Carbon dynamics in apple orchards in New Zealand and their integration into Life Cycle Assessment

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Edouard Périé

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Abstract

Soil carbon sequestration can help mitigate climate change and soil carbon contributes to many of the ecosystem services provided by the soil; thus soil carbon contributes to the sustainability of food production systems. However, changes in soil carbon are difficult and costly to measure due to two constraining characteristics: the spatial variability of the stocks as well as the typically small changes in carbon stocks over time. Consequently, environmental assessment tools such as Life Cycle Assessment (LCA) and carbon footprinting (CF) generally exclude the changes in soil carbon stocks from their analyses. Yet global supermarket chains use the results from these tools to inform consumers about greener products.

In New Zealand (NZ), production of horticultural products such as apples is very focussed on export markets. Therefore, if it can be demonstrated that the production of New Zealand apples maintains or increases the carbon stock of the orchard soil and above-ground biomass, this could lead to a reduced net CF and might enhance access to prime retailers' shelves in major export markets.

The main aims of this research were (a) to develop a practical method for measuring a statistically significant and powerful change in the soil-carbon stock of an apple orchard block in New Zealand, and (b) to assess a method to estimate the standing woody biomass carbon stock in apple orchards, in order to provide reliable data for the CF of NZ apples. Since there are no data available, this research sought to quantify the changes in soil-carbon stocks in apple orchards by means of a chrono-sequence.

A review of LCA and CF case studies accounting for changes in soil-carbon identified the need to focus on collecting deep, site specific, geo-localised and time-dependent soil-carbon data, as well as communicating its variability and statistical uncertainty for interpretation and transparency of LCA and CF results. Therefore, in a first step to develop a protocol for quantifying the carbon stocks in the soil, a four-year-old apple orchard block was intensively sampled to one meter depth to measure the soil-carbon stock and the spatial patterns. It was found that the soil-carbon stock was influenced

by tree planting pattern, and the minimum sampling requirements were determined to detect, from sampling every 20 years, a change of the mean (175.1± 10.8 t C/ha) of 10 % due to the spatial and temporal characteristics of soil carbon. This required sampling nine sites in a systematic grid in the orchard block, with four pooled samples per site evenly distributed between and outside the wheel tracks, at a total cost of NZ$1,590 per sampling campaign. This cost of monitoring seems affordable as it is equivalent to just 0.5% of the value of export apples at ship-side in New Zealand. While price premiums could compensate for it, using the carbon market seems unrealistic at present because the price of carbon would need to reach at least NZ$182/tonne.

To inform development of a protocol for quantifying the carbon stocks in the woody biomass in a commercial apple orchard block, the relationship between the trunk cross-sectional area (TCA) and the woody dry mass (DM) of the trees was assessed using 10 trees that were destructively harvested. It was found that using this relationship together with a high number of TCAs measured *in situ* in the orchard block facilitated the rapid and cost effective estimation of the woody biomass carbon stocks at the orchard block scale. At the end of the orchard life, the carbon has been stored out of the atmosphere for the lifetime of the trees and this contributes to reduced climate change. Furthermore, at the end of life the trees may be burned for convenience, chopped for firewood or transformed into biochar and applied to soils. It was found that the biochar scenario provided the largest reduction, and that this benefit was equivalent to 0.7% of the carbon footprint of apples exported to Europe. The choice of a time horizon for the assessment was found to be critical, with comparative results varying up to three fold between the 20 year and the 100 year time horizons.

Regarding changes in soil carbon stocks over time, the four-year-old orchard block was part of a 12 year-old chronosequence, also including a one-year, a six-year and a twelve-year old block. The same sampling protocol was carried out in these three other blocks. It was found that all orchard blocks had relatively high soil-carbon stocks. Moreover, there was no significant difference in soil-carbon stocks at the 5% level between the one-year-old, the six-year-old and the twelve-year-old blocks of the chronosequence. Based on the soil-carbon stocks of these three blocks, current management

practices seem to be maintaining these carbon stocks over time. Therefore, unless management practices are modified, monitoring may not be required. However, this maintenance of relatively high soil-carbon stocks in orchard systems is beneficial for climate change and the ecosystem services provided by the soil. It should therefore be treated as such in LCA and CF studies although a method is yet to be developed.

In addition, despite a high similarity with the other blocks, the four-year-old block showed a higher, significantly different soil-carbon stock, and the levels of variability in soil-carbon stocks were found to be different between all the blocks. This demonstrates the high local specificity of soil-carbon stocks. The six year-old block displayed a coefficient of variation (14%) larger than the other blocks, and so an analysis of sampling requirements was conducted for this block. A change of 10% of the mean could, in theory, be observed by collecting a total of 78 samples, bulked two by two, for carbon content, and using 39 bulk density profiles, all to one meter depth. The associated cost of monitoring is NZ$ 9,420 and is equivalent to 1% of the value of export apples at ship-side in New Zealand. Monitoring soil-carbon stocks would seem therefore affordable, even in the more variable orchard block.

Overall, this research has made four main contributions to the science. Firstly, a robust, practical and adaptable protocol for monitoring soil-carbon stocks in apple orchards has been developed. Secondly, a rapid and cost effective method to estimate the carbon stock in standing woody biomass has been verified for use in commercial apple orchard blocks; accounting for this biomass carbon stock may lead to a net reduction of up to 4.6% of the New Zealand based (cradle to NZ port) CF of apples exported to Europe; Thirdly, a chrono-sequence of orchard blocks has suggested that current management practices in apple orchards appear to achieve the maintenance of high soil-carbon stocks over time, and it is suggested that this maintenance should be recognised as beneficial in CF and LCA studies. Finally, soil carbon stocks have been found to be spatially variable within and between similar orchard blocks; therefore LCA and CF studies should use site specific data and communicate the uncertainty of their soil-carbon stock estimates.

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Without Nathan Arnold, I wouldn’t have gone through attempting to sample 640 soil cores down to one metre, in winter, in a cloud of petrol-engine fumes. Your leadership to get the job done “no matter what” is a skill that very few people have. Thank you heaps, and all the best to you and your family!

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Finally, I dedicate this work to my beloved family, in particular:
To my parents Claude M.T. Jaraudias and Jean L. Périé, who provided the environment for my development. You are the best parents a child could dream of. To my sister, Adèle A. Périé, who I am very proud of. To my wife Elise, and to my son, Manaaki P. Périé, may you always be healthy, happy and well, and look towards the future.

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%C	Carbon content
ATA	Allocated Tree Area
BD	Bulk Density
C	Carbon
CF	Carbon Footprint
CV	Coefficient of Variation
LCA	Life Cycle Assessment
NZ	New Zealand
NZD	New Zealand Dollar
SD	Standard Deviation
SE	Standard Error

Chapter 1:

Introduction & Objectives

"[…]in the late 1950s, the National Weather Service began measuring the levels of carbon dioxide in our atmosphere, with the worry that rising levels might someday disrupt the fragile balance that makes our planet so hospitable."

"[…] our planet is changing in ways that will have profound impacts on all of humankind."

"Sticking your head in the sand might make you feel safer, but it's not going to protect you from the coming storm."

"[…]that image in the photograph, that bright blue ball rising over the moon's surface, containing everything we hold dear -- the laughter of children, a quiet sunset, all the hopes and dreams of posterity -- that's what's at stake. That's what we're fighting for. And if we remember that, I'm absolutely sure we'll succeed.

Barrack Obama, President of the United States of America, 25th June 2013, Georgetown University, Washington, D.C.

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1.1. Climate change and its drivers

Changes in the global climate have been observed in recent years. There has been an increase in the global average temperature, changes in the trends of precipitation and increasing drought events, a decrease in the amount of ice on the Earth, and rising sea and ocean levels (IPCC 2013). These climate trends are attributable to the increase in the greenhouse gas (GHG) concentrations in the atmosphere, such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (IPCC 2007; IPCC 2013). Indeed, following 10,000 years of relative stability in atmospheric CO_2 below 285 ppm, human activities during the industrial era of the last 250 years have resulted in an increase up to a level of 379 ppm in 2005, half of which occurred in the last 30 years (IPCC 2007; IPCC 2013). As shown on Figure 1.1, the concentration of CO_2 in the atmosphere exceeded 400 ppm for the first time, on daily average, in June 2013 at the Mauna Loa Observatory, in Hawaii. The Intergovernmental Panel on Climate Change (IPCC)[1], in its Fifth Assessment Report, states that "carbon dioxide is the largest single contributor to historical radiative forcing from either the perspective of changes in the atmospheric concentration of CO2 or the impact of changes in net emissions of CO2". The IPCC has established that globally, fossil fuel combustion is responsible for more than 67% of this increase in atmospheric CO_2. Emissions due to changes in land use, mainly deforestation and subsequent vegetation burning, plus a smaller contribution from changes in agricultural practices, are considered the major cause of the remainder (IPCC 2007; 2013). Methane and nitrous oxide are two other important GHGs, and both showed a dramatic increase over the last 250 years, mainly due to human activities (IPCC 2007; 2013). The increase in atmospheric methane is mainly

[1] The IPCC states its definition and role on its website: http://www.ipcc.ch. *The IPCC is a scientific body under the auspices of the United Nations (UN). It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change. It does not conduct any research nor does it monitor climate related data or parameters.*
[…] One of the main IPCC activities is the preparation of comprehensive Assessment Reports about the state of scientific, technical and socio-economic knowledge on climate change, its causes, potential impacts and response strategies. The IPCC also produces Special Reports, which are an assessment on a specific issue and Methodology Reports, which provide practical guidelines for the preparation of greenhouse gas inventories."

due to “emissions from wetlands, ruminant animals, rice agriculture and biomass burning, with smaller contributions from industrial sources including fossil fuel-related emissions”, while the increase in nitrous oxide in the atmosphere results from “agriculture and associated land use change” (IPCC 2007; 2013).

