Carbon and Carbon Dioxide Sequestration Estimates at Selected Trees for Canterbury Planting Sites

By

Jane Colenso, Eilish Maddock, Chida Chapagain, Caleb James, Antonia Olszewski

GEOG309 Research for Resilient Environments and Communities
Research Project Report

October 2020

Table of Contents

Executive summary

The growing urgency for climate change action and Aotearoa New Zealand's (NZ) commitment to carbon (C) neutrality has seen a rise in the interest of quantifying the C sink that is the country's native forests. Conducted alongside Steve Bush of Trees for Canterbury (TFC), a charitable and eco-conscious plant nursery, this research quantifies the C sink established by TFC to address the research question: *What are the C stocks and carbon dioxide (CO_2) sequestration levels of four TFC planting sites?*

Three components at each site were quantified to generate site-wide C stock totals, including above-ground biomass (AGB), below-ground biomass (BGB), and soil. Previous GEOG309 research had quantified the AGB C at the four sites (Downie et al., 2019) and BGB C was quantified from these numbers using a root-shoot ratio of 25%. To quantify soil C, a total of 66 soil samples were taken across 14 sample plots within the four planting sites, with a further 12 taken on nearby unvegetated ground. Samples were dried and incinerated at 550°C for three hours to remove soil organic matter (SOM), and from this, soil organic carbon (SOC) was estimated. The SOC was averaged and extrapolated across each planting site to provide both an absolute C value and a value of C per hectare (ha). Absolute C values were converted to CO_2 for comparison to NZ emission data.

C values for NZ soils expressed in the literature ranged from 100–150 t C/ha^{-1}. The values obtained in this study were higher, with a range of 149–214 t C/ha^{-1}. These values were potentially overestimated due to the use of a high factor when converting SOM to SOC or a result of the small sample size. C stocks for NZ AGB and BGB in the literature were <50 t C/ha^{-1}, which is comparable with the range of values of 8–19 t C/ha^{-1} observed in this study. A total of 4,360 t C was found to be stored across the four planting sites, equating to a total of 15,987 t of CO_2.

Prominent time and financial limitations, as well as incomplete secondary data, impacted sampling and analysis methodology opportunities. Several assumptions had to be made surrounding the homogeneity of soil bulk density, vegetation density, and soil C. Given the control tree stand age has on C stocks, future studies should regularly estimate site-wide C totals to track temporal sequestration changes as the four sites age. If resources allow, an increase in sample size will generate more reliable findings and decrease uncertainty.

1. Introduction

The global interest in quantifying C stocks and assessing CO_2 sequestration levels continues to rise in parallel to growing concerns of climate change. Almost three times the amount of C is stored in the terrestrial biosphere than in the atmosphere, meaning small perturbations in terrestrial C can significantly impact the atmosphere (Tate et al., 1997). Soil C sequestration is the most simple and effective method for reducing atmospheric concentration of greenhouse gases (Pan et al., 2007; Sun et al., 2008).

Between 1990 and 2015, NZ's gross greenhouse gas emissions increased by 24% (Ministry for the Environment [MfE], 2017). CO_2 is a major contributor, increasing by 41% within the same time period (MfE, 2017). The rate of C sequestration is directly influenced by deforestation and forest degradation (Gibbs et al., 2010), and deforestation and land conversion are a primary cause for increasing CO_2 emissions. By converting native forest to other land-uses 180,000 ha of forested land has been lost (MfE, 2017). These transformations have been detrimental to national and global emissions. Thus, it is crucial to gain a greater understanding of the potential NZ's native forests have as C sinks.

NZ, alongside numerous other nations, have committed to the Kyoto Protocol and the Paris Agreement to achieve C neutrality (Ministry for Primary Industries [MPI], 2015). Recent legislation, such as the Zero Carbon Act, has also seen NZ commit to reducing C emissions (MfE, 2019). One of NZ's primary strategies to accomplish this goal is the 'One Billion Trees Programme' which aims to offset the adverse impacts caused by rising emissions through a combination of reforestation and afforestation (MPI, 2015; Te Uru Rakau, 2018).

Founded in 1990 by Tim Jenkins, TFC is a charitable and eco-conscious plant nursery. They are heavily involved in the community through providing native plants and hosting planting days, as well as providing environmental education (Trees for Canterbury [TFC], 2019). To this day, TFC have planted/donated more than one million plants to the community, greatly contributing to the One Billion Trees Programme (TFC, 2019).

Steve Bush, the manager of TFC and this project's community partner, proposed the idea of quantifying total C stocks and CO_2 sequestration levels at four TFC planting sites. The idea was to build on from a previous GEOG309 project by Downie et al. (2019), which investigated the C stocks in the AGB at Ōtukaikino Reserve (ŌR), Styx Mill Reserve (SMR), Travis Wetland Reserve (TWR) and Charlesworth Reserve (CR). This project aims to quantify site-wide C stocks and CO_2 sequestration levels within the same four plots, by estimating the BGB and soil C stocks in combination with existing AGB C stock estimates. This will increase the understanding of the impacts TFC has in offsetting NZ's CO_2 emissions.

