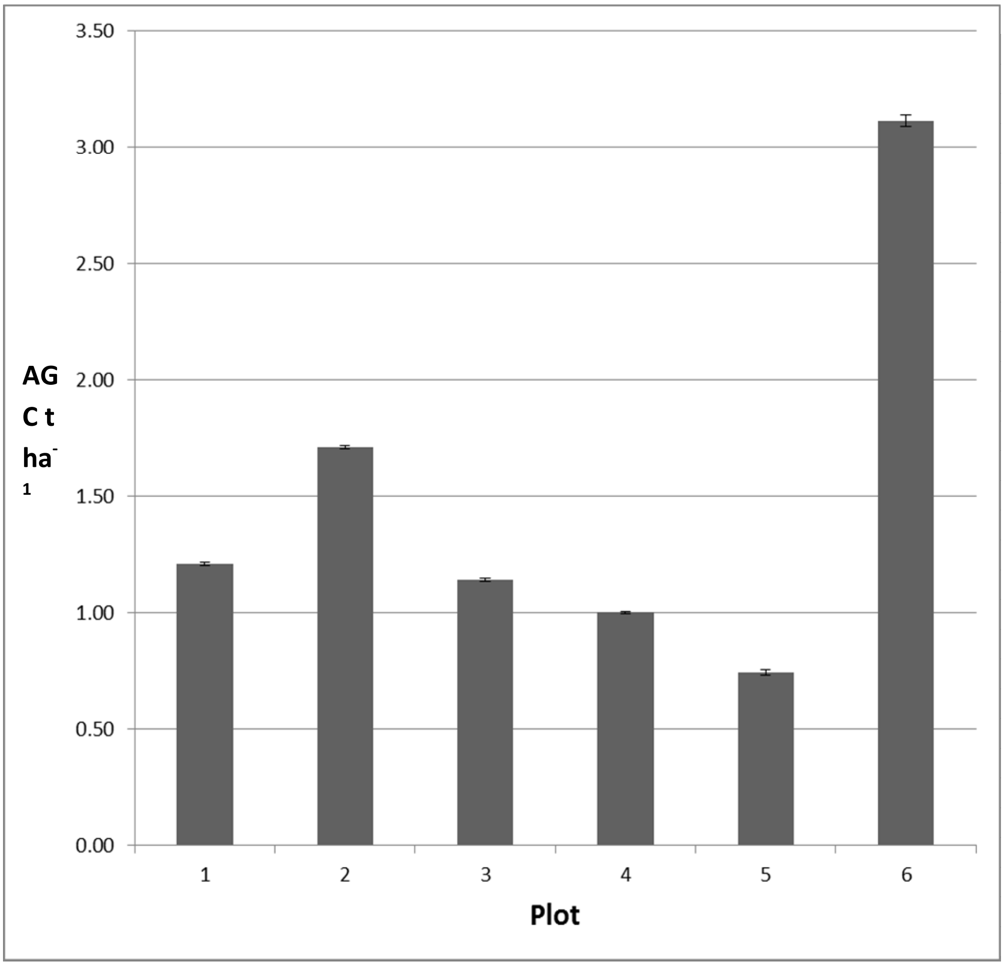

Fig. 10. Barchart showing total AGC (t ha^{-1}) within each study plot, using the across-plots mean WSG (error bars represent 1 SE, plot 1 n=18, plot 2 n=31, plot 3 n=19, plot 4 n=25, plot 5 n=12, plot 6 n=21).

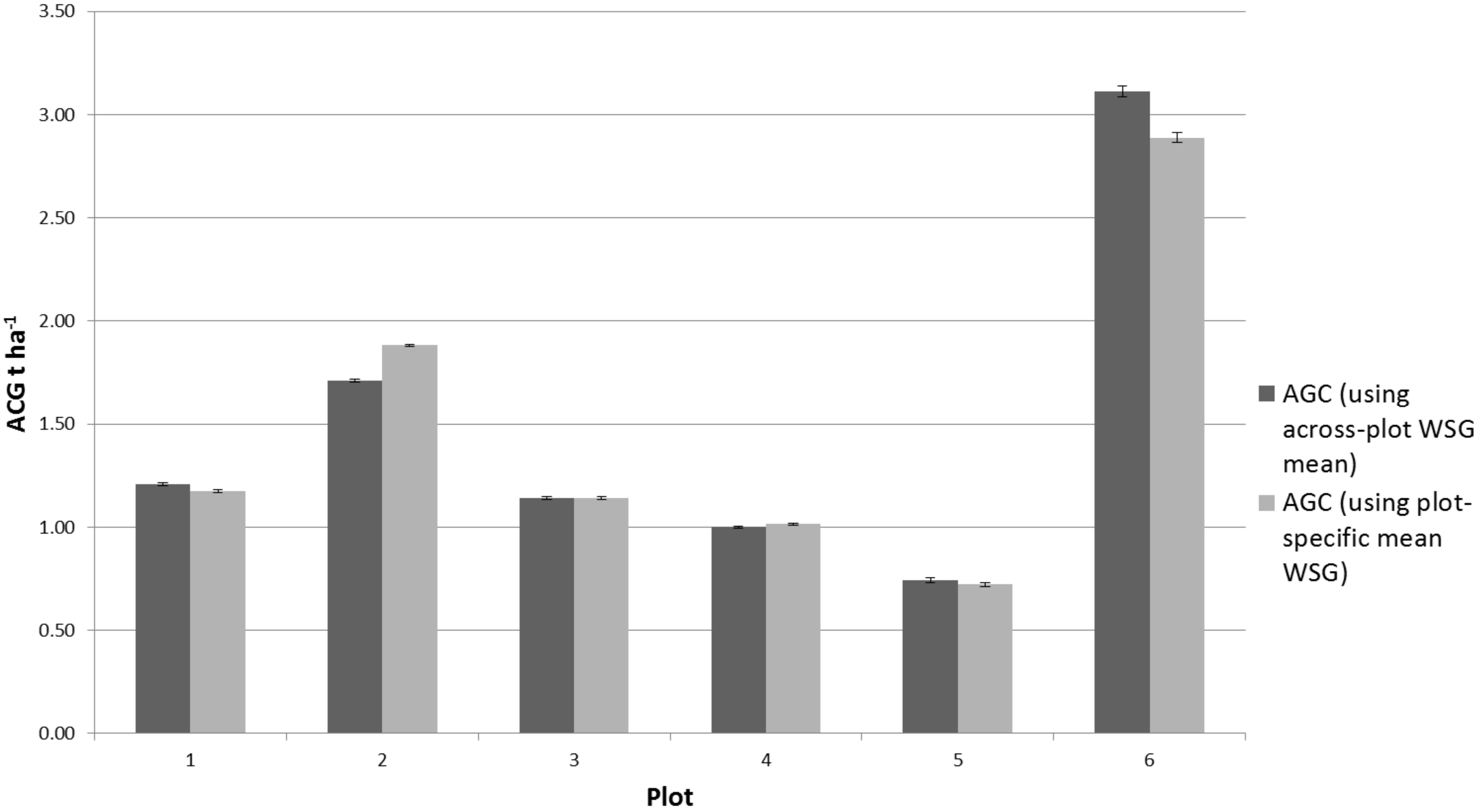

Fig. 11. Barchart comparing differences in total AGC (t ha^{-1}) within each study plot, using across-plot and plot-specific WSG (error bars represent 1 SE, plot 1 n=18, plot 2 n=31, plot 3 n=19, plot 4 n=25, plot 5 n=12, plot 6 n=21).

The total amount of AGC per plot was then averaged (mean) giving an estimated 1.49 ± 0.35 tn ha^{-1} (1 s.e., n = 6) using the across-plots WSG values, and 1.47 ± 0.32 tn ha^{-1} (1 SE, n = 6) using the plot-specific WSG values. These values can then be multiplied by the value of the current planted area of the Millennium Forest (35 hectares) to give an estimate of the potential carbon storage of the site, which was 52.15 ± 12.25 tonnes using the across-plots mean WSG, and 51.45 ± 11.2 tonnes using the plot-specific WSG means.

From these values we can also approximate a rate of carbon sequestration since intensive plantings began at this site in the year 2000 of between 3.43 and 3.48 tonnes of carbon per year (total carbon value / 15years).

6.2 Litter

The carbon stock in the litter carbon pool was determined to be the lowest of all the pools studied within the Millennium Forest site.

Table 4. Litter (kg ha^{-1}) per plot, based on one quadrat per plot.

Plot	Litter per plot (kg ha^{-1})
1	0.02
2	0.04
3	0.30
4	0.43
5	0.06
6	0.01

The largest amount of litter collected was at plot 4 (0.43 kg), with the next largest amount collected at plot 3 (0.30 kg). For the remaining plots the amount of litter collected was very low (less than 100g) [see table 4].

The average (mean) litter over all the plots was 0.14 ± 0.07 kg ha^{-1} (1 SE, $n = 6$). The value was then multiplied by the total area (35 ha) of the restoration site which gives a total of approximately 4.9 ± 2.45 kg of carbon held in the leaf litter within the restoration site.

6.3 Deadwood

Coarse woody debris above the threshold of 2 cm diameter was only found at four plots; there was none collected at plots 1 and 3. No standing deadwood was found within the plots. The total amounts of carbon in deadwood found for each decomposition class can be seen in table 5. It was determined that this carbon pool held the penultimate smallest carbon stock within the Millennium Forest during this study.