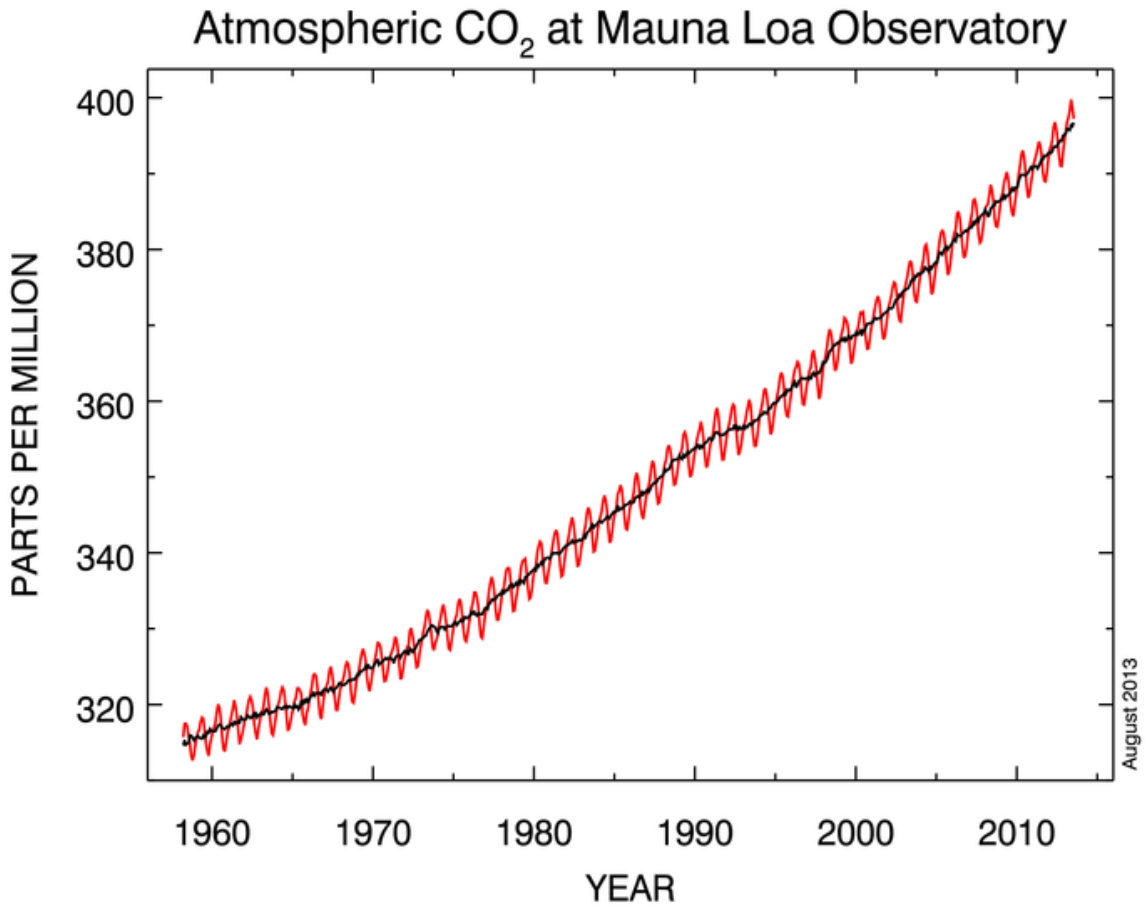

Figure 1. 1 Changes in the atmospheric CO_2 concentration at the Mauna Loa Observatory, Hawaii, August 2013. Source: NOAA (2013)

1.2. Climate change mitigation

A number of climate change mitigation strategies have been identified by the IPCC, in order to reduce anthropogenic emissions globally, and also to enhance removal of GHGs from the atmosphere. The IPCC (Smith et al. 2007) calculated the mitigation potential embedded in each economic sector that could be realised by year 2030 estimated for different prices of carbon in the carbon market. The building sector has the highest overall mitigation potential, independently of the price of carbon and at a low price of carbon (<US$20/tonne CO_2eq):

The energy supply sector comes second, followed by the transport sector (third), the agricultural sector (fourth), the forestry sector (fifth), the industry sector (sixth) and the waste management sector.

However, the ranks of the various sectors changes for a high price of carbon (<US$100/tonne CO_2eq): while the building sector remains first, the agricultural sector has the second highest potential to mitigate climate change, followed by the industry, the energy supply sector, forestry, transport and waste management (Barker 2007). These changes of rank are mainly due to the financial incentive to implement mitigation measures brought by the higher price of carbon on the carbon market.

As opposed to other sectors, agriculture's potential to mitigate climate change relies very much on utilizing the GHG sink potential of the soil, rather than reducing emissions. Removals of CO_2 from the atmosphere through soil-carbon sequestration represents 89% of the agricultural mitigation potential (Smith et al. 2007). The remainder is principally dependent on more efficient use of nitrogen fertiliser (reduction of N_2O emissions) and reduction of enteric fermentation from ruminants (reduction of CH_4 emissions).

1.3. The composition and roles of soil carbon

After a brief description of soil carbon and its formation processes, this section focuses, first, on the capacity of soil-carbon sequestration to mitigate climate change and second, on its various roles in sustaining ecosystem services, many of which are vital to the long term survival of life on Earth.

1.3.1. Soil carbon composition

Soil carbon is commonly divided in two: soil organic carbon (SOC), and soil inorganic carbon (SIC) (Batjes 1996; Lal 2008). SOC is the major constituent of soil organic matter (SOM) and comprises plant-, animal-, and microbe-derived material at all decomposition stages (Post and Kwon 2000). SIC is composed of secondary carbonates, created by dissolution of

atmospheric CO_2 followed by its re-precipitation due to cationic interactions in the soil profile (Lal et al. 2007). The total carbon stock of the soil includes both organic and inorganic carbon.

Organic matter enters the soil from above the ground, with the fall of plant tissues on the soil surface followed by its mineralisation, and from below ground, through roots turnover and root exudates. Historically, the transformation of above ground plant residues to soil carbon has received more interest than that of below ground inputs (Rasse et al. 2005). However, there is now evidence that soil carbon is mostly composed of root derived carbon (Schmidt et al. 2011). For example, Kong and Six (2010) reported that after less than one year, around 52 % of root derived C remained in the soil versus only 4% of shoot derived C. Similarly, Rasse et al. (2005) reviewed the contribution of roots to soil carbon to be on average 2.4 times that of shoots, and suggest that this ratio is likely to become higher for the deeper soil horizons. This highlights the plant roots as a major contributor to SOC dynamics. In addition, the spatial allocation pattern of the roots in the soil profile, which depends on vegetation type i.e. perennials develop deeper roots than annual plants, contributes to SOC dynamics (Jobbagy and Jackson 2000).

Carbon is also transported in soils when it is in solution, in the form of dissolved organic carbon. DOC originates from plant litter, root exudates and microbial biomass, and is strongly influenced by hydrology (precipitation and soil water fluxes) and sorption dynamics, with an important role of clay minerals in the soil (Kalbitz et al. 2000; Neff and Asner 2001). Neff and Asner (2001) modelled DOC fluxes in terrestrial ecosystems and concluded that DOC represented 25% of the total carbon embedded in a one metre deep soil profile, while roots accounted for the remaining carbon.. A small portion of DOC is exported (leached) to stream and river waters, because sorption mechanisms, mainly by clay minerals, occur through the soil profile (Hope et al. 1994). Therefore, soil hydrology impacts SOC dynamics, and the clay fraction of the soil plays an important role in stabilizing soluble organic carbon.

Although an important contributor to soil hydrology, there is, to my knowledge, no available information on the effect of water table fluctuations on soil carbon dynamics.

When attempting to describe soil carbon dynamics, two main modelling approaches are used: The physical fractionation approach and the approach based on recalcitrance, interactions and accessibility are briefly described below.

In the physical fractionation approach: soil is divided into pools allowing different degrees of stability, and changes in the soil carbon stock are represented by the transfers between these pools, mediated by soil organisms (Schimel 1994; Post and Kwon 2000). Inputs from vegetation are separated by their decomposability and constitute a part of a “labile” or “light fraction” organic matter, which is highly decomposable by microbes and a “heavy fraction”, stabilised by organo-mineral complexation, through microbial mediation. This approach identifies climate (precipitation and temperature), soil texture (clay content) and the lignin content of inputs to be the main factors governing soil carbon dynamics. Even if this representation is “primarily conceptual by nature” (Six et al. 2002), it provides a practical mean to model soil processes.

The second approach describes mechanisms behind stabilisation and destabilisation processes, based on three characteristics: the molecular recalcitrance of organic matter components, the molecular interactions between organic and inorganic components, and the accessibility to organic components by degrading organisms (Sollins et al. 1996; Six et al. 2002; Lutzow et al. 2006). In this approach, recalcitrance is described as the property of organic molecules to resist degradation, due to their chemical composition and spatial conformation. Although historically considered to be the main mechanism of organic matter preservation in soils, chemical composition does not explain long term stabilisation of OM in soils and its importance is relative to other substrate availability (Lutzow et al. 2006). The chemical composition of organic matter is probably relevant only in surface soils and for the initial stages of decomposition (Lutzow et al. 2006). More likely, micro organisms’ and

enzymes' accessibility to a combination of substrates determines OM degradation rates (Schmidt et al. 2011). Accessibility is an important regulator of OM persistence because physical protection through occlusion in aggregates delays decomposers' access to their substrate (Sollins et al. 1996). The third characteristic, organo-mineral interactions, or the strong chemical associations between organic matter and soil mineral particles allows the long term stabilisation of OM (Lutzow et al. 2006). In deeper soil horizons, aggregation and organo-mineral interactions seems to be dominant processes for OM stabilisation (Lutzow et al. 2006)

Both approaches highlight the importance of the clay fraction in organic matter stabilization. This is also supported by Jobbagy and Jackson (2000) who found that clay content was the best predictor of SOC below 20 cm depth using data from 694 soil profiles. Interestingly, they also observed a systematic and important negative correlation of SOC with sand at all depths (down to 1 metre). In addition, the type of clay and its chemical composition can also alter soil carbon dynamics (Kleber et al. 2007) Overall, soil texture is a major player in SOC dynamics.

Therefore, the understanding of the mechanisms regulating organic carbon persistence in the soil is moving towards an integrated view where accessibility and interactions are dominant processes, and prevailing inputs are from the rhizosphere, particularly in the deeper soil horizons (Schmidt et al. 2011).

1.3.2. Soil-carbon sequestration to mitigate climate change

Soils are the largest pool of terrestrial carbon in the biosphere (Schlesinger and Bernhardt 2013). The global estimated size of the soil pool corresponds to more than three times the atmospheric pool and more than four times the terrestrial biotic pool (Batjes 1996; Lal 2004a; Lal 2004b; Lal 2008). Therefore, soils have the potential to act either as a source or sink for atmospheric CO_2 (Post et al. 2001). The historical loss of soil-carbon to the atmosphere resulting from the conversion of natural ecosystems to agricultural systems, also called land

use change, is estimated to be more than 50 PgC (Paustian et al. 1998; Lal and Follett 2009). Globally, the top metre of soil has lost around 30% of its “initial stock” of carbon (Post and Kwon 2000), and “as much as 75% under particular conditions” (Lal 2004a). However, some authors argue that this loss of soil-carbon can be reversed (e.g. Lal 2010). According to (Lal 2004a), agricultural soils have the potential to store 0.4 to 1.2 Pg C/year, representing 5% to 15% of global GHG emissions per year

However, the capacity for realising the full potential of soil-carbon sequestration for climate change mitigation is debated in the science community. Soil-carbon sequestration is described as a temporary measure for climate change mitigation. Two reasons are advanced for this:

- Firstly, some researchers argue that the soil-carbon sink is limited in size (Stewart et al. 2007).
- Secondly, the changes in management practices, if not maintained, could result in the release of the previously sequestered soil-carbon (Lal 2004).

Therefore, soil-carbon sequestration is likely to prove very efficient at sequestering atmospheric CO_2 in the short term, for the first 20-30 years of its implementation (Mondini and Sequi 2008). This will “buy us time” until the development and adoption of energy technologies that emit less GHGs (Mondini and Sequi 2008)

Several mitigation strategies, through the implementation of measures that sequester carbon in the soil, have been identified by the IPCC to enable agriculture to help mitigate climate change. These include the restoration of cultivated organic and degraded soils, improvement of cropland, grazing land, livestock and changes in rice management.