2. Literature review

Due to the comprehensive dynamics of this project, a broad understanding of past research was required for an effective approach. A wide variety of literature was reviewed, providing guidance on methods and concepts critical for this project's accuracy.

Sampling and analysis methodology are important for an effective approach and accurate results. The combined effects of biological, physical and chemical processes over time cause spatial variation in soil properties. (Santra et al., 2008). Due to this large spatial and temporal variability, efficient estimation of SOC stocks and their changes before and after planting remains a challenge (Allen et al., 2010). Therefore, thorough evaluation of the methods used in previous studies to quantify C and CO_2 sequestration estimates were required. A study conducted by Makinde et al. (2017) assessed the C sequestered in an afforestation project in Oulwa, Nigeria. This research highlights the importance of the use of Landsat imagery and GIS processes to ensure accurate grids and sampling location. The use of a Garmin GPS receiver to accurately navigate to each sampling location was crucial (MacDicken, 1997).

Soil and tree characteristics are essential for understanding the impacts on C concentration in above and below-ground forested ecosystems. An important soil characteristic expressed by Graham et al. (2019) and Grüneberg et al. (2014) is bulk density. Bulk density is the weight of soil in a given volume. This project aimed to quantify C stocks in the top 30cm of soil, therefore, it is vital bulk density is determined to ensure accurate calculation of soil C. Environmental factors, such as soil moisture, are an important consideration within bulk density samples in order to avoid skewed results. Consideration of tree stand age was found to be equally important as it correlates with increasing C stocks. Li et al. (2018) described these impacts, providing evidence of this trend through research on tree shrub species, *Caragana intermedia*. Beets et al. (2014) also found total biomass C densities in tree stands of various ages were significantly different ($p<0.05$). It is important these findings are considered for accurate quantification of soil C and a precise interpretation of findings. This is particularly important as TFC sites are relatively young.

Beets et al. (2014) and Wei et al. (2013) concluded a significant difference in C storage between tree species. The two studies also found this to attribute to forest types. TFC sites are entirely made up of NZ endemic species, resulting in consideration of forest type being important for interpreting results. Literature regarding the endemic species of NZ is minimal, therefore, these results are only a partial understanding of the sites' C storage potential. Comprehensive research into endemic forests would increase the reliability of this project's results.

3. Methods

3.1. Research design and GIS

The methodological framework for this research was based on the collection of primary quantitative field data, the use of secondary quantitative field measurements, and developed methodologies from previous studies. Due to this project being a continuation of previous research undertaken by Downie et al. (2019), soil sampling was conducted within the same sample plots to achieve continuity. Figure 1 shows the individual components in which planting sites were divided into. Each 10 x 10m sampling plot represented a planting area, and the combination of planting areas comprised the planting site. The coordinates of the three sample plots at ŌR and SMR, and the four sample plots at TWR and CR were obtained and imported into ArcGIS (Figure 2; 3; 6). Coordinates were converted into XY points and then joined in their respective group of four to form polygons. Five soil sampling points were generated within each of the 14 sample plots, as illustrated in Figures 4, 5, and 7 (Chang et al., 2016). A simple random sampling method was chosen to determine these locations (Jensen & Shumway, 2010). Using ArcGIS's 'Create Random Points' tool, a total of 70 points were generated. Each point was assigned a northing and easting using the 'Add XY Coordinate' tool in order to locate it in the field. Coordinates were then uploaded into two handheld Garmin Rino 650 GPS units.

Figure 1. This image illustrates how the planting sites were divided up. The 10 x 10m sampling plot was where all samples and measurements were acquired. There were three sampling plots within SMR. These sampling plots are situated within a planting area. The combination of the three planting areas comprises the planting site.

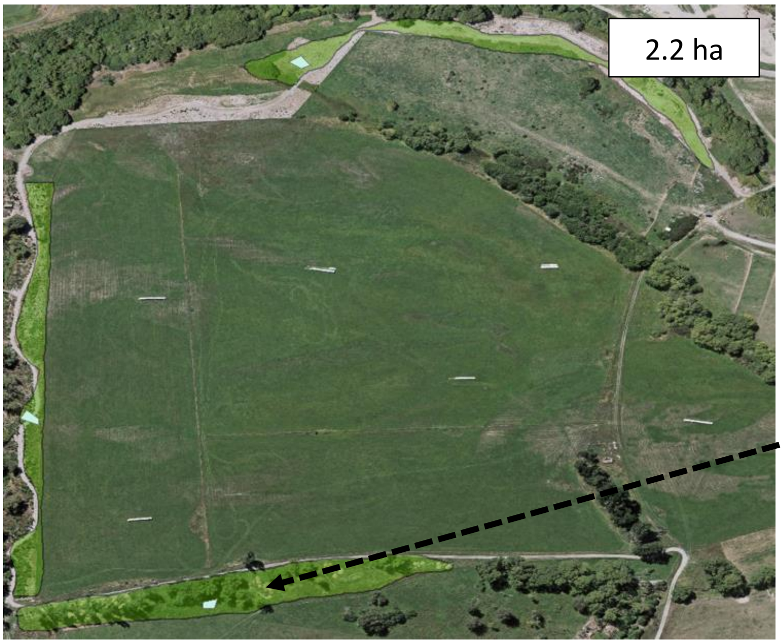

Figure 2. ŌR planting site.