Table 5. Carbon (kg ha^{-1}) in deadwood per plot, by decomposition class.

Plot	Decomposition class	Average WSG (g cm^{-3})	Carbon (kg ha^{-1}) in each decomposition class	Total carbon (kg ha^{-1}) per plot
1	-	-	-	**0**
2	2	1.81 ± 0.06 (n=5)	14.56 ± 0.33	**14.56 ± 0.33**
3	-	-	-	**0**
4	1.5	1.34 ± 0.02 (n=2)	37.82 ± 6.07	**42.56 ± 6.42**
	2	0.41 ± 0.02 (n=4)	4.74 ± 0.35	
5	1	0.63 (n=1)	2.84	**6.91**
	1.5	0.65 (n=1)	4.07	
6	1.5	0.60 (n=1)	0.88	**4.21 ± 0.47**
	2	0.54 ± 0.04 (n=2)	3.33 ± 0.47	

All of the pieces of deadwood collected were in relatively early decomposition stages (2 and under) [see table 5], where the wood was not rotten enough for a nail to be pushed through it easily. The largest amount of deadwood was found in plot 4 (42.56 ± 6.42 kg) and the smallest was collected in plot 6 (4.21 ± 0.47 kg).

The total amount of deadwood collected was then averaged (mean), giving an estimated 11.37 ± 1.20 kg ha^{-1} across the plots. This can be multiplied by the value of the current planted area of the Millennium Forest (35 hectares) giving an estimate of the potential carbon stored in deadwood at the Millennium Forest: 397.95 ± 42 kg.

6.4 Belowground biomass

Belowground biomass was revealed to be the second smallest carbon pool within the Millennium Forest. On average, plot 1 contained the most BGC and plot 4 the least; however, the results across the plots were all very variable [fig. 12].

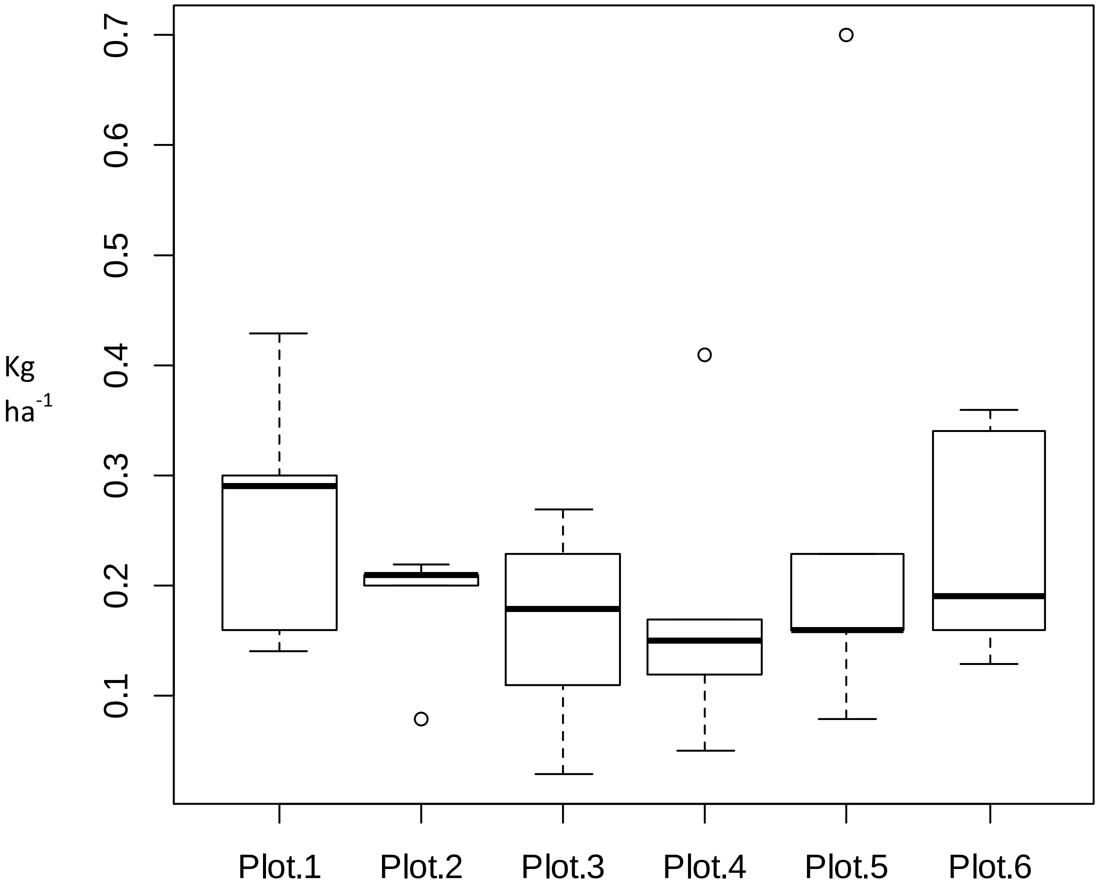

Fig. 12. Boxplots showing average (median) BGC (kg ha^{-1}), the range of BGC and minimum and maximum non-outlier values recorded for trees across the study plots. The circles represent outliers.

Each core was then totalled giving the sum of BGC for each plot and then converted to a kg ha^{-1} figure; the results are shown in table 6. Overall, plots 1 and 5 held the highest amount of BGC (1.32 ± 0.05 kg; and 1.32 ± 0.11 kg respectively) with plot 6 holding the second highest amount (1.18 ± 0.05 kg). Plot 3 held the least amount of BGC (0.82 ± 0.04 kg).

Table 6. Total BGC (kg ha^{-1}) in each plot

Plot	BGC (kg ha^{-1}) (1 SE, n = 5)
1	1.32 ± 0.05
2	0.91 ± 0.03
3	0.82 ± 0.04
4	0.91 ± 0.06
5	1.32 ± 0.11
6	1.18 ± 0.05

The total amount of BGC was then averaged (mean) giving an approximate average of 1.08 ± 0.06 kg ha^{-1} across the plots. This value was then multiplied by the total area of the Millennium Forest restoration site (35 hectares) giving a total of approximately 37.8 ± 2.1 kg of carbon held in the belowground biomass within the restoration site.

6.5 Soil

Average (mean) dry BD was largely found to be over 1 g cm^{-3} for all of the plots [fig. 13] with the exception of plot 3 which had an average dry BD of 0.95 ± 0.04 g cm^{-3}. Control plot 1 had the largest average dry BD value (1.38 ± 0.06 g cm^{-3}) overall, while plot 5 had the highest average BD value of the study plots (1.34 ± 0.04 g cm^{-3}).

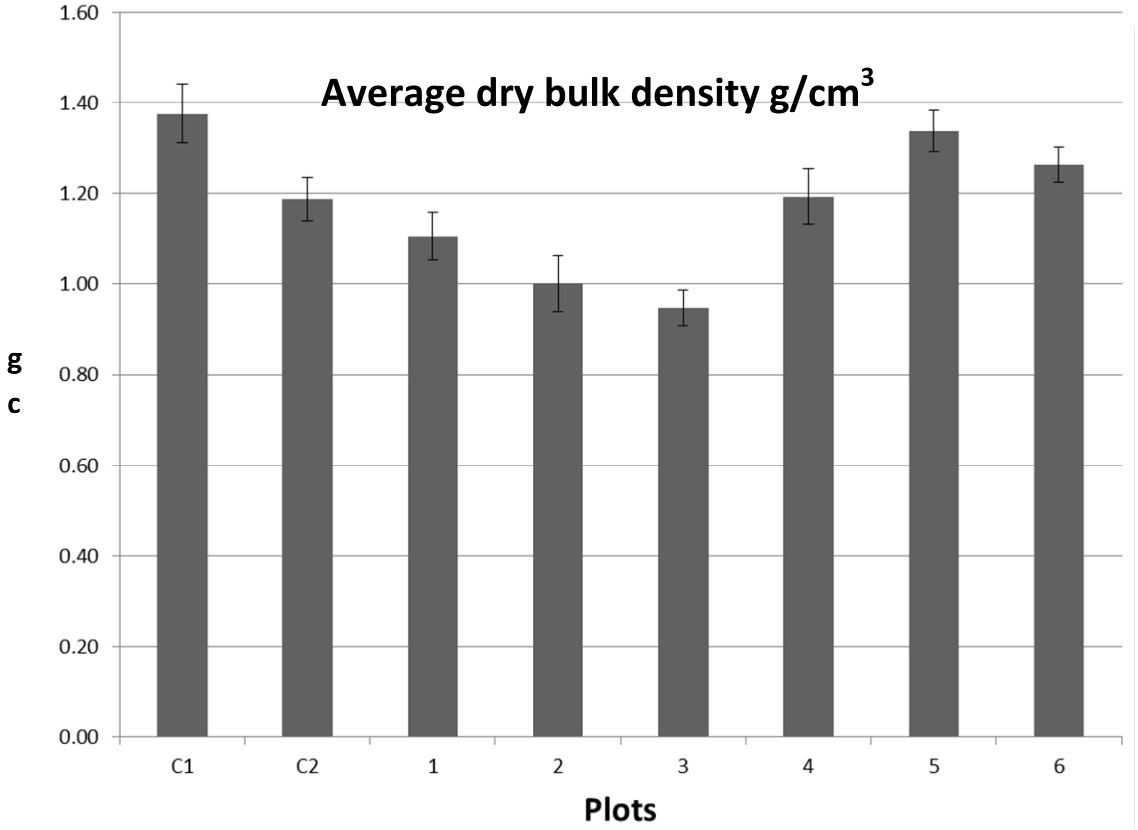

Fig. 13. Average (mean) dry bulk density (g cm^{-3}) in each plot. (error bars represent 1 SE. C1 n=8, C2 n=15, plot 1 n=14, plot 2 n= 15, plot 3 n=15, plot 4 n=14, plot 5 n=15, plot 6 n=15).