Here, a clear separation between the technical mitigation potential and the economic mitigation potential of such measures can be observed, with some measures having a high technical potential, but requiring a high price of carbon to be implemented (Fig. 1.2). For example, the restoration of cultivated organic soils, such as peat lands, could store important

amounts of soil-carbon. However, this measure strongly depends on the price of carbon in the carbon market, and therefore on an economic incentive for farmers to stop cropping these productive lands. On the other hand, improving cropland management is the most promising measure because of its high soil-carbon sequestration potential at no or little extra cost (Smith et al. 2007). This involves changes in management practices, such as the adoption of agronomic practices that provide more inputs to the soil (e.g. new varieties, perennial crops), more efficient/reduced use of added nutrients (e.g. fertilisers, pesticides), reducing soil disturbance (reduced tillage), better water management, rice management, implementation of agro-forestry and land cover (use) change (Smith et al. 2007).

Furthermore, a clear distinction is made between land use and management (LU) and "land cover (use) change" (LUC), also called land conversion. While included in the "cropland management" category by Smith et al. (2007), the mitigation measure LUC could as well be considered a different category, because this measure does not only involve a change in management practices. Indeed, in addition to the need to improve food security, land use conversion could demand a complete modification of major characteristics and requirements for the field concerned. For example, the objectives of the farmer for that field, the management expertise required, the organisation of the farm, the outcome products and therefore the economic returns, and the target markets could be different. This is highly unlikely to happen for the sole purpose of climate change mitigation, as the cost involved for such major changes would require enormous financial incentives to be put in place. Smith et al. (2007) describe LUC as "the most effective method to reduce emissions" but highlight that land conversion "comes at the expense of agricultural productivity" and is therefore an option for "surplus" or "of marginal productivity" agricultural lands.

In conclusion, soil-carbon sequestration could play a major role in mitigating climate change (Post et al. 2001; Smith et al. 2007; Stockmann et al. 2013). The potential of agriculture to mitigate climate change, at least in the short term, rests primarily on soil-carbon sequestration in existing croplands and grasslands, through the modification of management

practices without a change in land use. Therefore, considering the relevance of soil-carbon sequestration to mitigate climate change and the limited feasibility of land use conversion, unless specified otherwise, this thesis focuses on changes in soil-carbon stocks as a result of land use, rather than as a result of LUC.

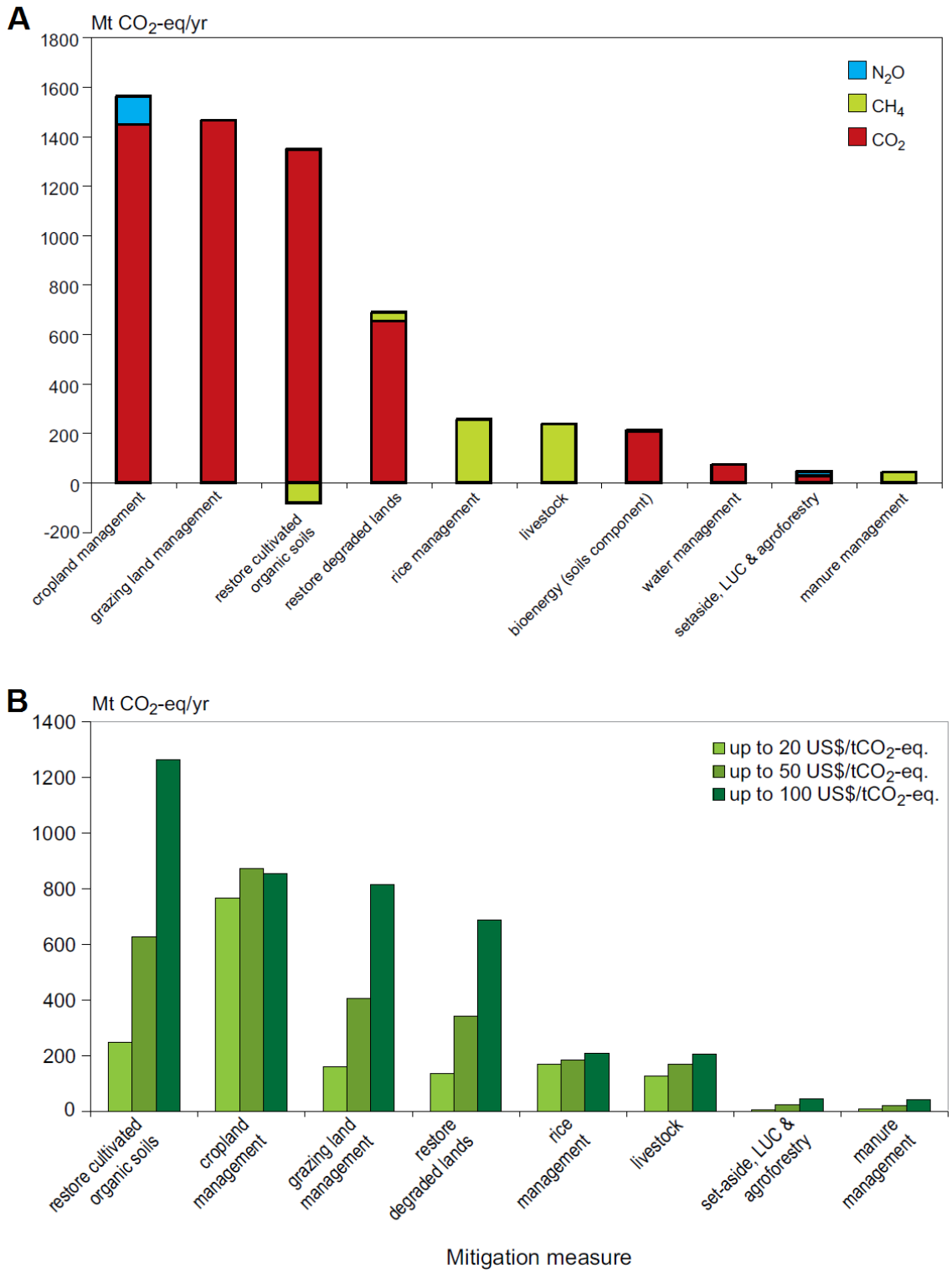

Figure 1. 2 Climate change mitigation potential of various measures in agriculture by 2030. A: Technical potential "without considering economic or other barrier" and B: Economic potential depending on the price of carbon in the carbon market (Adapted from Smith et al. (2007)). The ordinate represents the reduction/sequestration potential, in 106 tonnes of CO2-equivalent per year, of various mitigation measures. Overall, economic potentials are much lower than full technical potentials. For a low price of carbon (<20 US$/tCO$_2$-eq), "cropland management" has more than three times the mitigation potential of any other measure.

1.3.3. Soil-carbon sequestration to sustain ecosystem services

Increasing soil-carbon of agricultural fields through changes in management practices can provide numerous benefits to ecosystems, as well as mitigating climate change. The Millennium Ecosystem Assessment[2] (MEA 2005) provides the rationale for and describes "the benefits that people obtain from ecosystems": ecosystem services. Figure 1.3 highlights the provisioning, regulating, cultural and supporting services provided by ecosystems, and shows their linkage with the constituents of human well-being.

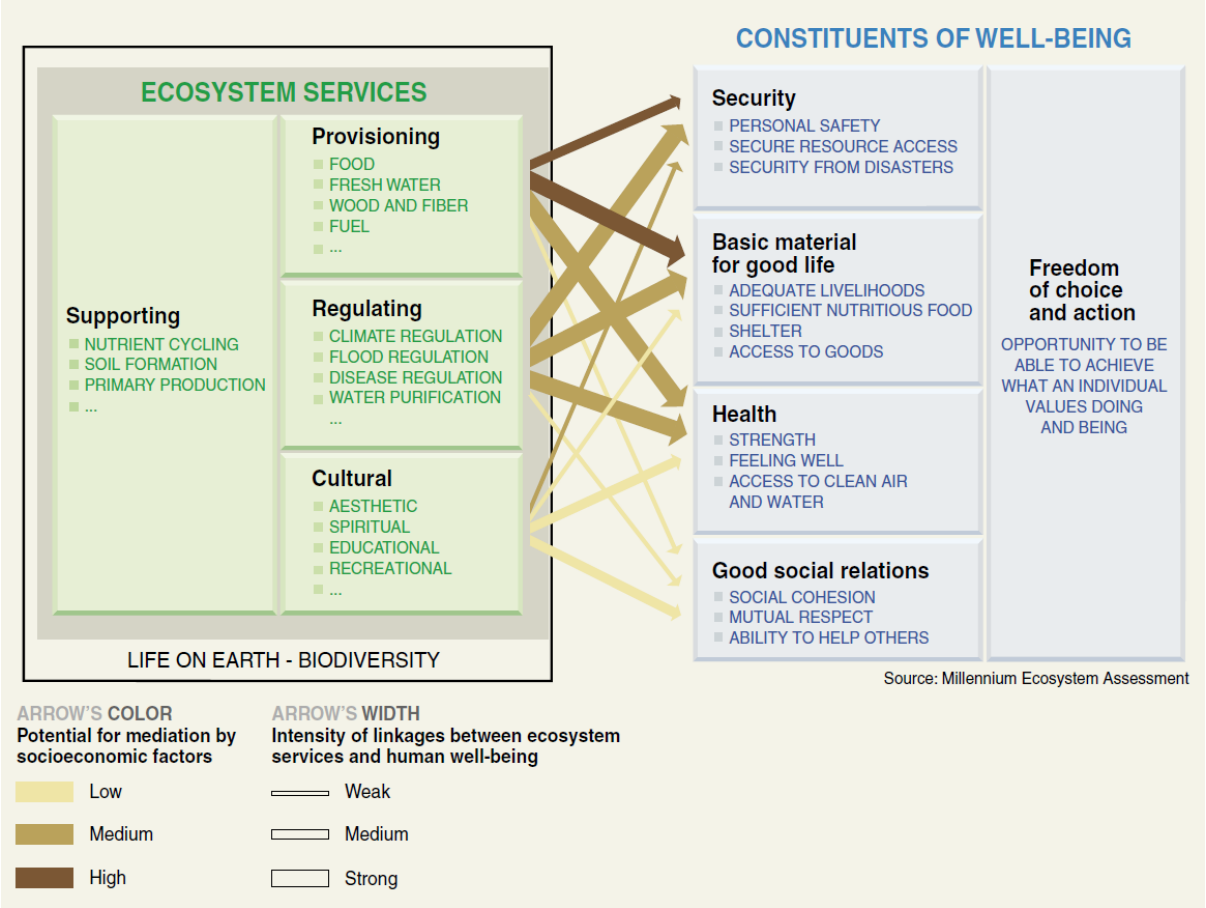

Figure 1. 3 Linkages between the services provided by ecosystems to the human population and the constituents of the well being of humanity. Source: MEA, 2005, pVI.