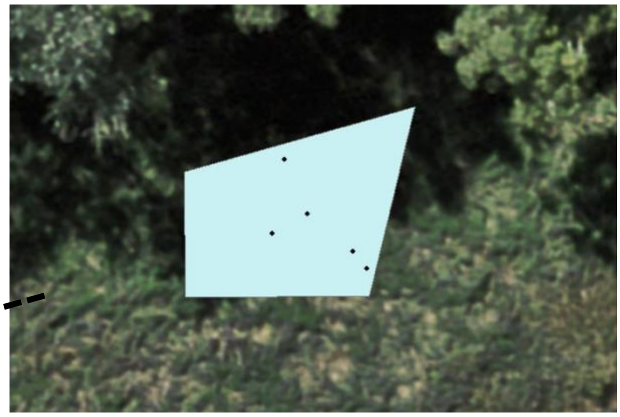

Figure 4. ŌR sampling plot 1, with randomly generated points.

Figure 3. CR planting site.

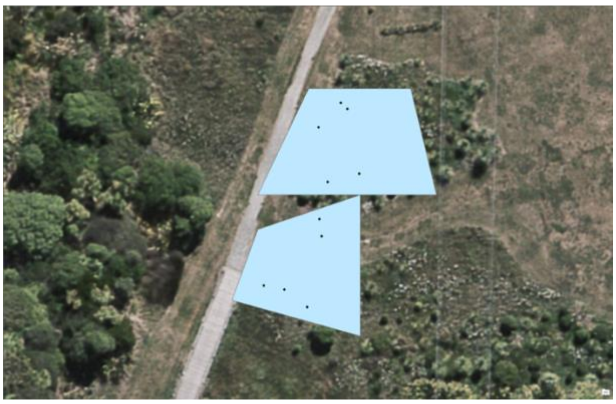

Figure 5. CR sampling plots 1 and 2, with randomly generated points.

Figure 6. TWR planting site.

Figure 7. TWR sampling plot 4, with randomly generated points.

3.2. Field work

The pre-recorded points were located in the field. The points were obtained within an estimated 1-2m error. However, due to the proximity of the points to each other and the dense overhead vegetation, up to a 5m error may be associated with each point. Once each point was located, the top 30cm of soil was sampled using an auger. This was completed for all five points within the sample plot. On occasion, issues were encountered with accessing the randomly selected sample points. At SMR there were occasions where only the first 15cm of the soil was obtainable as a result of obstructing stones. In some cases, the sampling point was completely inaccessible due to dense vegetation. A similar issue arose at CR, where vegetation was obscuring the soil at the sampling point location. In the case of these occurrences, an accessibility sampling method was utilised (Jensen & Shumway, 2010). However, four sampling points were not collected as they were completely unobtainable. This occurred at OR and TWR, where sampling points were located on a paved surface.

Soil samples were also obtained at each of the planting sites on unvegetated ground. This proved to be difficult given in most locations ground void of trees was scarce. Due to the locations also being available for public use, a large portion of unvegetated ground was paved over. At ŌR, much unvegetated ground was on private property or occupied by livestock. This meant the unvegetated samples were limited to a specific location and were chosen based on the accessibility sampling method. At CR, ŌR and SMR, three unvegetated samples were collected at the same location. However, for TWR, two samples were collected at one location while the third was taken from another location around 1km away.

A representative measurement of the soil density was also taken at each sample plot. This was completed by using a core sampler, which housed a plastic tube of a known volume. This was inserted twice into the ground to capture the top 30cm of soil. The plastic tube was placed into a bag and weighed. These measurements were also completed at the unvegetated locations.

3.3. Laboratory analysis

The loss-on-ignition (LOI) method was chosen for soil sample analysis. LOI is a well-developed and cost-effective method for quantifying soil C stocks (Ravindranath & Ostwald, 2008; Salehi et al., 2011; Dean, 1974; Hoogsteen et al., 2015). The LOI method involves incinerating soil samples to remove the SOM. This is the non-mineral portion of soil (Ravindranath & Ostwald, 2008) largely made up of animal and plant residue at various stages of decomposition (Salehi et al., 2011). The amount of SOC can be quantified using the difference in soil weight before and after incineration.

All 78 samples were dried in a 40℃ oven for four days to remove soil moisture. The samples were then put through a 2mm sieve to remove any rocks and debris. Soil aggregates larger than 2mm in diameter were crushed and passed through the sieve until an adequate sample size was achieved (Graham et al., 2019). Following this, each sample was dried for a further 24 hours at 105℃ to ensure all water in the samples was evaporated, as to not skew results.