On average (median), plot 3 contained the lowest rates of SOC per soil sample [fig. 14], while plot 1 held the highest; however, the data in plot 1 though had a large spread and the results are thus more variable. The results for plot 2 held the most variability of all the plots, which is likely a reflection of the use of the pestle and mortar rather than the ball mill which was used to grind the soil for the remaining plots. On average, the samples within the control plots held a higher SOC content than 50% of the study plots (plots 2, 3 and 4).

The total amounts of carbon found in the soil [fig. 15] were determined to be the largest of all the terrestrial carbon pools within the Millennium Forest with the smallest total (plot 3) estimated to be 5.79 ± 0.13 t ha^{-1}. Plot 5 held the highest total SOC of the plots (10.76 ± 0.13 t ha^{-1}), with plot 6 containing a tonne less than that. Again, control plots 1 and 2 were found to hold larger amounts of SOC (9.87 ± 0.16 t ha^{-1} and 8.95 ± 0.16 t ha^{-1} respectively) than 50% of the study plots (plots 2, 3 and 4).

The average (mean) SOC (t ha^{-1}) across the study plots was calculated to be 8.50 ± 0.66 tonnes to a depth of 20cm. From this the total value of SOC held within the 35 hectares of currently planted Millennium Forest soils (to a depth of 20 cm) was estimated to be 297.5 ± 23.1 tonnes.

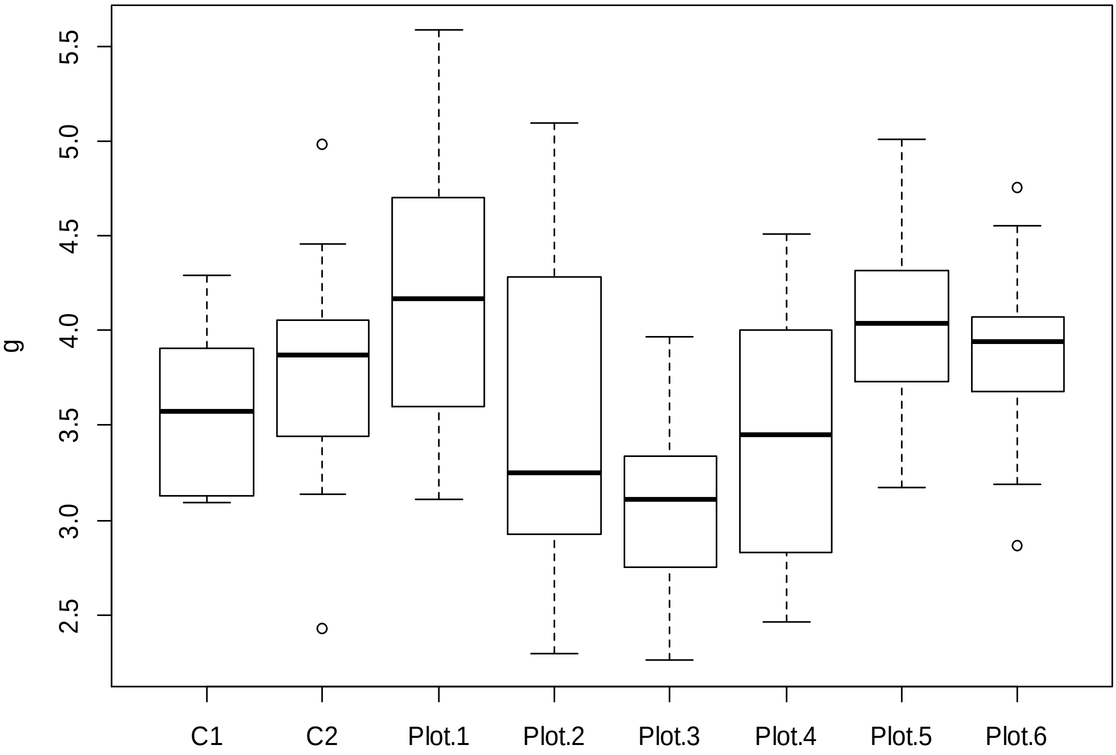

Fig. 14. Boxplots showing average median SOC (g), the range of SOC values and minimum and maximum non-outlier values recorded for the collected samples for each plot. The circles represent outliers.

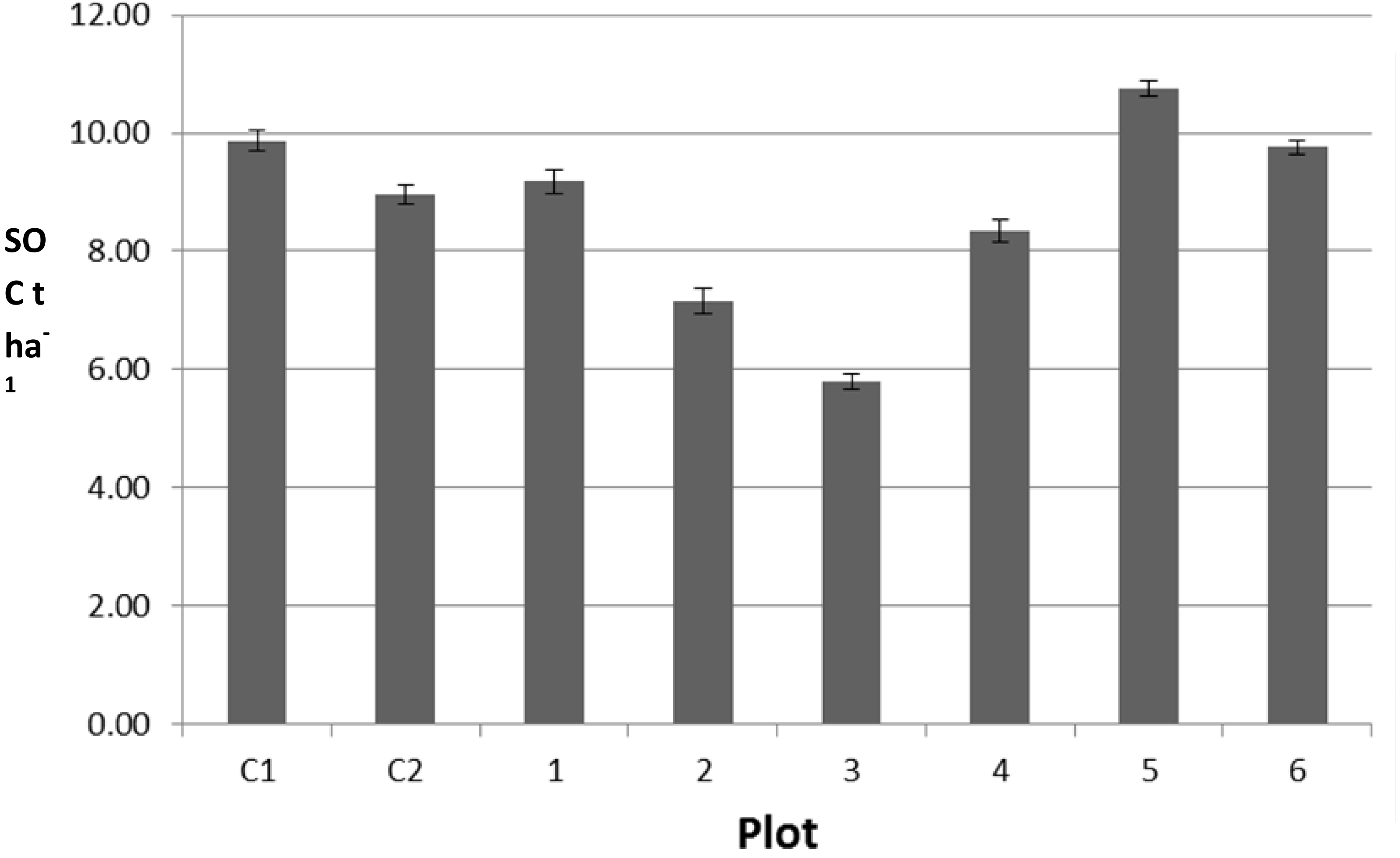

Fig. 15. Average (mean) SOC (tn ha^{-1}) per plot (error bars represent 1 SE. C1 n=8, C2 n=15, plot 1 n=14, plot 2 n= 15, plot 3 n=15, plot 4 n=14, plot 5 n=15, plot 6 n=15)

6.6 Soil nutrients

Values of soil Electrical Conductivity (EC) [see fig. 16] were variable across all the plots (control and study). The average value of the rainwater control value was calculated to be 130 ± 80 µS cm and the values from each plot were recorded to be significantly higher. EC was found to be extremely high in plot 1 where it exceeded the levels readable by the probe and was thus recorded as 9000+. Relatively high values were also recorded from plots 3 and 4 (6430 and 6160 µS cm^{-1} respectively), and also from control plot 1 (5000 µS cm^{-1}). The lowest EC was recorded at plot 5 (850 µS cm^{-1}).