Soils are highly important for ecosystem services: "[…] Being the essence of all terrestrial life and ecosystem services, we cannot take the soils for granted. Soil is the basis of survival for

[2] The Millennium Ecosystem Assessment states: "*The Millennium Ecosystem Assessment was carried out between 2001 and 2005 to assess the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contributions to human well-being.[…] The assessment focuses on the linkages between ecosystems and human well-being and, in particular, on "ecosystem services.""*

present and future generations” (R. Lal, quoted in FAO and CTIC (2008)). Analogously, Dominati et al. (2010) demonstrated that soils play a major role in land functioning, and this allows the provision of a number of ecosystem services, as shown on Figure 1.4. For example, the ecosystem service “provision of food, wood and fiber”, depends highly on the physical support and the supply of water and nutrients provided by the soil, to plants (Dominati et al. 2010).

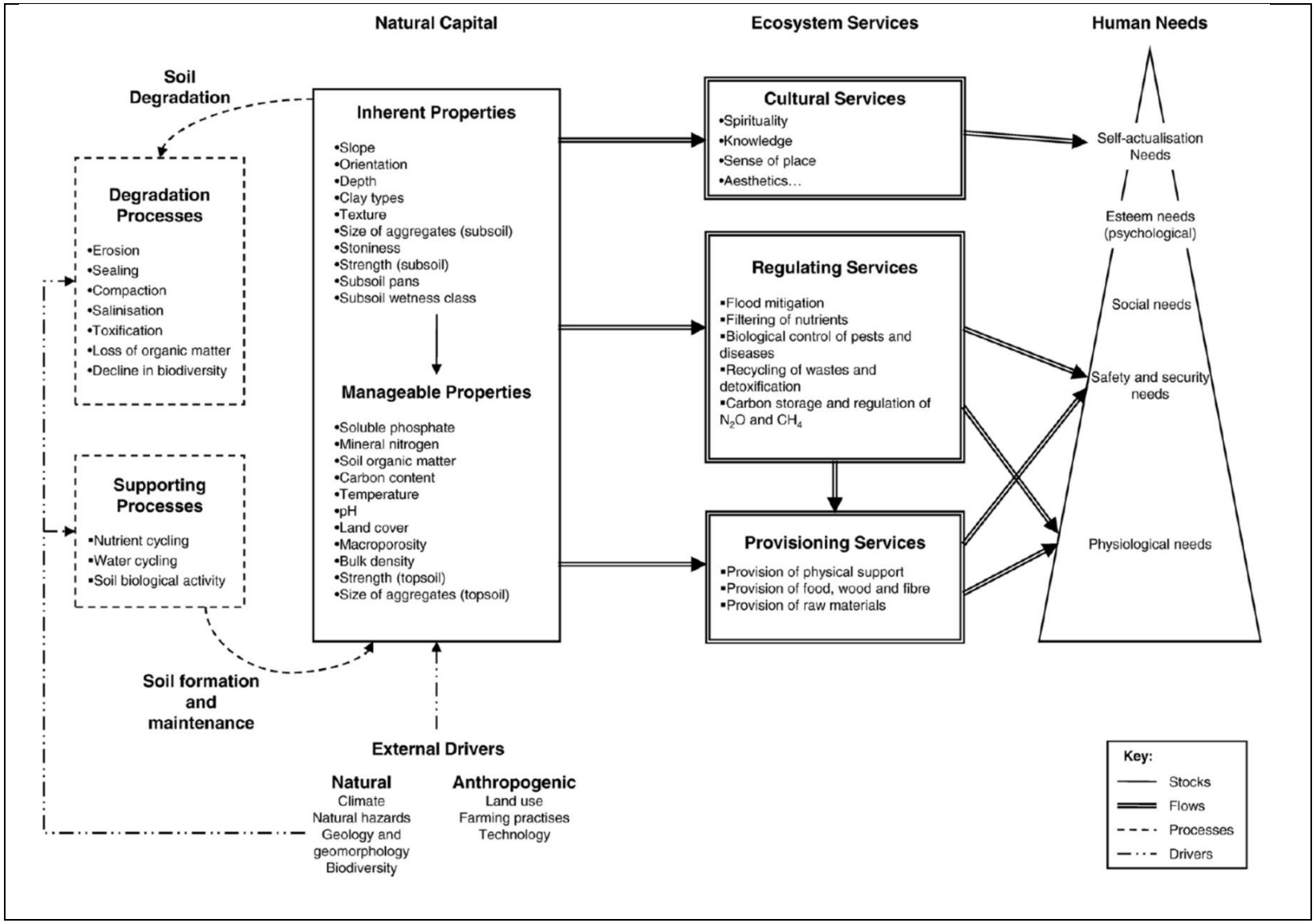

Figure 1. 4 Framework for the ecosystem services delivered by the soil. Source: Dominati et al. (2010).

Soil-carbon participates in a range of complex soil processes including retaining water and nutrients, improving soil structure, and providing a source of energy to micro-organisms (Lal, 2004a). Therefore, a change in soil-carbon stocks can affect several soil functions, and then modify qualitatively and quantitatively the ecosystem services provided by the soil. For example, Chapter 2 of the "United Nation Environmental Programme (UNEP) Year Book 2012" (Victoria et al. 2012) identifies the multiple benefits of soil-carbon to maintain ecosystem services. The authors outline: "The amount and dynamics of soil-carbon are major determinants of the quantity and quality of these [ecosystems] services [provided by soils]".Furthermore, the authors explain how a decrease in soil-carbon "results in a general loss of soil functioning and soil biodiversity, […] increases the susceptibility of soil to water or wind erosion, […] alters nutrient and water cycling, […] exacerbates flooding and reduces groundwater recharge during rain events" which […] "aggravates water shortages and drought conditions." In the same way, the carbon management "framework for action" of the FAO and CTIC (2008) summarizes this by noting that: "By properly managing the carbon in [the soil of] agricultural ecosystems, we can have less erosion, less pollution, clean water, fresh air, healthy soil, natural fertility, higher productivity, increased biodiversity and sustainability".

Overall, increasing the stocks of soil-carbon is essential to enhance the multiple services provided by ecosystems, as well as mitigating climate change in the short term. As well, Smith et al. (2012) emphasised that maintaining soil-carbon stocks is globally recognised as an imperative for "sustainable land management and therefore to managing land degradation and biodiversity conservation". According to the authors, in this sense, simple maintenance of soil carbon is highly beneficial, and can be considered as beneficial as increasing the soil-carbon stocks in soil that are high in carbon.

Strategic and sound soil-carbon management in agricultural systems is therefore vital for tackling the serious challenges currently faced by humanity, including climate change and future food security.

1.4. The soil paradox and GHG accounting guidelines

The previous sections have shown that agricultural soils can play a major role in enhancing ecosystem services as well as mitigating climate change. Maintenance of, or better still, increase in soil-carbon can be regarded as one of the main tools to achieve these goals.

In parallel, since the establishment of the IPCC, there is a growing international acceptance of climate change. This led to the rising awareness amongst governments, industries and individuals of the need to quantify and reduce the GHG emissions associated with production, use and disposal of goods and services. Consequently, protocols and guidelines to quantify GHG emissions have been developed at three levels: the country level, the company and the product level.

- At the country level, the "IPCC Guidelines for National GHG Inventories" (IPCC 2006) constitutes the reference document for GHG accounting. These guidelines provide a specific methodology for soil carbon accounting, and are therefore briefly described in section 1.4.1.
- At the company, level, industries have identified a way of differentiating themselves in the market place (Roy and Vézina 2001). For example, Tesco and Walmart, two major supermarket chains, have set and communicated targets to reduce GHG emissions from their own stores and whole supply chains[3]. Another example is the Carbon Disclosure Project (CDP), a not-for-profit organisation working with many investors and major companies worldwide to encourage quantification and disclosure of GHG emissions.
- At the product level, the labelling of products is seen as a strategy to allow businesses and consumers to make informed choices about the GHG implications of the products they buy and use (Cohen and Vandenbergh 2012). However, the GHG

3 Tesco: http://www.tescoplc.com/index.asp?pageid=632 accessed on 13 August 2013.
Walmart: http://corporate.walmart.com/global-responsibility/environment-sustainability accessed on 13 August 2013.

quantification per unit of product can be done for a wide range of purposes other than labelling, such as learning, or with the aim to reduce GHG emissions.

As a result, methodologies such as Life Cycle Assessment (LCA) and carbon footprinting have been developed to evaluate impacts on the environment per unit of product or service, from "cradle-to-grave" (i.e. over the product life cycle). LCA calculates the potential environmental impacts from the extraction of raw materials, through production, use and waste treatment within a product system, across a range of impact categories, such as resources depletion, eutrophication, climate change, toxicity and human health (Baumann and Tillman 2004). The general principles of LCA are described in Appendix A1.1, together with LCA developments regarding soil carbon accounting. The carbon footprint of a product is a quantification of the GHG emissions, removals and storage over the life cycle of a product, and is therefore focused on the climate change impact of production systems on the environment. The methodology is based upon LCA.

Finally, this section briefly presents the major GHG-accounting protocols and guidelines developed at the product level, because this research is focused on a production system that produces one product: apples (see section 1.7). For each protocol or set of guidelines presented, the description focuses on how these schemes assess soil-carbon maintenance and/or change.

1.4.1. Assessment of soil-carbon at the country scale

The Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) [4], aims at fighting climate change by engaging countries to set GHG emissions

[4] The UNFCCC provides a short background on their website (http://unfccc.int): "*In 1992, countries joined an international treaty, the United Nations Framework Convention on Climate Change, to cooperatively consider what they could do to limit average global temperature increases and the resulting climate change, and to cope with whatever impacts were, by then, inevitable.*
By 1995, countries realized that emission reductions provisions in the Convention were inadequate. They launched negotiations to strengthen the global response to climate change, and, two years later, adopted the Kyoto Protocol. The Kyoto Protocol legally binds developed countries to emission reduction targets. The Protocol's first commitment period started in 2008 and ended in 2012. The second commitment period began on 1 January 2013 and will end in 2020.
There are now 195 Parties to the Convention and 192 Parties to the Kyoto Protocol." The Kyoto Protocol was ratified by a vast majority of countries, with the notable exception of the United States of America.

limits and to make reduction commitments. Participating countries are listed in “Annex 1” of the Kyoto Protocol. In order to quantify these emissions, the IPCC developed the “Guidelines for National GHG Inventories” (IPCC 2006). The IPCC guidelines provide guidance as well as an indication of what is “good practice” for quantifying and reporting GHG emissions and removals. Most countries that ratified the Kyoto Protocol of the UNFCCC have used the IPCC default guidelines to report their emissions (Lokupitiya and Paustian 2006).

The calculation of GHG emissions and removals is organised in three tiers that “*that range from default emission factors and simple equations to the use of country-specific data and models to accommodate national circumstances*” (IPCC 2006). Therefore, reporting under a higher tier indicates a higher level of accuracy, and lower uncertainty in the reported values.