Approximately 10g of soil from each sample was weighed into a separate crucible and ignited in a furnace. Initially, a method introduced by Dean (1974) was followed, which recommended the samples be incinerated for one hour at 550℃. However, the SOM in the first round of samples was not fully incinerated. Thus, the method was adapted to follow a study undertaken by Hoogsteen et al. (2015) which saw the samples incinerated for three hours.

3.4. Below-ground biomass and soil carbon calculations

The above-ground portion of tree biomass was previously estimated by Downie et al. (2019) in an allometric equation incorporating tree height and diameter at breast height (DBH). To account for C stocks within the total tree biomass, BGB was estimated using a root-shoot ratio. In New Zealand forests, BGB is typically 25% of the volume of AGB (Beets et al., 2012; Coomes et al., 2002), thus the AGB C values calculated by Downie et al. (2019) were multiplied by 1.25 to return total tree biomass C. BGB for ŌR, however, could not be calculated due to site accessibility issues encountered during the previous project.

The difference in soil weight following ignition represented SOM and was converted into a percentage. SOM (%) was multiplied by a factor of 0.5 to obtain the SOC (%), as SOM is approximately 50% SOC (Pribyl, 2010). The average SOC value within each planting area then provided an average SOC value across each planting site. A bulk density equation was then used, as provided by Huang et al. (2019) (Equation 1), which returned a value of C in t per ha for each site.

$$\text{SOC (t ha}^{-1}\text{) = SOC (\%) x bulk density (g cm}^{-3}\text{) x depth (cm)} \quad (1)$$

Soil C tonnage per ha was multiplied with each planting site's total area to provide the total planting site soil C stock. The tree biomass C stocks were then added to this to provide total planting site C. C is a fraction of CO_2, as a result of the ratio between their atomic weights (Romm, 2008). The atomic weight of C is 12 atomic mass units, while the weight of CO_2 is 44. To estimate each site's total CO_2 sequestration, total C tonnage was multiplied by the ratio of 44/12 (Romm, 2008).

4. Results

4.1. Soil carbon tonnage per hectare at the four planting sites

Figure 8 demonstrates which sites had the greatest C stock irrespective of size. CR had the greatest C stock at 214 t C/ha^{-1}, followed by TWR with 194 t C/ha^{-1}. SMR and ŌR had the lowest amounts with 182 t C/ha^{-1} and 149 t C/ha^{-1}, respectively.

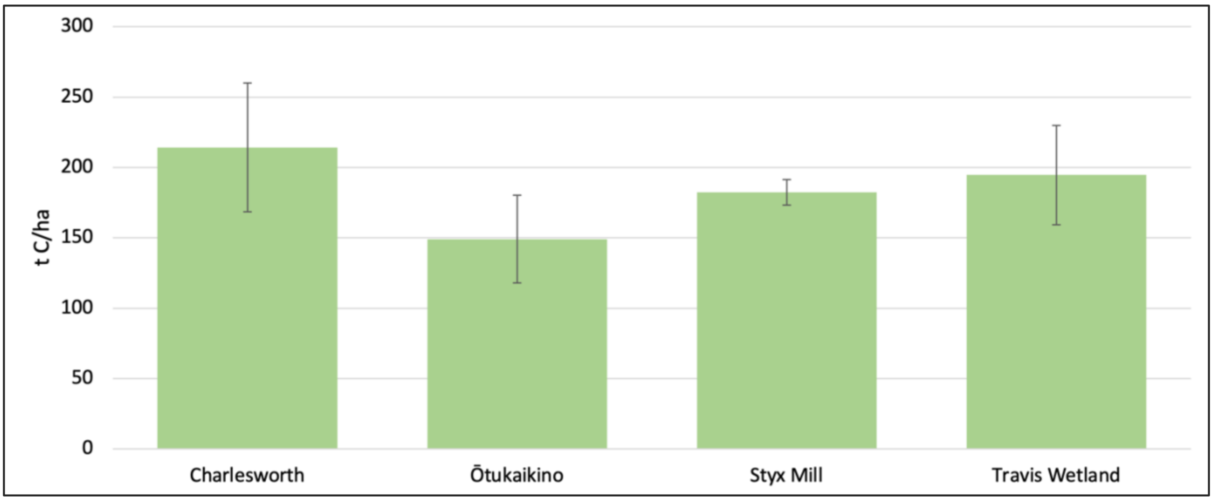

Figure 8. The soil C tonnage per hectare (t C/ha^{-1}) for each planting site. CR has the greatest C stock on a per hectare basis, followed by TWR, SMR and ŌR.