The acidity of the soil was also recorded as pH [see fig. 17]. The rainwater control was found to be fairly alkaline (8.5 ± 0.2 pH), while all the of pH values recorded for the plots were lower than this. The study plots all contained soils measuring pH between 6 and 7. Control plot 1 held the most acidic soil (5.7) of all the plots tested, while control plot 2 was more alkaline with a value over 7.

The results for calcium, nitrate and potassium were very variable across the plots [see fig. 18]. Averages for the rainwater control were as follows: calcium 4 ± 1 ppm; nitrate 136.5 ± 113.5 ppm; potassium 62 ± 19 ppm. The highest value for calcium was recorded at study plot 1 (830 ppm), followed by plot 3 (670 ppm). For the remaining plots (including the control plots) the calcium content was below 200 ppm. The highest recorded value for nitrate was taken at plot 4 (790 ppm); the remaining study plots all had much lower values for nitrate. The next largest value was recorded at control plot 2 (500 ppm). The largest value for potassium was recorded at plot 4 (930 ppm), with values for the remaining study plots all presenting at 200 ppm or less. Control plot 2 also had the higher value of potassium (350 ppm) out of the two control plots.

Levels of sodium within the plots were also documented [see fig. 19] and were generally found to be much higher than the results for calcium, nitrate and potassium. The average for the rainwater control was 68.5 ± 41.5. The largest amount of sodium recorded was at plot 4 (5800 ppm), with the second largest value recorded at plot 3 (3200 ppm). Plot 1 also had just over 3000 ppm of sodium within the soil, with all the remaining recordings falling below 3000 ppm.

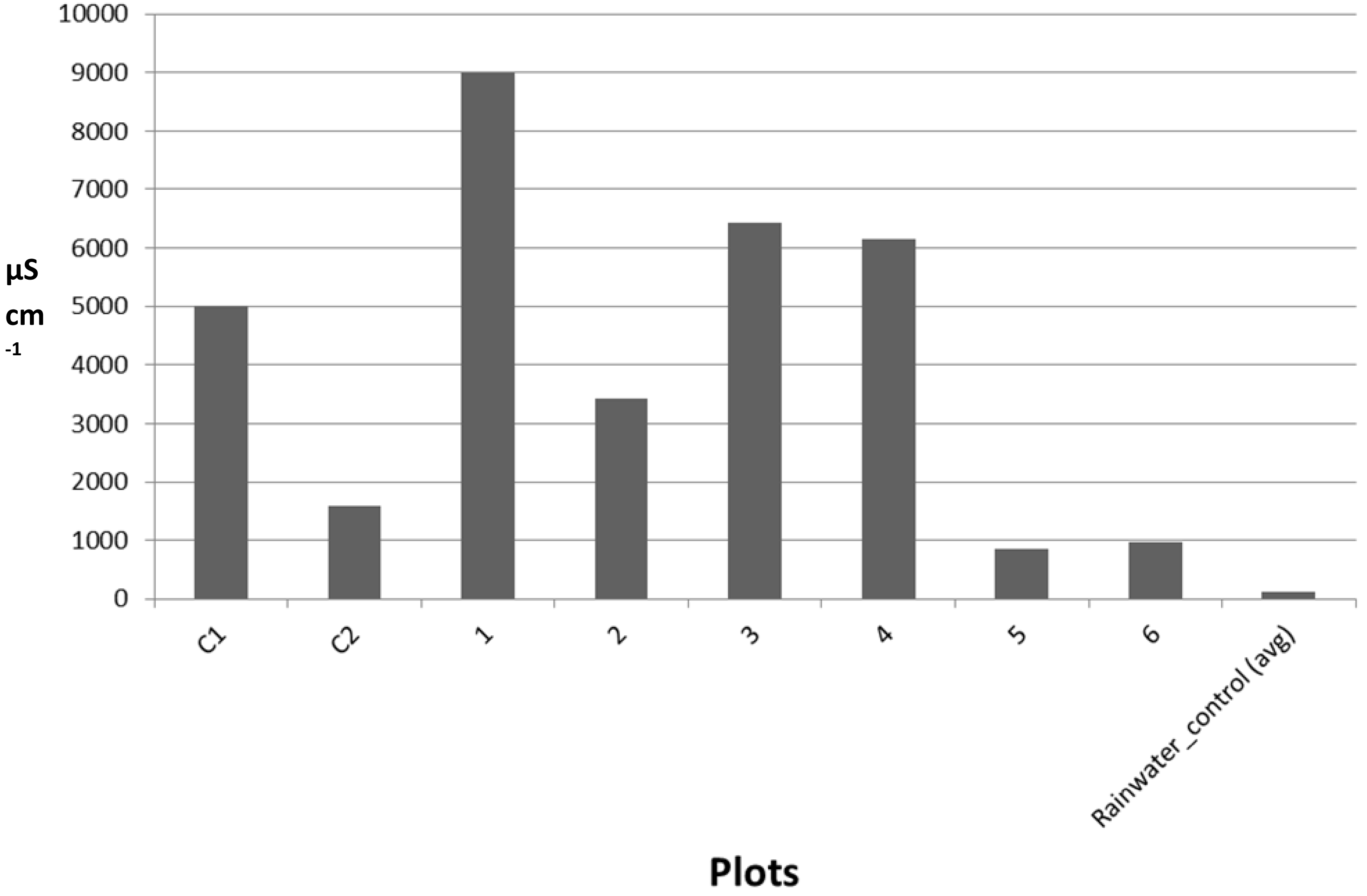

Fig. 16. Measurements of soil EC within each control and study plot. One reading was recorded for each plot.

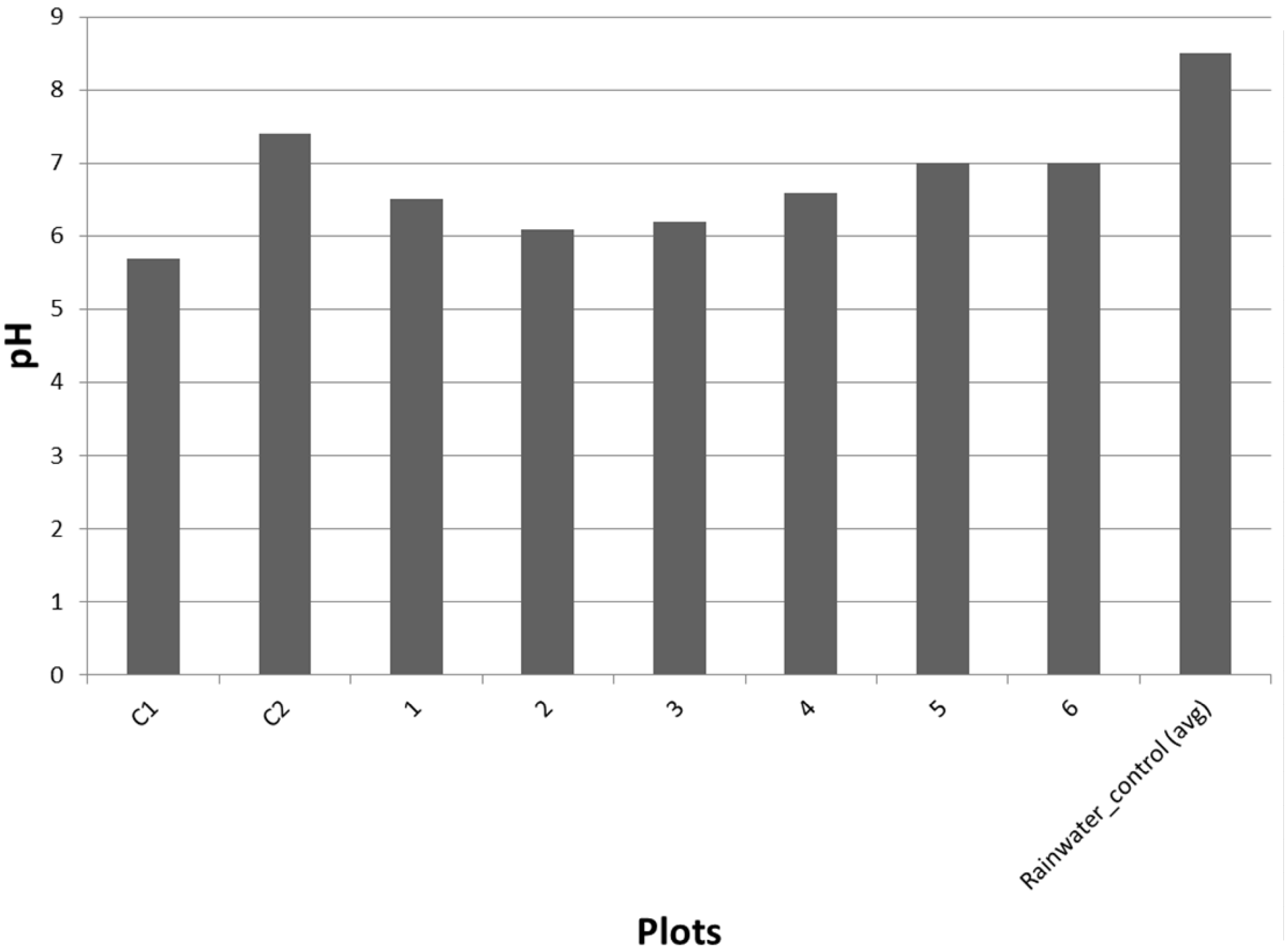

Fig. 17. Measurements of soil pH within each control and study plot. One reading was recorded for each plot.