The tier-based methodology developed by the IPCC to carry out the inventory and report GHG emissions at a country level provides the tools to estimate changes in soil-carbon stocks, regardless of practical constraints such as data availability. Tier 1 only requires the use of default stocks and coefficients provided by the guidelines. Reporting under Tier 2 involves using the same equations, default stocks and coefficients as developed for Tier 1, but requires the use of country specific data to improve some components used for the calculation. Finally, Tier 3 reporting requires capturing annual variations of soil-carbon stocks in specific locations through either dynamic modelling or measurements, or both. Reporting under Tier 3 can be carried by using mechanistic models, which have been updated and verified thanks to benchmark monitoring sites that are regularly sampled. Alternatively, it is possible to use a measurement-based inventory through regular monitoring. Due to the segregation of the framework into three distinct tiers and the expression of uncertainty, it allows for a clear understanding of the level of spatial differentiation and accuracy of the estimates used regarding changes in soil-carbon stocks. To illustrate the method, an example of Tier 1 calculations for changes in soil-carbon for cropland remaining cropland is presented in Appendix A1.2.

Despite the facts that country-scale methods are in place to quantify GHG emissions and that the calculation can be conducted almost without data, more than 65 % of the Annex 1 countries (i.e. countries that ratified the Kyoto Protocol) did not report agricultural soil emissions and removals, which includes changes in soil carbon stocks (Lokupitiya and Paustian 2006). Furthermore, most of the countries who reported these have done so using only a Tier 1 methodology (Lokupitiya and Paustian 2006), which is the least demanding method for reporting GHG emissions.

1.4.2. Assessment of soil carbon at the product level

A number of different guidelines for Carbon Footprinting (CF) have been rapidly developed (see Bolwig and Gibbon (2009) for an overview of various schemes available). However, the flexibility of these guidelines and several methodological issues hinder the comparability of equivalent products which have used and interpreted different standards for their PCF calculations (Plassmann et al. 2010). Overall, there is a general agreement that a "single, globally recognized protocol for standardized carbon footprint methodologies" is needed (Plassmann et al. 2010; Cohen and Vandenbergh 2012). So far, three protocols with this aim have been developed:

- Public Available Specification 2050 (BSI 2011)

  The "PAS2050: 2011 Specification for The assessment of life cycle greenhouse gas emissions of goods and services" (PAS 2050 (BSI 2011)) aims at establishing a consistent and credible way of assessing GHG emissions over the life cycle of products and services (see also Appendix A1.3). The PAS 2050 was the world's first published standard for product carbon-accounting in 2008, and the updated version was published in 2011. Interactions with the International Standard Organisation and the Greenhouse Gas (GHG) protocol initiative development teams have helped harmonise the updated framework with the GHG product protocol (see below).

- GHG product protocol (WRI and WBCSD 2011)

The “GHG Protocol Product Life Cycle Accounting and Reporting standard” (GHG Product Protocol or GHGPP) (WRI and WBCSD 2011) is part of a series of three standards which define the rules and guidelines for accounting and publicly reporting GHG emissions and removals of corporations, of their products and of their value chains. The protocols also provide guidance to quantify GHG reduction opportunities of particular projects (see Appendix A1.3).

- ISO TS 14067 (ISO 2013)

  The International Standard Organisation (ISO) Technical Specification (TS) 14067 on carbon footprint methodology has been developed based on several years of discussions amongst member bodies (see Appendix A1.3). It was published as a Technical Specification in 2013.

Sections 1.4.2.1 to 1.4.2.4 focus on the three carbon footprint protocols presented above, as these are the most advanced documents towards an international agreement for product GHG accounting, and detail how each protocol considers soil carbon in a land use context.

1.4.2.1. Consideration of soil carbon in the PAS2050

The Publicly Available Specification (PAS) for “The assessment of life cycle greenhouse gases of goods and services” ((PAS 2050 (BSI 2011)) was first published in 2008. Both versions of the sections considering soil carbon are presented in Box 4.

Box 1.1: Quotes from PAS 2050: 2008 and PAS 2050: 2011 regarding the treatment of soil-carbon change as a result of land use in PAS 2050 (2008, 2011).

PAS2050 (2008):

> ***5.6 Treatment of soil-carbon change in existing agricultural systems***
>
> *Changes in the carbon content of soils, either emissions or sequestration, other than those arising from direct land use change (see 5.5) shall be excluded from the assessment of GHG emissions under this PAS.*
>
> ***Note 1** The above requirement refers to changes such as tilling techniques, crop types and other management actions taken in relation to agricultural land. It does not refer to the impact of land use change on carbon emissions which is included in 5.5.*
>
> ***Note 2** While it is recognized that soils play an important part in the carbon cycle, both as a source and sink for carbon, there is considerable uncertainty regarding the impact of different techniques in agricultural systems. For this reason, emissions and sequestration arising from changes in soil-carbon are outside the scope of this PAS. Inclusion of carbon storage in soils will be considered further in future revisions of this PAS.*

PAS2050: 2011:

> ***5.7 Treatment of soil-carbon change in existing systems***
>
> *Where not arising from land use change (5.5), changes in the carbon content of soils including both emissions and removals shall be excluded from the assessment of GHG emissions under this PAS unless provided for in supplementary requirements in accordance with the principles set out in 4.3.*
>
> *Where supplementary requirements relating to soil-carbon change have been*

Box 1.1 (continued):

developed for the product being assessed in accordance with the principles set out in 4.3, they should be used.

Note 1 *This exclusion refers to changes such as tilling techniques, crop types and other management actions taken in relation to agricultural land. It does not refer to the impact of land use change on carbon emissions, which is included in 5.6.*

Note 2 *Soils are important in the carbon cycle, both as a source and a sink for carbon, and it is acknowledged that scientific understanding is improving regarding the impact of different techniques in agricultural systems. For this reason, provision is made for future supplementary requirement or revision to the PAS 2050 requirements that could facilitate the inclusion of emissions and removals arising from changes in soil-carbon.*

Source: PAS 2050: 2008 (BSI, 2008) and PAS 2050: 2011 (BSI, 2011)

As can be seen in the quote in Box 4, changes in soil-carbon stocks as a result of current land use and management practices were excluded in the 2008 version of the PAS 2050. Furthermore, "*Note 2"* highlighted "considerable uncertainty" and therefore referred to a future revision of this document, following the acknowledgement that "*soils play an important part in the carbon cycle, both as a source and sink for carbon*" (see Box 1.1).

The revised version of PAS 2050, published in 2011, still kept the changes in soil-carbon as a result of land use outside the scope of the document. Nevertheless, changes in soil-carbon stocks associated with changes in management practices can be provided in supplementary requirements[5], if they exist.

[5] "Supplementary requirements" are defined by the PAS 2050: 2011 as "life cycle greenhouse gas emissions quantification requirements applicable to a particular product type or product sector, to enhance the application of PAS 2050." They must follow a number of principles, according to article

Changes in soil-carbon stocks as a result of land use change, in contrast, “shall” be considered (paragraph 5.6, p10-11. BSI, 2011), and Annex C of the PAS 2050: 2011 provides estimates of GHG emissions for the conversion of forest or grassland to annual or perennial cropland.

The maintenance of soil carbon stocks as a result of land use is not mentioned in the PAS 2050.

1.4.2.2. Consideration of soil carbon in the GHG Product Protocol

The GHG Protocol: Product (GHGPP) Life Cycle Accounting and Reporting Standard (WRI and WBCSD 2011) provides a protocol for creating an inventory of, and reporting, GHG emissions, plus identifying reduction opportunities along the product life cycle.

The GHGPP does not mention soil-carbon change as a result of land use in the “requirements” sections of the protocol, but it is addressed in Annex B. Their statement is provided in Box 1.2.

Box 1.2: Treatment of soil-carbon change in the GHG Product Protocol.

B.3 Soil carbon

[…] soil-carbon loss can continue even after land-use change as a result of land-use practices such as harvesting and fertilizer application. On the other hand, switching land use practices can improve the carbon stock of soil, resulting in CO2 removal. Companies may include soil-carbon change as a result of land-use practices in their inventory results if they are able to reasonably estimate the emissions or removals. Companies should report whether the soil-carbon change is included in the inventory results.

Source: Appendix B. Land-Use Change Impact (WRI and WBCSD 2011).

4.3 of PAS 2050: 2011, such as “broadly recognised” at least at the sector or industry level, and “inclusive and consensus based” i.e. developed through a transparent process open to stakeholders.

It appears that accounting for a change in the soil-carbon stock as a result of land use is voluntary and conditional upon the ability of companies to "reasonably estimate" soil carbon change, under the GHGPP. The specific meaning of "reasonably estimate" these changes is not explained by the standard. The maintenance of soil carbon is not mentioned in the standards.

In addition, the GHG Protocol Initiative has released in May 2014 an "Agricultural Guidance" (WRI and WBCSD 2014), in order to supplement the GHG Corporate Protocol. Soil-carbon stock changes as a result of management practices are included on a voluntary basis in the "Agricultural Guidance" of the GHG Corporate Protocol. This document allows for a combination of field measurements, empirical models, emission factors and process-based models to be used to calculate GHG emissions. However, a tier-based structure such as the one used by the IPCC is not proposed. A long, but non exhaustive, list of potential calculation tools is presented in Annex 1 of the guidance, but the choice of which tool is best to use is left to the discretion of the practitioner. Furthermore, the definition of emission thresholds[6] in order to exclude supposed small sources of emissions is declared "not compatible with the completeness principle" of the Agricultural Guidance. Therefore, each potential emission and removal is required to be quantified under the GHG Corporate Protocol.

1.4.2.3. Consideration of soil carbon in the ISO TS 14067

The International Standard Organisation (ISO) Technical Specification (TS) 14067 (ISO 2013) on carbon footprint methodology was published in 2013. Insufficient agreement among the participating parties prevented its ratification as an international standard. Paragraph 6.4.9.5 of ISO TS 14067 considers soil-carbon change as a result of land use, although a definition of soil carbon is not provided in this document.

[6] The GHG corporate protocol provides the following comment about "emission threshold":
"*Sometimes it is tempting to define a minimum emissions accounting threshold (often referred to as a materiality threshold) stating that a source not exceeding a certain size can be omitted from the inventory. Technically, such a threshold is simply a predefined and accepted negative bias in estimates (i.e., an underestimate)*."

Box 1.3: Treatment of soil-carbon change in ISO TS 14067.

6.4.9.5 Soil carbon change

If not calculated as part of LUC, the GHG emissions and removals occurring as a result of soil carbon change should be assessed and should be included in the CFP. Where included, it shall be assessed in accordance with internationally recognized methods such as the IPCC Guidelines for National Greenhouse Gas Inventories and shall be documented separately in the CFP study report.

If a national approach is used, the data shall be based on a verified study, a peer reviewed study or similar scientific evidence and shall be documented in the CFP study report.

***NOTE 1** Soil carbon change can occur in the absence of land use change, where ongoing management to produce a product results in a net increase or decrease in soil organic matter, e.g. due to continuous tillage.*

***NOTE 2** There is on-going research to develop methodology and models, and provide data for the inclusion of soil carbon change in GHG reporting.*

Source: ISO/TS:2013 14067 (ISO 2013)

Accounting for soil carbon change, if not as a part of LUC, is voluntary under ISO TS 14067, as signified by the use of the expression “should be assessed” (underlined in Box 1.3). Nonetheless, assessed soil-carbon change shall be done in accordance with the tier-based framework of the IPCC Guidelines for National GHG Inventories (IPCC, 2006).