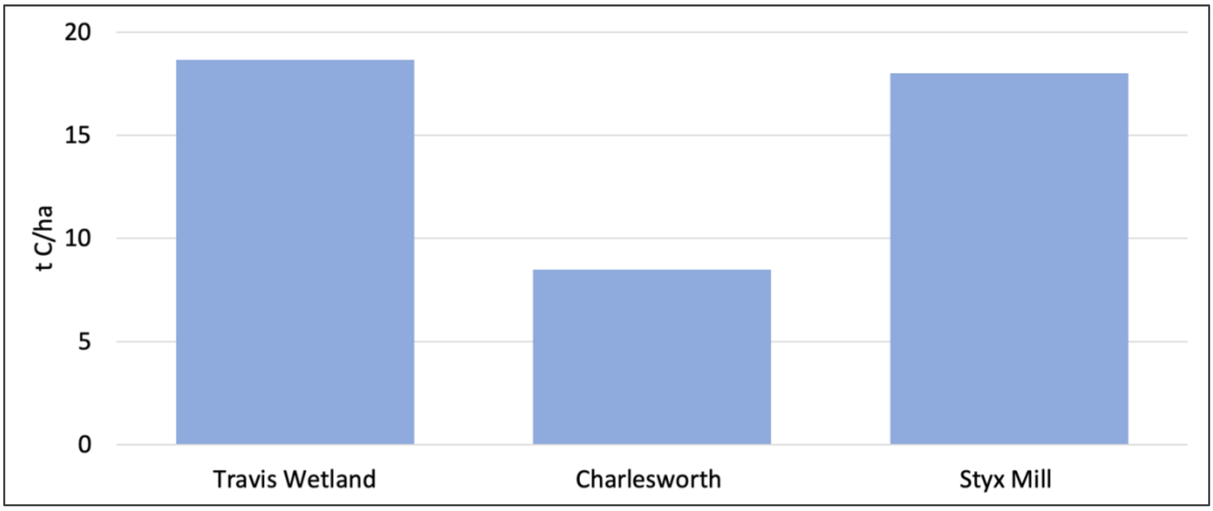

Figure 9. The tree biomass (AGB/BGB) C tonnage per hectare (t C/ha) for each planting site. TWR and SMR have almost identical tree biomass C stocks, with CR having the smallest.

Figure 9 shows the tree biomass (AGB/BGB) C stocks per ha at each planting site. TWR and SMR had almost identical tree biomass C stocks of 19 and 18 t C/ha^{-}1, respectively. CR had the smallest tree biomass C stock of 8 t C/ha^{-1}.

4.2. Differences in carbon stocks between unvegetated areas and planted sites

Figure 10 shows the differences between the SOC in the four planting sites and in nearby unvegetated areas. CR and ŌR have higher C stocks in the unvegetated areas compared to the planting sites. However, at CR and SMR, the opposite can be seen. ŌR exhibits the only statistically significant difference ($p < 0.05$).

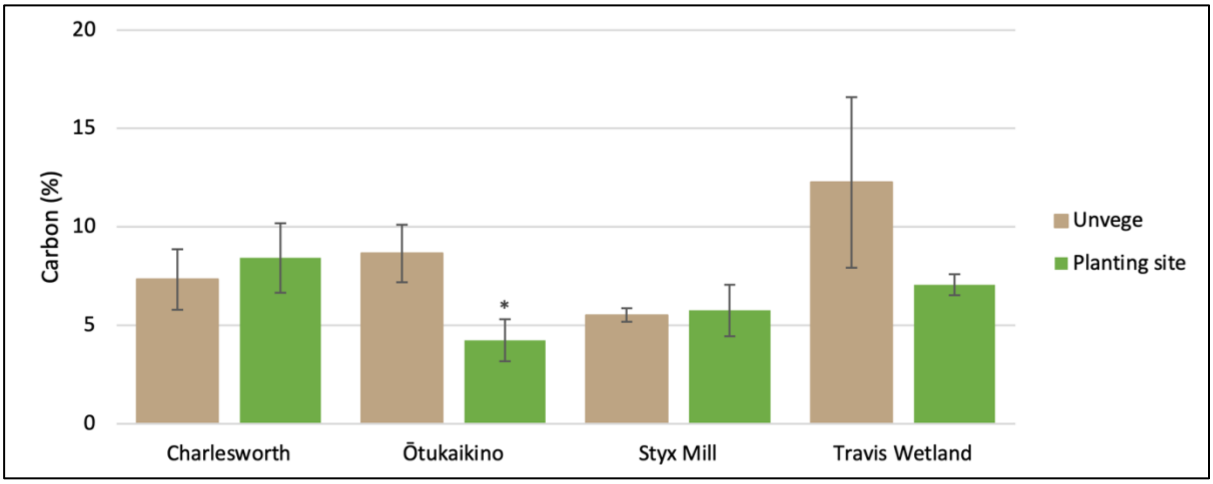

*Figure 10. Comparison between the SOC (%) measured between the four planting sites (green) and the nearby unvegetated areas (brown). * statistically significant difference at ŌR.*

4.3. Total C stocks and CO_2 sequestration estimates at the four planting sites

Table 1 shows the total C and CO_2 stocks at each planting site, as well as the size of each site. A clear trend in the data shows C and CO_2 stocks increase with increasing planting site size.

Table 1. The total C and CO_2 stocks at each of the four planting sites.