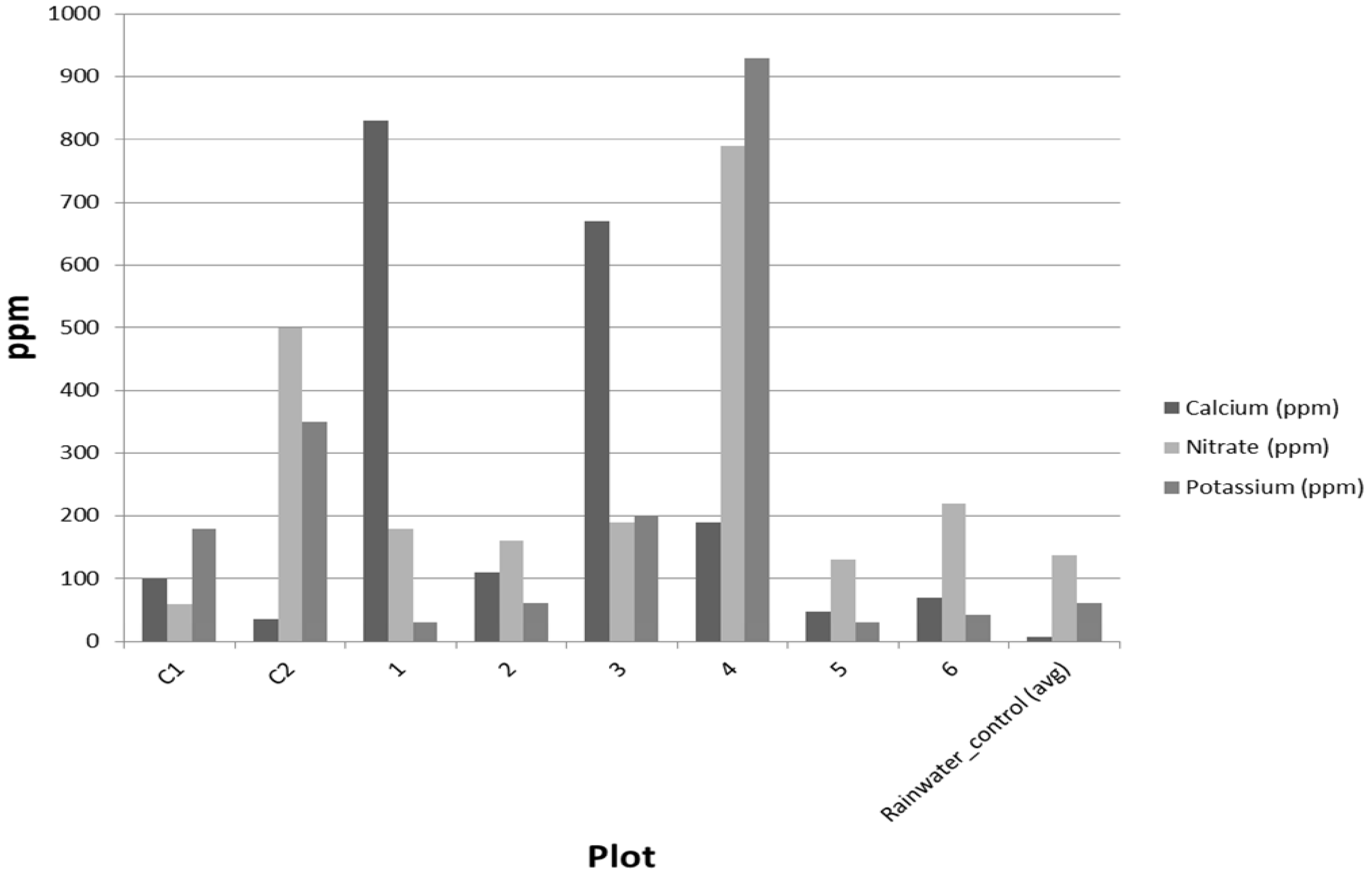

Fig. 18. Measurements of soil calcium, nitrate and potassium (ppm) within each control and study plot. One reading of each was recorded for each plot.

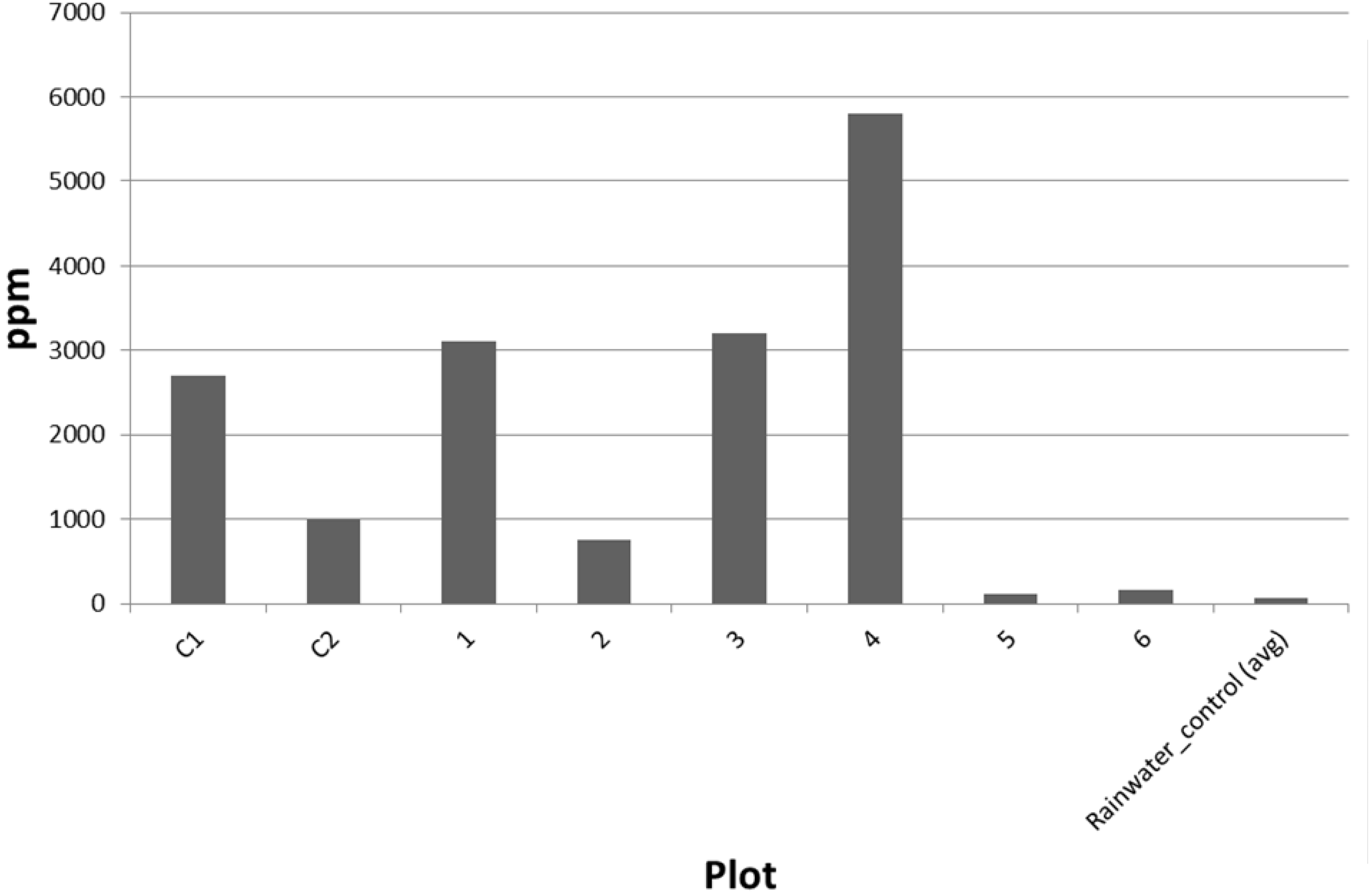

Fig. 19. Measurements of soil sodium (ppm) within each control and study plot. One reading was recorded for each plot.

6.7 Multi-variate analysis (principal components analysis)

For each of the PCAs the first two principal components (PCs) were retained as they explained over 99% of the variance in the data.

For the first PCA [fig. 20], PC1 explained 98.3% of the variance in the data and PC2 explained an additional 1.2%. The PCA of the carbon data revealed a high correlation between the AGC, litter and BGC, with a much weaker correlation between these three variables and the deadwood; SOC had the least correlation with these variables. The PCA also indicated that the highest amount of SOC was held in plot 5.