Furthermore, “Note 2” (see Box 1.3) highlights the need for more data, methods and models to be published in order to integrate the changes in soil-carbon associated with land use.

The ISO TS 14067 provides a somewhat ambiguous definition of direct land use change[7] (dLUC), being the "change in human use or management of land within the product system being assessed". This allows for the interpretation of changes in soil carbon as a result of changes in management practices as "direct land use change". This is important because ISO TS 14067 demands, "when significant", that changes in soil-carbon stocks arising from dLUC to be assessed. The use of internationally recognised methods, such as the IPCC guidelines (IPCC, 2006) is required in order to account for dLUC GHG emissions and removals.

To summarize, the ISO TS 14067:

- Has not been globally accepted as an international standard
- Does not include soil carbon change as a result of land use as compulsory
- Contains an ambiguity regarding the inclusion of changes in management practices as a part of direct land use change.

1.4.2.4. Similarities and differences of the protocols

The treatment of maintenance of, and changes in, soil-carbon stocks as a result of land use by the PAS2050, the GHG Product Protocol and the ISO TS 14067 presents similarities and differences that are discussed in this section.

In a similar way in the three protocols, integrating change in soil-carbon stocks as a result of land use (as opposed to land use change) is not compulsory and is at best voluntary. Furthermore, both the PAS 2050: 2011 and the ISO TS 14067 foresee a potential inclusion of changes in soil-carbon associated with land use in the next revision of the documents (see "Note 2" in both Box 1.1 and Box 1.3). These two facts could lead to negative consequences: A business could then, intentionally or not, decide to maintain a management practice damaging soil carbon stocks rapidly in order to increase productivity in

[7] Direct Land Use Change (dLUC) is opposed here to indirect Land Use Change (iLUC), a change in land use that occurs outside the product system as a consequence of dLUC. The assessment of iLUC is excluded from the ISO TS 14067.

the short term, such as full tillage[8], without taking this depletion into account in their carbon footprint This would then make it easier to increase the previously depleted soil-carbon stocks. And once the protocols have been revised and demand the inclusion of soil carbon as a result of land use; that business could change its management practice and claim GHG removals. As a result, this could

- Enhance climate change in the short term due to the release of soil carbon to the atmosphere,
- Degrade, albeit temporarily, ecosystem services provided by soils due to soil carbon depletion,
- Be unfair for businesses that did change their management practices earlier to reduce the decrease of, maintain, or increase soil-carbon stocks.

On the other hand, the inclusion of LUC soil-carbon changes is required by all three documents. This is somewhat ironic since most of the future climate change mitigation potential of agriculture is embedded in the management of existing croplands through soil-carbon sequestration rather than land conversion (see section 2.1.3.1, this chapter).

Furthermore, the three protocols do not provide a definition of soil carbon, which could result in non-inclusion of this parameter in carbon footprint due to ignorance of its importance. In particular, in the case of agricultural products, data on changes in carbon stocks above and below ground are limited and therefore these data are often omitted from the PCF calculations. However, such data can significantly change the CF results in the case of products compared that originate from different geographical areas (Plassmann et al. 2010). Therefore, defining soil carbon and emphasising its importance could encourage companies to develop their own datasets, and help fill the data gap.

Finally, maintenance of soil carbon is not mentioned in any of the protocols.

[8] For example, Jackson et al. (2003) state that: “Tillage events contribute to decreased soil quality by increasing emissions of greenhouse gases, and increasing the potential for nitrate leaching to groundwater, and these negative aspects must be weighed against the benefits of tillage for increasing the health and productivity of some crops.”

On the other hand, soil carbon change as a result of land use is completely excluded from the default calculation in the PAS 2050, as opposed to the GHG Product Protocol and the ISO TS 14067 where it is included as an optional additional calculation. Several researchers highlighted the inappropriate nature of this exclusion. For example, Koerber et al. (2009) stated that excluding exchanges of CO_2 between the soil and the atmosphere "fundamentally flawed" the PAS 2050, in a study assessing the on-farm carbon balance of vegetables produced in different countries and imported to the UK. Regarding the treatment of soil carbon, this results in a lack of harmony between the three protocols that aim at producing a single, globally recognised standard for product carbon footprinting.

1.4.3. Reasons for non-compulsory accounting

There is a paradox between the demonstrated importance of maintenance and increases in soil-carbon stocks , and the lack of compulsory accounting methods for GHG accounting at the product level. There are two major reasons for this paradox.

Firstly, a method to allow reliable and practical measurement of maintenance or changes in soil-carbon stocks is lacking (Post et al. 2001; Conant et al. 2011). The UNEP Year Book 2012 (Victoria et al. 2012) reports on "a critical need to develop universally agreed and reproducible field and laboratory methods for measuring, reporting and verifying (MRV) changes in soil-carbon over time". The accurate measurement of these changes is difficult because of the lateral and vertical variability of soil carbon, combined with the small changes relative to the stock (Post et al. 2001; VandenBygaart et al. 2007; Conant et al. 2011).

Secondly, there is a critical lack of soil carbon data. Smith et al. (2012) reviewed the capability to estimate changes in soil carbon stocks as a result of land use and management at all scales, and concluded that soil databases are limited to global scale estimates because they carry large uncertainties. Furthermore, the authors emphasised the

impossibility of soil carbon models to reliably predict changes without previous testing, parameterization and calibration with site specific data.

Therefore both accurate and practical methods, and site-specific data are needed to assess the changes in soil carbon stocks as a result of land use and management. These missing tools have so far prevented compulsory soil-carbon assessment in GHG accounting protocols.

1.5. Implications for New Zealand

1.5.1. New Zealand GHG commitments under the Kyoto protocol

At the national scale, and under the Kyoto Protocol of the UNFCCC, New Zealand (NZ) committed to return to their 1990 yearly GHG emission level by the end of the first commitment period (2008-2012). This level is calculated as a yearly average over the 5 years of the current commitment period. In 2012, the agricultural sector was the biggest contributors to New Zealand GHG emissions, accounting for 46% of national emissions. The energy sector was the second largest contributor with 42% of New Zealand GHG emissions (MfE 2014). So far, NZ used the IPCC guidelines (IPCC 2006) to calculate and report its GHG emissions in 2011. According to the NZ Ministry for the Environment's website[9], New Zealand exceeded its target for the first commitment period. However, New Zealand has now decided not to participate to the second commitment period (2013 – 2020) of the Kyoto protocol, preferring to focus on the "Global Research Alliance on Agricultural Greenhouse Gases […] which addresses the crucial question of how we feed a growing global population without adding to emissions"[10].

[9] http://www.mfe.govt.nz/publications/climate/greenhouse-gas-inventory-2014-snapshot/snapshot.pdfaccessed 13 August 2013.

[10] http://unfccc.int/resource/docs/cop18_cmp8_hl_statements/Statement%20by%20New%20zealand.pdf accessed on 8 November 2013.

The New Zealand economy is largely relying on agricultural exports. According to the World Bank, exports represented 30% of the New Zealand Gross Domestic Product (GDP) in 2010[11]. A large number of products are then exported to overseas' markets. The growing interest from consumers for "greener" products drives the willingness of New Zealand exporting industries and sectors for product and supply chain GHG accounting, in order to use it as a marketing tool.

1.5.2. Implication for New Zealand agricultural exports

The diffusion of LCA and carbon footprinting as a tool to communicate the environmental impacts of products to consumers was preceded by the "food miles" concept. This concept characterises the distance between production and retail countries and was largely disadvantaging New Zealand, since it is situated far away from its export markets (McLaren 2007). This is particularly relevant for the New Zealand agricultural sector. Indeed, agricultural products represented about half the goods exported from New Zealand in 2012[12].

Specifically, fruit and nuts were the 7th exported commodity by value in 2012, behind dairy, meat, wood, mineral fuels, machinery and miscellaneous goods (Statistics New Zealand 2013). While for the export goods ranked 1 to 6, the major export markets were generally the People's Republic of China and the United States of America (USA), the main importer of NZ fruit (by value) is the United Kingdom, followed by the USA, the Netherlands and "other European" countries. Therefore, NZ fruits main export markets are generally located in Europe, more than 18 000km away from their production sites, which reinforces the need for this industry to show and improve their environmental performance, in order to gain premium prices. Within the NZ fruit industry, the apple industry is particularly affected by such requirements.

[11] http://data.worldbank.org/indicator/NE.EXP.GNFS.ZS accessed 13 August 2013.
[12] http://www.newzealandnow.govt.nz/investing-in-nz/opportunities-outlook/economic-overview accessed on 15 August 2013.

1.6. Implications for the New Zealand apple industry

According to the New Zealand horticultural "FreshFacts" [13], apples are the third largest horticultural export by value, following wine and kiwifruit. Europe, the UK and Ireland receive 43.3% of total exports, while Asia accounts for 35%. The most exported variety is Royal Gala (33%) followed by Braeburn (22%) and Jazz (12%), although Braeburn is slowly being replaced by new varieties due to consumer demand. Export apples are grown on just over 8300 hectares of land in two main regions, the Hawke's Bay and Nelson. In total, 96% of export apples are grown following the Integrated Fruit Production sustainability (IFP) program[14]. The New Zealand average yield of 62.9 tonnes of apples per hectare[15] for the year 2013 which is the highest yield in the World. Apple orchards in New Zealand are managed in smaller management units called "orchard block". In general, each block contains one apple variety (scion) grafted on one rootstock (root variety, mainly determining tree size), all planted the same year and managed (e.g. spraying, pruning, irrigation) the same way. Generally, orchard blocks are replaced within 15-30 years after planting, often following a decrease in productivity, or for variety replacement, following changing market demand.

The NZ apple industry is strongly driven by exports. Depending on the apple variety, 65% to 82% of the 2010 production[16] arriving at the packhouse was shipped overseas, mainly to Europe (Pipfruit NZ 2010). Unfortunately, the food-miles concept was used to target the NZ apple image, for example by creating an advert depicting a New Zealand apple over which oil was poured generously, as a symbol of the fuel oil used by the apple's shipping cargo. This was followed by a considerable debate in the scientific community about the relevance of the food-miles concept to assess the environmental impacts of products, as depicted by Edwards-Jones et al. (2008). As a result, in 2008, the New Zealand Ministry for Agriculture

[13] http://www.freshfacts.co.nz/file/fresh-facts-2013.pdf, accessed 23 June 2014.
[14] http://www.produceofnewzealand.org/about/cleanandgreen/ , accessed 23 June 2014.
[15] This yield includes all grades of apples: export, local market and juice.
[16] Average of 59% in 2013, according to:
http://www.pipfruitnz.co.nz/News_and_Events.aspx?cms_584_param_detail=3192 (accessed 23 June 2014)

and Forestry (MAF) and the industry body that promotes and represents the New Zealand pipfruit industry, Pipfruit New Zealand, commissioned a study to establish an “illustrative” carbon footprint of NZ apples exported to the UK. The results of this study by McLaren et al. (2009) are presented in Figure 1.6.