	TWR	*CR*	*SMR*	*ŌR*	*Totals*
Total planting area (ha):	11.84	1.57	5.78	2.20	21.39
Total planted site C (t):	2524.71	349.66	1157.77	327.96	4360.10
Total CO2 (t):	9257.27	1282.11	4245.18	1202.52	15,987.08

5. Discussion

The results showed variation in the total C stocks at the four selected TFC planting sites (Table 1). These variations were expected given the difference in planting site size. However, despite ŌR having a larger planting site, CR has a larger C stock. This can be attributed to the inability to measure tree biomass C stocks at ŌR. The combined total for all the planting sites is 4360 t C, which equates to 15,987 t CO_2.

The results produced in this study can be placed within the context of the wider literature. Tate et al. (1997) investigated the C stocks within NZ's vegetation and soils by reviewing the national databases. It was reported soil C estimates for the Canterbury region are around 100–150 t C/ha^{-1}, and AGB and BGB C estimates are <50 t C/ha^{-1}. The soil C results from this study are higher than those reported in Tate et al. (1997), ranging from 149–214 t C/ha^{-1}. This could be attributed to the differences in methodology. The factor of 0.5 used to convert SOM into SOC may have caused results to be higher. Furthermore, the high C stocks in TWR may be due to wetland's ability to store high concentrations of C (Ausseil et al., 2015; Minasny et al., 2017). The tree biomass C results are within the range Tate et al. (1997) outlines. The small values obtained for the tree biomass results may be due to the young age of the planting sites, as each site is no more than 21 years old (S. Bush, personal communication, September 24, 2020).

The four sites are dominated by gley soils, with TWR also having noteworthy amounts of organic soil (Manaaki Whenua, 2019). Gley soils are typically waterlogged as a result of their low elevation and high water table. This results in the soil becoming chemically reduced. Organic soils also have a high available water holding capacity. The pore space within waterlogged soils become filled with water and reduces the air content, creating anaerobic conditions. These conditions, present in both soil orders, restrict a large proportion of soil microbes from decomposing organic matter which leads to a build-up of SOM (McLaren & Cameron, 1996). This could also have contributed to the higher C stock estimates for the four sites compared to that of the literature.

The results show variation in C stocks between planting sites and unvegetated areas. Paul et al. (2002) looked at 43 global studies comparing the C stocks of 204 sites before and after afforestation or reforestation. Soil C was found to be highly variable among younger tree stands (<10 years). On average, a decrease of 3.46% of C was lost from the top 10cm of soil per year relative to the soil C measured in the first five years. This was followed by a decrease in the rate of C loss, leading to an eventual rise around 30 years after planting. This is an important consideration when interpreting the data from TFC sites, where the site's tree stand ages are not well documented. This makes it difficult to determine the impact as tree stand age is a major influence on soil C stocks (Paul et al., 2002).

The higher C stocks within the unvegetated areas can be explained by the past land-use. Much of NZ’s contemporary grasslands were converted from native forest. This has allowed for the retention of a significant portion of C formerly stored within forest ecosystems. The conversion to grassland also results in the continuation of C inputs to the soil (Tate et al., 1997). This helps to explain why the unvegetated soil has a significantly larger C stock than the planted areas at ŌR. Variations in decomposition rates of litter, which are dependent on litter type, species and canopy cover, may also have contributed to this result (Gliksman et al., 2017; O’ Connell & Sankaran, 1997, as cited in, Paul et al., 2002; Paul et al., 2002).

Christchurch resident emissions data can be used to contextualise the obtained results. Between July 2016 and June 2017, 2.49 million t of CO_2 was emitted in the city, which equates to 6.6 t per person (Christchurch City Council, 2018). Therefore, the four TFC planting sites have sequestered one year's worth of CO_2 emissions of 2,422 Christchurch residents to date.

5.1. Assumptions

Key assumptions for this project were the sample plots were representative of the total planting area at each of the locations, and the AGB C stocks calculated in 2019 were representative of current AGB C stocks. Furthermore, soil density measurements were assumed to be representative of each planting area.

5.2. Limitations

It is important to note the results found in this study are a guiding factor of the C and CO_2 stocks within the four sites. Field and laboratory methodologies were limited, and processes were chosen based on appropriateness given the time and financial constraints. This may have introduced slight inaccuracies into the results. The use of the accessibility sampling method may have also introduced bias into the results.

There are several other processes beyond the scope of this project, and their exclusion could have resulted in an over or under-estimation of findings. This includes soil abiotic properties, such as texture and pH, and climatic factors (Manning et al., 2015). The results are believed to be a reliable estimation of C and CO_2 stocks, however, C already in the soil prior to TFC plantings is accounted for within the measurements. This means not all the C measured in the soil can be attributed to the plantings.

The use of secondary data from the Downie et al. (2019) was a key limitation for this project. This was particularly prevalent for the calculation of the BGB. Due to the simplicity of the parameters included in the authors' allometric equation, a more detailed analysis on the BGB could not be completed. The accessibility issues faced by the previous group also meant a portion of data could not be calculated within this project.

Furthermore, the results are based on a small number of samples when compared to the size of the TFC plantings. This may have introduced inaccuracies as broad assumptions were made based on the degree of representability the samples had for the entire planting site.