For the second PCA [fig. 21], PC1 explained 91.4% of the variance in the data and PC2 explained an additional 8.3%. The PCA of the soil data did not reveal any strong correlations between any of the soil nutrient variables. Only potassium and nitrate had some form of correlation with each other. Plot 4 was shown to have a strong relationship with sodium and to a lesser extent potassium and nitrate, which reflects the previous section. Similarly, plot 1 has a strong relationship with EC and to a lesser extent calcium.

For the third PCA [fig. 22], PC1 explained 91.4% of the variance and PC2 explained an additional 8.3%. The analysis of all the data indicated that pH was the only soil nutrient variable which was highly correlated with any of the carbon data. Calcium, nitrate and potassium all had a weaker correlation with the carbon data, while sodium and EC appear to have a very weak correlation with the carbon data.

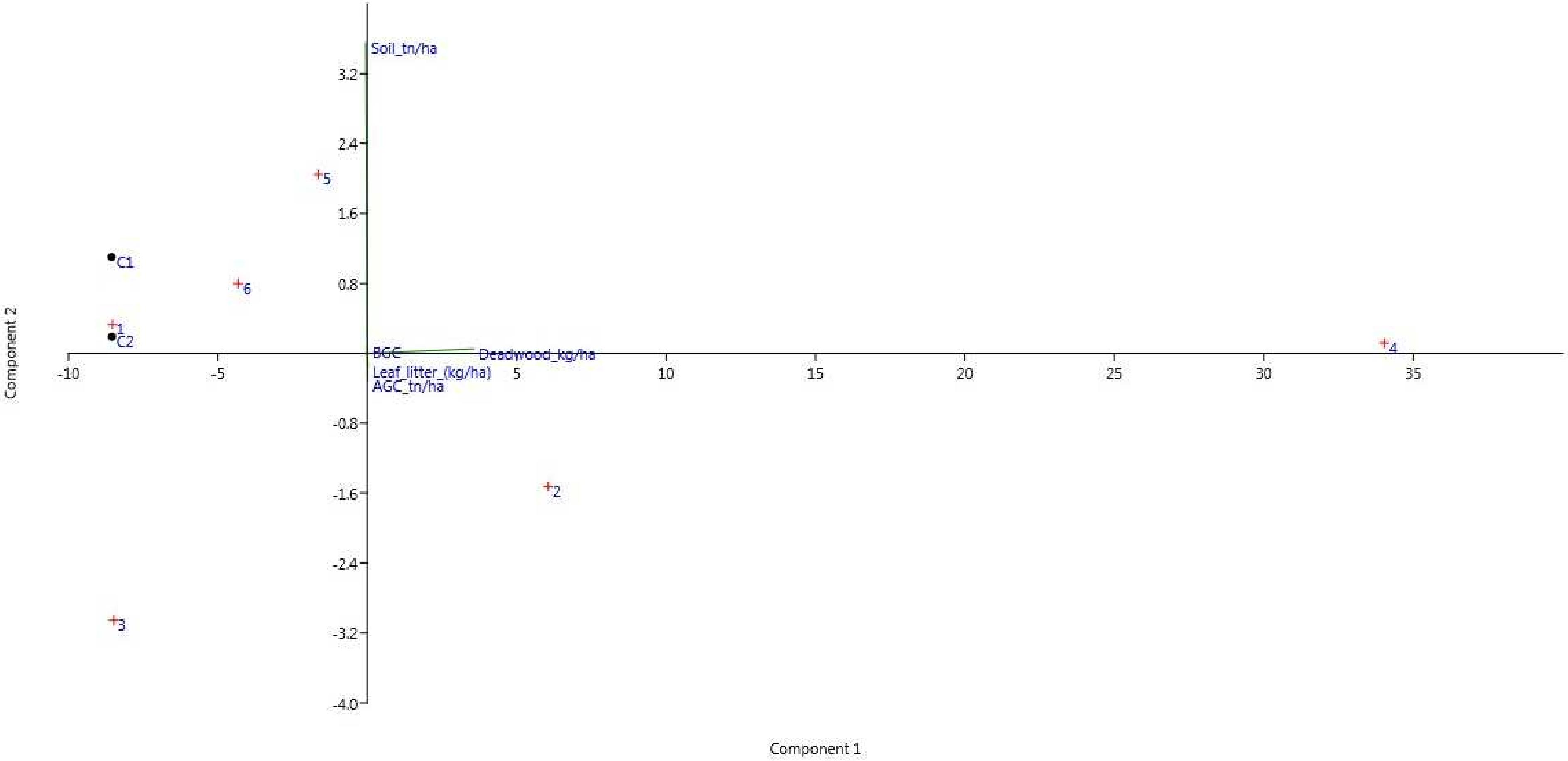

Fig. 20. Axes 1 and 2 of a principal components analysis on the carbon data. The percentage variance of principle components 1 and 2 were 98.3% and 1.2% respectively.

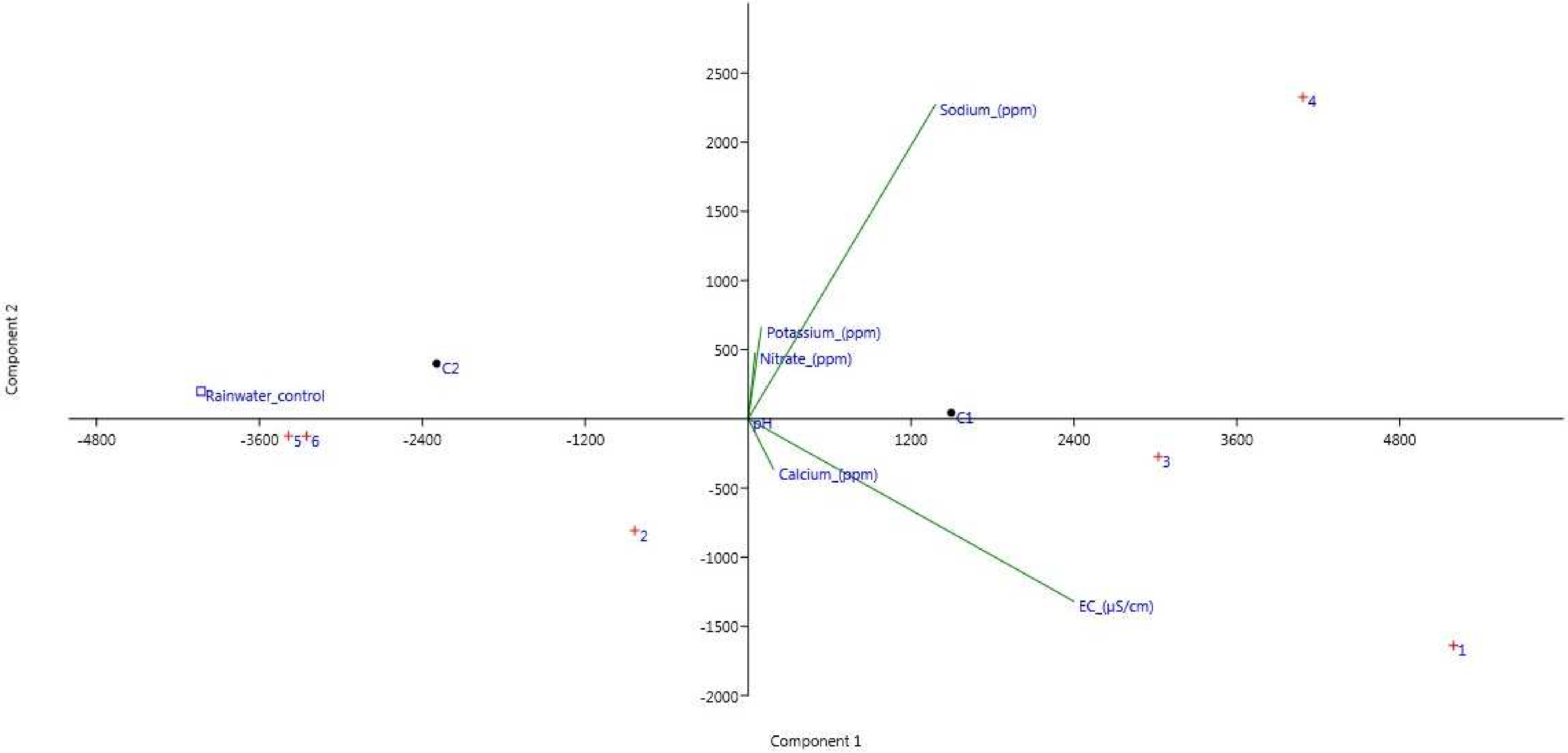

Fig. 21. Axes 1 and 2 of a principal components analysis on the soil nutrient data. The percentage variance of principle components 1 and 2 were 91.4% and 8.3% respectively.