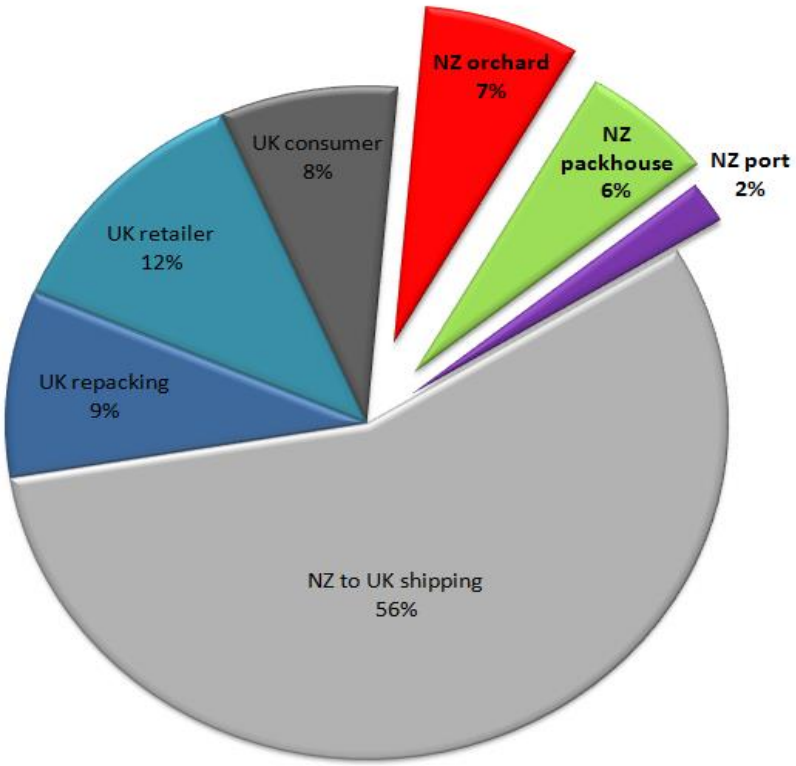

Figure 1. 5 Partitioning of the life cycle greenhouse gas emissions of a kilogram of New Zealand Royal Gala apples (IFP) exported to the UK. Source: McLaren et al. (2009).

The carbon footprint of New Zealand apples exported to the UK is 0.9kg CO2eq / kg apple. This figure is specific to Royal Gala apples grown following the IFP program. Within this life cycle, the New Zealand-based footprint, including the orchard, packhouse and port emissions, represents 15% of the GHG emissions.

In the context of global retailers using the environmental aspect of the product they sell as a marketing tool (see section 1.3.2), a reduced carbon footprint of New Zealand apples may not only constitute a competitive advantage, but it could be a requirement for market access in the future. Therefore, the New Zealand apple industry is interested in finding ways to reduce their carbon footprint. In this regards, if the soil of apple orchards were to act as a

carbon sink, the NZ apple industry could better its “green” image on overseas markets, as well as mitigate climate change and enable benefits from enhanced ecosystem services.

1.6.1. Accounting for above-ground biomass carbon

Perennial cropland systems can store substantial amounts of carbon in their above ground vegetation (Albrecht and Kandji 2003). Through photosynthesis, atmospheric CO_2 is sequestered for several years, or decades, in the woody biomass of apple orchards (Palmer 2011).

However, the carbon stored temporarily in woody biomass of orchards is generally excluded from LCA and carbon footprint guidelines. For example, the PAS 2050 (BSI 2011) excludes biogenic carbon stored in plant and trees unless it results from LUC. Their statement is presented in box 1.4.

Box 1.4: Treatment of biogenic-carbon in the PAS 2050 (2011).

5.1.1 GHG emissions and removals to be included

[…]

Note 4*: Carbon incorporated in plants or trees with a life of 20 years or more (e.g. fruit trees) that are not products themselves but are part of a product system should be treated in the same way as soil carbon, unless the plants and trees are resulting from a direct land use change occurring within the previous 20 years.*

Source: PAS 2050 (BSI 2011)

In a similar way as soil carbon, one of the reasons for this omission is that an agreement on a common methodology has not yet been reached (Brandão et al. 2013). Yet, taking this temporary carbon storage into account could affect the results of LCA and carbon footprint studies (Levasseur et al. 2012).

In apple orchards, few data are available about the standing stocks of woody biomass in apple orchards, and there are few methods to quantify this biomass rapidly and cost effectively. Furthermore, the potential impact of this biogenic carbon has not yet been assessed in apple orchards.

1.7. Research objectives

To address the issues identified in Section 1.1 to 1.6 of this Chapter, the main aim of this research is to develop a practical methodology to measure a statistically significant and powerful change in the soil carbon stock of an apple orchard block in New Zealand, and a methodology to estimate the ongoing biomass carbon stock in apple orchards, in order to provide reliable data for the carbon footprint of New Zealand apples.

Since there are no data available on changes in soil-carbon stocks in apple orchards, this research seeks to quantify these changes by means of a chrono-sequence.

The specific objectives of the research are therefore:

1. To quantify the spatial variability, both horizontally and with depth, of the soil's carbon content, bulk density and carbon stock in an apple orchard block, in order to define the minimum sampling requirements to measure and monitor these soil parameters at the orchard block scale, and to infer the cost of such monitoring.
2. To determine the possibility of observing a statistically significant and powerful change in soil carbon stocks using a chronosequence of four orchard blocks aged 1 to 12 years after planting.
3. To develop a method to quantify the woody biomass carbon stock in an apple orchard block on a routine basis, and to estimate the importance of this carbon stock for the carbon footprint of NZ apples.
4. To define standard protocols to measure and monitor soil carbon stocks and woody biomass carbon stocks in apple orchards.

1.8. Structure of this dissertation

This dissertation consists of six chapters. After this introductory chapter, Chapter 2 to 5 present the results of the experiments conducted to achieve the specific research objectives of this thesis (see section 1.7).Chapter 6 contains the summary, discussion and conclusions.

1.8.1. Structure of Chapters 2 to 5

Chapter 2 to 5 have been written in the view of peer reviewed publication. Therefore, they each include all the necessary sections for this purpose: Introduction, Methods, Results and discussion, Conclusions and References.

However, in order to make this dissertation a comprehensive body of work, the introduction and conclusions sections in each Chapter provide the link between them and unite the dissertation as a whole research project. In other words, these sections, particularly the introduction sections of each chapter, are hybrids between introductions for standalone publication and bridges between the various chapters.

1.8.2. Focus of each chapter

Chapter 2 reviews the Life Cycle Assessment (LCA) and carbon footprint (CF) case studies that account for the changes in soil-carbon. Firstly, the importance of including these changes in CF case studies is quantified. Secondly, the eight major issues highlighted in the case studies are discussed. Finally, the related research needs are identified.

Chapter 3 presents the detailed methodology and results of intensive soil sampling at both the tree and the orchard-block scales in one apple orchard block. The quantified variability of the soil's carbon content, bulk density and carbon stock determine the minimum sampling requirements for measuring and monitoring soil carbon stocks in any apple orchard block. The cost of a monitoring campaign is also quantified with regards to the carbon market and the price of a kilogram of apples.

In the research presented in **Chapter 4,** the same investigative sampling strategy as that used in the study presented in Chapter 3 was used to study three additional apple orchard blocks of different ages. The four orchard blocks, aged between one to twelve years, constitute a chrono-sequence and display the potential to estimate a change in soil-carbon stocks. The possibility to define a standard protocol to monitor the changes in soil carbon stocks that is applicable to all apple orchard blocks is investigated. Finally, the practical and economic implications of measuring and monitoring the changes in soil carbon stocks in apple orchard blocks are presented.

Chapter 5 presents a review of the literature quantifying the woody biomass in trees of apple orchards, and discusses requirements for integration of woody biomass data of perennial cropping systems in LCA and CF. Following on-orchard measurements, a rapid and cost effective method to quantify the woody biomass carbon stock in an apple orchard block is proposed. Also, the potential impact on the carbon footprint of New Zealand apples of various end-of-life scenarios for the apple trees is quantified.

Finally, **Chapter 6** provides a summary of the thesis, discussion and conclusions.

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Chapter 2:

Soil carbon in LCA and carbon footprint -

A review of case studies

Table of Contents

2.1. Introduction

Soil carbon is a major component of the terrestrial carbon cycle, and can play a critical role in mitigating climate change, and in enhancing soil health and fertility (see Section 1.5).

Life cycle Assessment (LCA) and Carbon Footprint (CF, also called GHG balance[1]) studies seek to quantify the environmental impacts of products, processes and activities over their entire life cycles from extraction of raw materials through manufacture, distribution, use and on to final waste management. However, as discussed in Section 1.6, LCA and CF guidelines generally exclude soil carbon from the compulsory part of the assessment because of a lack of standard monitoring methods and data. As a result, many LCA and CF studies have excluded this parameter when assessing the impact of land-based production systems on the environment (Plassmann et al. 2010; Kimming et al. 2011; Venkat 2012). However, the studies that do account for soil-carbon stock and change highlight a number of issues related to interpretation of the results and their subsequent use to support decision-making.

The objective of this chapter is to review the LCA and CF case studies that account for changes in soil-carbon stocks in order to identify the main issues associated with soil carbon accounting.

LCA and CF studies usually distinguish three categories of activities that contribute to changes in soil carbon:

- Land Use (LU, also called land management). This category includes the effect of ongoing land management, such as the cultivation of apple trees, but also of changes in land management on soil-carbon stocks, as can happen when increasing the number of fertiliser applications or the quantity of irrigation water.

[1] Both carbon footprint and GHG balance assess the flows of greenhouse gases in and out of a system. For this reason, they are both used interchangeably in this chapter. Most commonly, “GHG Balance” is used when assessing natural systems such as land and soil, while carbon footprint is used when assessing industrial systems, such as businesses and the life cycle of products.

- Direct Land Use Change (LUC or dLUC). This category can be defined as activities resulting in a qualitative change in the particular production output of the land area under study, such as the introduction or replacement of a crop in a crop rotation, or the transformation of a peach orchard into an apple orchard.
- Indirect Land Use Change (iLUC) involves a change in a particular land area that is not part of the study but that occurs as a result of dLUC, in order to compensate for the change in production outputs caused by dLUC. Here dLUC leads to a decrease in supply of a land-based commodity which may, in turn, lead to forest clearing elsewhere to replace this commodity, for example.

2.2. Materials and methods

In order to identify the LCA and CF case studies that take into account soil carbon, the following algorithm was entered in the Web Of Science[2] database search: (("ghg balance" OR "'greenhouse gas balance" OR "carbon footprint" OR "LCA" OR "life cycle assessment") AND ("soil carbon" OR "soil C" OR “SOC”)).

This search was first conducted in September 2013. After removal of the few duplicates, it resulted in 131 publications, including 119 peer reviewed articles, 1 book section and 11 conference articles. There were 8 references for which the full text could not be accessed including 3 journal articles, 4 conference papers and 1 book section. However, these references were either not relevant or the abstracts information indicated that they would not have affected the results of this review. Furthermore, relevant publications were added following a recent update.