6. Conclusion

A total of 4,360 t C is stored across the four planting sites, which equates to a total of 15,987 t CO_2. The estimation of C stocks per ha at each site returned slightly higher values than many reported in the literature. This could be a consequence of aforementioned limitations, such as the small sample size or the SOM to SOC factor. However, at two of the four sites, nearby unvegetated areas exhibited a higher C stock than that of the planting sites. The literature deems this not uncommon due to the history of NZ's grasslands and the disruption of soil C catalysed by afforestation and reforestation.

Future recurring C stock measurements should be taken at the four TFC planting sites to track C sequestration rates as the sites age. The literature suggests the sites' C stocks could surpass neighbouring unvegetated areas once tree stands are older than 30 years. With the growing cruciality of native forests as sinks for rising C emissions, quantifying their impact is invaluable.

TFC have planted and donated over one million trees, with a goal of two million and beyond. The results of this research capture their impact at this moment in time, but the impact they are having toward NZ's C neutrality goal will continue to grow.

Acknowledgements

We would like to acknowledge the support of John Thyne and Clive Sabel for their assistance with GIS, Justin Harrison and Chris Grimshaw for their advice on field and laboratory equipment, and Riley Downie, Jessica Faris, Hayley Lam, and Lydia Shirley for the use of their research as a foundation to ours. We would also like to thank Steve Bush and Robin Stove from Trees for Canterbury for their time, enthusiasm, and providing us the opportunity to undertake this research. Finally, we would like to acknowledge the support of our supervisor, Alexandra Meister, for helping guide us throughout the duration of our research.

References

Allen, D. E., Pringle, M. J., Page, K. L., & Dalal, R. C. (2010). A review of sampling designs for the measurement of soil organic carbon in Australian grazing lands. *The Rangeland Journal, 32*(2), 227–246. DOI: 10.1071/RJ09043

Ausseil, A. E., Jamali, H., Clarkson, B. R., & Golubiewski, N. E. (2015). Soil carbon stocks in wetlands of New Zealand and impact of land conversion since European settlement. *Wetlands Ecology and Management, 23*(5), 947–961. doi:10.1007/s11273-015-9432-4

Beets, P. N., Kimberley, M. O., Oliver, G. R., Pearce, S. H., Graham, J. D., & Brandon, A. (2012). Allometric equations for estimating carbon stocks in natural forest in New Zealand. *Forests, 3,* 818–839. doi: 10.3390/f3030818

Beets, P. N., Kimberley, M. O., Paul, T., Oliver, G., Pearce, S., & Buswell, J. (2014). The inventory of carbon stocks in New Zealand's post-1989 natural forest for reporting under the Kyoto protocol. *Forests*, *5*(9), 2230–2252. Doi:10.3390/f5092230

Chang, X., Bao, X., Wang, S., Zhu, X., Luo, C., Zhang, Z., & Wilkes, A. (2016). Exploring effective sampling design for monitoring soil organic carbon in degraded Tibetan grasslands. *Journal of Environmental Management, 173,* 121–126. doi: 10.1016/j.jenvman.2016.03.010

Christchurch City Council. (2018). *Christchurch community carbon footprint 2016/17.* Retrieved September 28, 2020, from https://ccc.govt.nz/assets/Documents/Environment/Climate-Change/Christchurch-Community-Carbon-Footprint.pdf

Coomes, D. A., Allen, R. B., Scott, N. A., Goulding, C., & Beets, P. (2002). Designing systems to monitor carbon stocks in forests and shrublands. *Forest Ecology and Management, 164,* 89–108.

Dean, W. E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. *Journal of Sedimentary Petrology, 44*(1), 242–248.

Downie, R., Faris, J., Lam, H., & Shirley, L. (2019). *Estimation of carbon sequestration levels in Trees for Canterbury plantings.* Retrieved July 20, 2020, from https://canterbury.ac.nz/science/schools-and-departments/geog/community-engagement/

Dymond, J., Ausseil, A., Kirschbaum, M., Carswell, F., & Mason, N. (2012). Opportunities for restoring indigenous forest in New Zealand. *Journal of the Royal Society of New Zealand, 43*(3), 141–153. doi: 10.1080/03036758.2012.736393

Graham, J., Voroney, P., Coleman, B., Deen, B., Gordon, A., Thimmanagari, M., & Thevathasan, N. (2019). Quantifying soil organic carbon socks in herbaceous biomass crops grown in Ontario, Canada. *Agroforestry Systems, 93,* 1627–1635.

Grüneberg, E., Ziche, D., & Wellbrock, N. (2014). Organic carbon stocks and sequestration rates of forest soils in Germany. *Global Change Biology, 20*(8), 2644–2662. doi:10.1111/gcb.12558

Gliksman, D., Haenel, S., Osem, Y., Yakir, D., Zangy, E., Preisler, Y., & Grünzweig, J. M. (2017). Litter decomposition in Mediterranean pine forests is enhanced by reduced canopy cover. *Plant and Soil, 422*, 317–329.