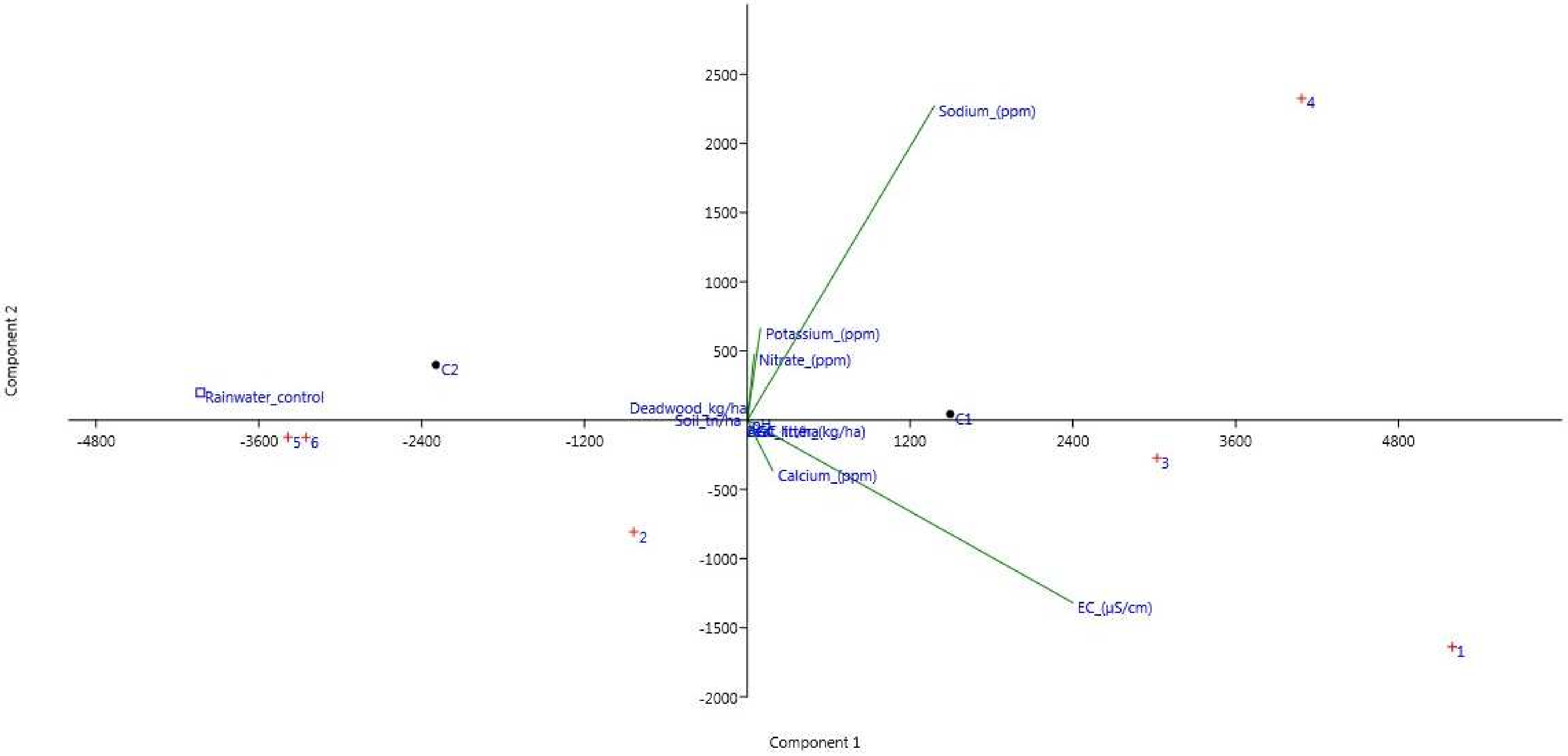

Fig. 22. Axes 1 and 2 of a principal components analysis on the carbon and soil nutrient data. The percentage variance of principle components 1 and 2 were 91.4% and 8.3% respectively.

7.0 Discussion

7.1 Carbon sequestration potential of the Millennium Forest

7.1.1 Aboveground carbon

AGC stored in live biomass was determined to be the second largest carbon pool within the Millennium Forest with approximately 52.15 ± 12.25 tonnes (using the across-plots mean). The numbers and sizes of trees within the plots can give some indication of the AGC potential within a plot. For example, plot 6 held the largest amount of AGC of all the study plots; this is reflected in the larger average trunk diameters and tree heights found within this plot, and thus larger amount of living biomass. In addition, plot 6 contained a large number of trees, the third highest number of trees of all the plots. Thus, it was to be expected that this plot would have a large amount of AGC stored within. The trees within plot 6 and the surrounding area are thought to be among the oldest planted within the forest and were (visually) noticeably larger during fieldwork. Similarly, plot 2 contained trees with much smaller trunk diameters and heights than plot 6; however, plot 2 recorded the largest number of trees of all the plots. Therefore, despite the smaller diameters and heights, the volume of biomass present within the plot resulted in plot 2 possessing the second largest amount of carbon of all the study plots. Plot 4 held, on average, the trees with the smallest diameters and tree heights and was the plot containing the second smallest amount of carbon. The only plot containing less carbon than this was plot 5, which also contained the least trees. Thus, increasing the biomass of *C. robustum* within the Millennium Forest will greatly increase carbon stocks within the restoration site.

Plot 4 and the surrounding area at the eastern extent of the Millennium Forest is thought to be among the first areas planted, however, plot 4 contained the smallest trees. It has been suggested locally that this area is at the limit of the natural *C. robustum* range, and is better suited to *C. rugosum* instead, but further study is needed to confirm this.

New planting techniques to increase initial growth rates after planting, and close gaps in the canopy quicker are presently being trialled by the SHNT at the Millennium Forest; these techniques involve dense plantings of *C. robustum* mainly within the newer compartments. These densely planted areas are then fenced off with rabbit-proof fencing and irrigated with sewage waste water. These management interventions appear to boost the initial growth stage of *C. robustum* and are resulting in faster growing trees which are quickly closing gaps in the canopy.

Although the largest trees documented by this study have yet to reach the much larger sizes of wild *C. robustum* at Peak Dale, they are still relatively young and theoretically have the capacity to achieve even greater volumes of biomass under ideal conditions. Thus, there is huge potential for future carbon storage capacity of the Millennium Forest when the current sizes of the majority of the planted trees within the site are compared with the larger trees, both within this site and at Peak Dale.

7.1.2 Litter

The literature states that this carbon pool adds little to the overall forest carbon stocks, as much of the carbon is released into the atmosphere through decomposition (Brown, 2002); the results of this study appear to corroborate this statement. The total amount of carbon estimated to be stored in litter within the Millennium Forest was negligible at approximately 4.9 ± 2.45 kg. However, a limiting factor in this method was that the total number of quadrats used to estimate litter stocks across the plots was very low (only one per plot); thus, a higher number of quadrats should first be undertaken in each plot and further analysed before eliminating this pool as a potential carbon store.

Another factor to consider is the presence of *C. edulis* within all of the study plots. C. edulis appears to delay decomposition of the *C. robustum* litter, as any litter which settles on top of *C. edulis* in place of bare ground appears to simply build up instead of decomposing. Where the planting trials have resulted in closure of canopy gaps, *C. edulis* perishes due to a lack of light and more *C. robustum* litter can reach the forest floor and begins to decompose. Consequently, litter stocks could prove valuable for carbon sequestration rates within the Millennium Forest in the future, once there are greater frequencies of closed canopies across the forest.

7.1.3 Deadwood

The amount of carbon stored in coarse wood debris in forests is thought to be significant (Brown, 2002); however, for this study deadwood was only collected from four study plots and of this, there was a relatively small amount. The largest amount of deadwood was collected from plot 4; this was to be expected as the trees in this area are thought to be among the oldest planted within the restoration site. Conversely though, the least amount of deadwood was collected from plot 6, which is also thought to hold older planted *C. robustum.*

An interesting detail from the deadwood data was that the entire amount of deadwood collected was in relatively early stages of decomposition; for the most decomposed wood it was still difficult to push a nail into the wood. This is perhaps not particularly surprising considering the maturity of the restoration site, as the trees have yet to fully mature through their life-cycle. However, the lack of advanced decomposition could also be due to low invertebrate activity at this site, which is needed to commence initial decomposition of wood. This is a concern that has also been raised by local conservationists and further study of the presence and distribution of invertebrates and their function within the site is undeniably needed.

7.1.4 Belowground carbon

While root biomass is generally considered to sequester a significant amount of carbon in forests (Vogt et al., 1998), estimations of BGC in this study were very low and indicated that this carbon pool was the second smallest within the Millennium Forest, with only litter carbon stocks being lower. However, a major limitation for the estimation of belowground carbon within this study was that there was not enough time to complete the re-sampling of the in growth cores in order to determine root production over the period of sampling. Thus, the BGC value is estimated on root biomass from the in growth cores only. Further intensive study of this carbon pool would be beneficial in establishing the reliability of this outcome.

7.1.5 Soil carbon

The most surprising result of the study was the quantity of carbon held within the soil; the soils of the Millennium Forest were found to hold the largest carbon stock of all the pools investigated. Although the literature states that soils hold the greater bulk of forest carbon stocks, and are considered to be the largest terrestrial carbon pool, the result for this study was still unexpected. This was mainly considering the heavy soil erosion that has occurred over the centuries and the present degraded condition of the Crown Wastes. It was also interesting that there did not appear to be a significant difference between the SOC in the study plots and the SOC in the control plots. It was thought that there would be more SOC in the study plots due to the presence of *C. robustum* and the resultant carbon sequestration in the soil from litter especially. However, the estimated SOC content in the control plots was larger than in 50% of the study plots, although there was no real difference in the values. Large swathes of the control plots were covered in *C. edulis*, which could explain the high SOC content of these plots, as *C. edulis* produces a significant amount of leaf litter which builds up and decomposes very slowly over time. While this means that carbon is still being sequestered within the soil from *C. edulis*, the time taken for the carbon from *C. edulis* to cycle through the ecosystem would take much longer than from decomposition of *C. robustum*.

The management intervention techniques used by the SHNT could potentially boost soil carbon sequestration rates within the Millennium Forest. Lal (2004) states that improved land management techniques can halt degradation and begin to increase rates of sequestration. Furthermore, the use of irrigation increases biomass production significantly, which in turn leads to SOC sequestration (Lal, 2004). Consequently, there is huge future potential for the SOC pool within the Millennium Forest restoration site.

7.1.6 Soil nutrients

The second question explored within this study was whether or not there was a relationship between the soil nutrients and the quantity of carbon produced within the Millennium Forest. The results of the principal components analysis suggested that pH was the only variable to have a strong correlation with the carbon data, and thus there must be some form of relationship between the two. Therefore, there does appear to be a relationship between the soil nutrients and the quantity of carbon stored within the Millennium Forest.

The high correlation of pH with the carbon results suggests that the acidity of the soil is an important factor when considering the carbon sequestration potential of the site. As there was no real difference between the acidity of the control plots and the study plots the *C. robustum* trees would have originally been planted on slightly acidic soil, which suggests that this species grows well on this type of soil.

7.1.7 Carbon sequestration potential of the Millennium Forest

The main question this study examined was whether planting *C. robustum* increases carbon stocks within the Crown Wastes. This study estimated approximately 349.7 ± 35.35 tonnes of carbon (9.99 ± 1.01 t ha^{-1}) to be stored within the Millennium Forest restoration site, throughout the five terrestrial carbon pools. As there was no real difference between the SOC values in the control plots and the study plots it is difficult to know how much SOC has been added to the soil as a result of the restoration efforts. However, although the area of the Crown Wastes is bigger than the Millennium Forest area, the main species present within the control plots (*C. edulis* and *A. semibaccata)* are not woody species and therefore do not contribute a great deal of live AGC to the area. While they do produce a large amount of litter (particularly *C. edulis*) this takes a long time to decompose and is unlikely to be adding much carbon to the soil. Consequently, the planting and establishment of *C. robustum* undoubtedly adds more carbon stocks to the area through the larger stocks of AGB and the carbon pools resulting from this (litter, deadwood and BGB) than the mono-patches of *C. edulis* and *A. semibaccata* present in the Crown Wastes. Thus, *C. robustum* does increase carbon stocks within the Crown Wastes, and over 15 years has increased the carbon store by 52.5 ± 12.20 tonnes.

7.2 A St Helena carbon off-setting scheme

It has been shown previously that the Millennium Forest currently stores a significant amount of carbon, which will only increase as the forest matures and the ecosystem functions are restored. It can be estimated that the resident population of St Helena currently produces approximately 2.29 tonnes of carbon annually (DFID, 2012). Estimates of CO_2 emissions from flights are 30.7 tonnes per trip (0.31 tonnes per passenger) (AECOM Ltd., 2011), although updated estimates based on recent information, such as flight destinations and aircraft to be used, are needed to give a true estimate of expected emissions. Establishing an island carbon off-setting scheme would allow both the local residents and those visiting the island to off-set their emission and contribute to a valuable endemic restoration project.

At this time the Millennium Forest site is unlikely to be suitable for off-setting schemes under the compliance market due to the larger fee required to join these schemes, and the stricter regulations applied to their projects. The restoration site could be eligible for a scheme under the voluntary market, but more in-depth research into the schemes available would need to be undertaken by the SHNT to find a scheme suitable for their requirements. However, given the amount of carbon currently stored within the site, and the time and resources needed to effectively monitor, report, and verify carbon stocks for international schemes, setting up a local scheme could be more financially viable for the SHNT and thus the restoration site at this time.

7.2.1 Co-benefits of a St Helena carbon off-setting scheme

While an increase in rates of carbon sequestration within the Millennium Forest is the main goal for any carbon off-setting scheme, there are a range of co-benefits that will also come with such a scheme. The tremendous re-growth of the trees within the Millennium Forest over the past 15 years has proven that the degraded Crown Wastes can be effectively rehabilitated, using ecological restoration. The continued restoration of an extirpated endemic forest, which will eventually become self-sustaining, will help to return lost ecosystem services to the area, providing a wealth of ecosystem processes and negating the need for intensive management of the forest. The scheme will also provide numerous recreational benefits for humans.

7.3 Limitations of the study

Other than those stated within the main discussion sections, the chief limitation of the study was that, due to time constraints on fieldwork, only six study plots could be completed in the summer fieldwork period. Ideally, more plots would be studied in order to see the variation across the site.

Another limitation not discussed above is that there was no laboratory analysis on sub-samples of the soil to verify the results of the LOI tests. However, the reason for this was that there were no soil testing laboratories available on the island, and the cost of transporting the samples to a lab overseas was out of the scope of this project. If funding is available in the future, this activity should be undertaken.

7.4 Further research

Aside from the suggestions detailed within the individual sections above, the main recommendation for further study would be to investigate the carbon storage potential of the wild trees at Peak Dale. These results could then be compared to the results of this study, and could provide an idea of the true carbon sequestration potential of the Millennium Forest site, were the trees ever to reach the sizes of those at Peak Dale.

Setting up more study plots could also be a target for future study, as eventually a site-specific allometric equation could be developed following more intensive research of the Millennium Forest site.

8.0 Conclusions

This study has found that the planting of *C. robustum* has increased the carbon stock within the Millennium Forest site over the past 15 years since intensive plantings began. This demonstrates that the restoration efforts are effective in rehabilitating the degraded soils of the Crown Wastes, and the site is a good candidate for a local carbon off-setting scheme. The analysis showed a high correlation of pH with the carbon values, suggesting that this species is adapted to grow on these slightly acidic soils. Thus, there is huge potential for future carbon sequestration in this area as the trees mature and plantings expand over the site.

The methods employed by this study can be used in further carbon assessment of the site or adapted for other sites, for further research into the carbon off-setting potential of St Helena's endemic trees. While the carbon store sequestered within Millennium Forest is small in global terms; the local potential of this site is clear. A carbon off-setting scheme will provide numerous co-benefits for the island, including valuable restoration of native habitat, re-establishment of ecosystem services, and also much-needed funding for an important restoration project.

Appendix 1: R script used to estimate aboveground biomass and carbon

Adapted from Platts, P. (2014). *Calculating carbon practical*. York: York Institute for Tropical Ecosystems.

```
setwd("Libraries/Documents")

#sets the working directory

getwd()

#checks that the working directory has changed



mftrees <- read.table(file.choose(), header=TRUE, sep="\t")

# loads the tree data - choose file which holds the table

mftrees

#checks the data just loaded is correct



mftrees$AGB <- 0.0673*(mftrees$WSG*mftrees$Diameter^2*mftrees$Height)^0.976
#estimates biomass using Chave et al.’s (2014) Model 4

mftrees$AGC <- 0.5 * mftrees$AGB

 #carbon is half the biomass



C.byplot <- aggregate(x=mftrees$AGC, by=list(mftrees$Plot), FUN="sum")

#sum carbon by plot

names(C.byplot) <- c("Plot", "AGC.kg")

#name the columns

C.byplot

#look at the table



C.byplot$AGC.kgha <- C.byplot$AGC.kg/0.04
```

```
#carbon in kg.ha, results stored in new column (20 x 20m =400m =0.04ha)
C.byplot
#look at table

C.byplot$AGC.tnha <- C.byplot$AGC.kgha /1000
# Convert results into the more conventional tonnes/hectare (1tn=1000kg)
C.byplot
#look at table

barplot(C.byplot$AGC.tnha, names=C.byplot$Plot, xlab="Plot", ylab="Aboveground Live Carbon (tn/ha)")
#view results on a bar plot

write.table(mftrees, "MF_trees_2015_withC.txt", quote=F, sep='\t')
write.table(C.byplot, "MF_trees_2015_withC_byplot.txt", quote=F, sep='\t')
# export the results into a table.
```

Abbreviations

AGB	Aboveground live biomass
AGC	Aboveground carbon
BD	Bulk density
BGB	Belowground biomass
BGC	Belowground carbon
C1	Control plot 1
C2	Control plot 2
CDM	Clean Development Mechanism
CH_4	Methane
cm	centimetre
CO_2	Carbon dioxide
DBH	Diameter at breast height
DFID	Department for International Development
EC	Electrical Conductivity
g	gram
GHG	Greenhouse gas
GW	Global warming
ha	hectare
h	height
IPCC	Intergovernmental Panel on Climate Change
JNCC	Joint Nature Conservation Committee
km	kilometre
LOI	Loss on ignition
m	metre

N_2O	Nitrous oxide
NPP	Net primary productivity
^oC	degrees Celsius
Pg	Petagram
r	radius
REDD+	Reducing Emissions from Deforestation and Forest Degradation)
RMS	Royal Mail Ship
SE	Standard error
SEI	Stockholm Environment Institute
SHG	St Helena Government
SHNT	St Helena National Trust
SOC	soil organic carbon
SOM	soil organic matter
t	tonne
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
WSG	Wood specific gravity

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