Hoogsteen, M. J. J., Lantinga, E. A., Bakker, E. J., Groot, J. C. J., & Tittonell, P. A. (2015). Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. *European Journal of Soil Science, 66,* 320–328. doi: 10.1111/ejss.12224

Huang, J., Hartemink, A. E., & Zhang, Y. (2019). Climate and land-use change effects on soil carbon stocks over 150 years in Wisconsin, USA. *Remote Sensing (Basel, Switzerland), 11*(12). doi:10.3390/rs11121504

Jensen, R. R. & Shumway, J. M. (2010). Sampling our world. In B. Gomez & J. P. Jones (Eds.), *Research methods in geography: a critical introduction* (pp. 77–90). Wiley-Blackwell.

Li, Q., Jia, Z., Feng, L., He, L., & Yang, K. (2018). Dynamics of biomass and carbon sequestration across a chronosequence of Caragana intermedia plantations on alpine sandy land. *Scientific Reports, 8*(1). doi:10.1038/s41598-018-30595-3

MacDicken, K. G. (1997). *A guide to monitoring carbon storage in forestry and agroforestry projects.* USA: Winrock International Institute for Agricultural Development.

Manaaki Whenua. (2020, February 18). *Maps and Tools*. S-Map Online. https://smap.landcareresearch.co.nz/maps-and-tools/app/

Manning, P., de Vries, F. T., Tallowin, J. R. B., Smith, R., Mortimer, S. R., Pilgrim, E. S., Harrison, K. A., Wright, D. G., Quirk, H., Benson, J., Shipley, B., Cornelissen, J. H. C., Kattge, J., Bönisch, G., Wirth, C., & Bardgett, R. D. (2015). Simple measures of climate, soil properties and plant traits predict national-scale grassland soil carbon stocks. *The Journal of Applied Ecology, 52*(5), 1188–1196. doi:10.1111/1365-2664.12478

McLaren, R. G. & Cameron, K. C. (1996). *Soil Science*. Oxford University Press.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., . . . Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma, 292*, 59–86. doi:10.1016/j.geoderma.2017.01.002

Ministry for Primary Industries [MPI]. (2015). *An overview of forestry in the emissions trading scheme.* Te Uru Rakau, Forestry New Zealand. Retrieved from https://www.teururakau.govt.nz/dmsdocument/6991

Ministry for the Environment [MfE]. (2019). *Climate Change Response (Zero Carbon) Amendment Act.* Retrieved October 10, 2020, from https://www.mfe.govt.nz/climate-change/zero-carbon-amendment-act

Ministry for the Environment [MfE]. (2017). *New Zealand's greenhouse gas inventory 1990–2015*. (Publication Number: ME 1309).

Paul, K. I., Polglase, P. J., Nyakuengama, J. G., & Khanna, P. K. (2002). Change in soil carbon following afforestation. *Forest Ecology and Management*, *168,* 241–257.

Pribyl, D. (2010). A critical review of the conventional SOC to SOM conversion factor. *Geoderma, 156,* 75–83. doi: 10.1016/j.geoderma.2010.02.003

Ravindranath, N. H. & Ostwald, M. (2008). *Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects.* Springer.

Santra, P., Chopra, U. K., & Chakraborty, D. (2008). Spatial variability of soil properties and its application in predicting surface map of hydraulic parameters in an agricultural farm. *Current Science, 95*(7), 937–945. https://www.jstor.org/stable/24103193

Salehi, M. H., Hashemi Beni, O., Beigi Harchegani, H., Esfandiarpour Borujeni, I., & Motaghian, H. R. (2011). Refining soil organic matter determination by loss-on-ignition. *Pedosphere, 21*(4), 473–482.

Schwendenmann, L. & Mitchell, N. D. (2014). Carbon accumulation by native trees and soils in an urban park, Auckland. *New Zealand Journal of Ecology, 38*(2), 213–220.

Scott, N. A., Tate, K. R., Giltrap, D. J., Tattersall Smith, C., Wilde, H. R., Newsome, P. J. F., & Davis, M. R. (2002). Monitoring land-use change effects on soil carbon in New Zealand: quantifying baseline soil carbon stocks. *Environmental Pollution (1987), 116,* S167– S186. doi:10.1016/S0269-7491(01)00249-4

Tate, K. R., Giltrap, D. J., Claydon, J. J., Newsome, P. F., Atkinson, I. A. E., Taylor, M. D., & Lee, R. (1997). Organic carbon stocks in New Zealand's terrestrial ecosystems. *Journal of the Royal Society of New Zealand, 27*(3), 315–335. doi:10.1080/03014223.1997.9517541

Te Uru Rakau. (2018). *One Billion Trees Fund: Report on policy and design recommendations.* Retrieved September 25, 2020, from https://www.mpi.govt.nz/dmsdocument/32908-3-appendix1-report-onpolicy-and-design-recommendations-oia

Trees For Canterbury. (2019). *Our story.* Retrieved September 25, 2020, from https://www.treesforcanterbury.org.nz