In Section 3, some additional peer reviewed articles are used to support arguments and highlight scientific findings that could have implication for the consideration of soil-carbon stock and change in LCA and CF studies.

[2] http://thomsonreuters.com/thomson-reuters-web-of-science/ accessed September 2013.

2.3. Results and discussion

2.3.1. Description of the literature body

From the 123 studies obtained with the database search, 101 studies included or discussed soil-carbon stock and change in the context of LCA and CF. A total of 20 full or partial LCAs (including 4 reviews of LCA studies) and 76 CF studies (including 16 reviews) were assessed. Furthermore, five of these 101 studies were focused solely on soil carbon, although the issues related to LCA and CF were discussed. Overall, some 96% of these studies were published in or after 2007.

Studies varied according to the land-based system they focused on. Many studies (47) were concerned with land-based bio-energy production systems. Other topics included annual crops (16 studies), livestock and feed crops (15 studies), forestry (6 studies) and perennial crops (6 studies). Other singularly treated topics included wetlands (Poffenbarger et al. 2011), coal mining (Fox and Campbell 2010), bio-plastics (Piemonte and Gironi 2011), and golf courses (Bartlett and James 2011).

Four studies considered soil carbon changes in the context of soil health and soil quality (Sheehan et al. 2003; Brandão et al. 2011; Mattila et al. 2012; Bosco et al. 2013) while all the other studies assessed or discussed the climate change impacts of changes in soil-carbon stocks.

2.3.2. Qualitative and quantitative importance of soil carbon accounting in LCA

In the case studies, the importance of accounting for soil-carbon stock and change in LCA and CF was expressed qualitatively as well as quantitatively.

Most studies emphasised the importance of taking soil carbon into account, although many did not quantify this importance. For example, some authors simply suggest that, according to their results, soil carbon should be accounted for (Cerri et al. 2011) while others stress its importance, such as Beauchemin et al. (2011) who highlight the “powerful influence of

carbon dynamics" on the GHG balance of beef production systems. Similarly, Koponen et al. (2013) states that integrating soil carbon change to the CF performance of various biofuels has "dramatic" consequences for these fuels "GHG saving" status in European regulatory schemes. Some authors prefer to emphasise the consequences of including or excluding soil carbon changes. For example, Benoist et al. (2008) describe soil carbon accounting as a "key element to obtain a reliable assessment". Hermansen and Kristensen (2011) outline that taking into account soil carbon changes is required for a "fair comparison" between dairy-based systems. In a similar way, Hamelin et al. (2012) explain that most LCA studies include a incomplete consideration of the carbon balance, and that considering soil carbon change would allow the "correct"[3] calculation of this balance.

The effects of changes in soil-carbon stocks on the GHG balance or the climate change impact category results were, or could be, quantified in 35 studies, and they ranged from +/- 1% to +/- 2,836%, depending on many factors and assumptions.

The largest effects of including soil carbon change in the calculations were reported in studies of LUC in bio-energy systems. For example, Gelfand et al. (2013) investigated the impact over 20 years of conversion (LUC) of marginal land to various bio-cellulosic ethanol production systems in the US mid-west. The effect of including changes in soil-carbon stocks could modify their farm GHG emissions results between +265% and –2,836% for a poplar plantation and "unfertilised herbaceous successional" land[4] as a new land use, respectively. The smallest effect of including soil carbon change was +120% for the conversion marginal land to no-till corn–soybean–wheat rotation (Gelfand et al. 2013). By comparison, Roedl (2010) found that the carbon sequestration in the soil following the replacement of "arable land" by a short rotation coppice plantation would reduce the net GHG emissions by 1,060% when using default soil carbon values from the European Commission. Another example is described by Plassmann et al. (2010) who estimated that accounting for worst-case LUC

[3] In this case, "correct" is employed by the authors in the sense of "exhaustive".
[4] Gelfand et al. (2013) do not provide a definition of "unfertilised herbaceous successional land", although it is likely that it refers to a grass-based biofuel plantation, such as switchgrass.

emissions from both soil and vegetation [5] could modify the CF results (per tonne of sugarcane) by up to 1900% for farms producing sugar from sugarcane. The authors concluded that while LUC emissions can affect the CF importantly, assuming an absolute worst-case scenario for LUC for products of unknown origin was problematic for sugar producers because sugar is often sold as a multi-origin product and these origins can change depending on the season.

The impact of accounting for soil carbon change due to land management and change in land management was somewhat less important than for LUC, but it was still substantial. It represented about 300% of the GHG emissions from of the agricultural production phase in a sugarcane field using an unburned harvesting systems in Brazil (Galdos et al. 2010), although the reduction only accounted for about one third of the life cycle GHG balance of bio-ethanol production that included the avoided fuel emissions due to the combustion of bio-ethanol. Furthermore, Plassmann et al. (2010) found, using sensitivity analysis, that including the losses in soil-carbon stocks due to LU management could increase the GHG balance results from 34% to over 170% for various sugarcane farms in Zambia and Mauritius. However, these losses are estimated from the literature and related to the cultivation of vegetables in Kenya. Another example is the potential impact of soil carbon sequestration due to no-till practices as shown by Labreuche et al. (2011). They found that these practices reduced the GHG balance of the production phase of a wheat-corn rotation by 38%. This reduction represented three to four times the GHG reduction due to the comparative decrease in fuel use in the no-till system.

Overall, the impact of taking into account changes in soil carbon due to both LU and LUC in LCA and CF can be substantial. This raises questions about the usefulness of the results of studies assessing the GHG balance of land based systems that exclude soil carbon change,

[5] As required by the 2008 version of the PAS 2050 when the origin of the product is unknown, and corresponds to the transformation of a natural forest to arable land in Malaysia, resulting in the loss of 37 tonnes of CO_2eq/ha/year from both the soil and vegetation.

or assume no change. However, many authors have highlighted a number of issues related to soil-carbon change accounting in LCA and CF. These are explored in Section 2.3.3.

2.3.3. Issues for soil carbon integration in LCA and CF

Several issues specific to the treatment of soil carbon in LCA and CF emerged as being particularly important in the case studies included in this review. Firstly, there is a critical lack of soil-carbon stock and change data. Secondly, there is a huge uncertainty associated with extrapolation of the available data for use in LCA and CF studies more generally. Thirdly, there is a paucity of data on the site-specific characteristics of soil-carbon stocks and temporal changes.

Three other issues were also commonly highlighted: the dearth of information about the timing of soil carbon emissions, removals and their impact on climate change; the lack of common agreement of the choice of a reference datum (or "reference situation"); and questions about the testing and validation of the models that predict soil carbon change. Finally, two issues were seldom discussed but were identified as important when they were mentioned: soil carbon associated with iLUC, and the permanent impact of a change in soil-carbon stocks. These issues are discussed below in Sections 2.3.3.1 to 2.3.3.8

2.3.3.1. Lack of data

In total, seven CF studies included measured data specifically collected for the purpose of the study, while 20 studies used data from the literature, including 10 studies that used IPCC data, and 23 studies that used or reported model estimates of soil-carbon stock and change.

Generally, LCA and CF studies that include assessment of soil carbon highlight a critical lack of data for soil-carbon stock and change for all land based systems. Missing data have been emphasised in LCA and CF studies of forests (e.g. Page et al. 2011), as well as agricultural production such as grasslands (e.g. Soussana et al. 2010), crop rotation (e.g. Sheehan et al. 2003), feed crops (e.g. van Middelaar et al. 2013), and a range of horticultural and vegetables crops (e.g. Venkat 2012).

Additionally, several authors identified a lack of data regarding soil carbon in feedstocks for the first, second and third generations[6] of biofuels and bioenergy production. These include sugarcane (e.g. Lisboa et al. 2011), Miscanthus, short rotation coppice (SRC) poplar, winter wheat and oilseed rape (e.g. Hillier et al. 2009), corn stover (e.g. Kim et al. 2009), SRC willow (e.g. Heller et al. 2003), grain based crop production (e.g. Robertson et al. 2011), woody Biomass To Liquid (BTL) (e.g. Sunde et al. 2011), switchgrass (e.g. Monti et al. 2012) and micro-algae (e.g. Bonin and Lal 2012). Specifically, in a review of 44 LCA studies of first and second-generation biofuels, Whitaker et al. (2010) concluded that "empirical data" of soil carbon pools and soil GHG emissions were generally lacking, and highlighted their "significant" potential impact on LCA outputs. More recently, in a review of a wide range of first, second and third generation feedstocks, Bonin and Lal (2012) stated, "[...] more data and methods to accurately calculate SOC under various bioenergy crops are vital for an accurate estimation with LCA".

Furthermore, soil-carbon stock and change data were reported as lacking at all spatial scales. For example, authors identified the urgent need for data at the global (e.g. Flynn et al. 2012), sub-continental (e.g. Europe (Soussana et al. 2010) and the regional scale (e.g. Fox and Campbell 2010), at the country or state scale (e.g. Iowa (Sheehan et al. 2003) and Thailand (Siangjaeo et al. 2011)) as well as at the local scale (e.g. Kimming et al. 2011a).

This lack of soil carbon data has several consequences. Firstly, in many studies, soil-carbon stock and change are simply excluded from the analysis. Secondly, if they are included, then various strategies are used to address the issue. Some authors assume a "steady state" of soil-carbon stocks. That is they assume carbon neutrality for the soil in their studies. However, this could be inappropriate as many systems may not be at equilibrium (Bonin and Lal 2012). Several authors use large scale, default, average soil-carbon stock and change

[6] First generations biofuels originate from plant sugars, starches and oils, extracted, for example from sugarcane, wheat or canola. Second generation biofuels originate from lignocellilosic biomass, for example from switchgrass, Miscanthus, and willow. Third generation biofuels are extracted from microalgae, and do not require large areas of land for cultivation.

factors from LCA databases or the IPCC values (Siangjaeo et al. 2011). However, as highlighted by van Middelaar et al. (2013) and in Appendix A1.2, the uncertainty associated with these reference data is huge and, according to Pawelzik et al. (2013), this leads only to a “rough first-order approximation” of soil-carbon stock and change.

Thirdly, another strategy is to use a model that incorporates and predict soil-carbon temporal changes to compensate for the lack of data (e.g. Hillier et al. 2009; Kimming et al. 2011a; Godard et al. 2013). However, there are various types of models representing natural processes and they all have advantages and limitations (see Section 2.3.3.6), and require data for testing and parameterisation (Smith et al. 2012). In the few cases that use this strategy (see Section 2.3.3.6), the uncertainty associated with the soil-carbon input data is high (e.g. Follett et al. 2012), which makes model estimates “highly contentious” (Page et al. 2011). According to a review of GHG accounting methods for land based production systems by Cowie et al. (2012), collecting data on changes in the soil-carbon stock is a research priority to improve dynamic models.

Several authors highlight the types of data needed for assessment of soil-carbon stock and change. Whitaker et al. (2010) argue that empirical data on soil carbon pools and fluxes plus soil GHG emissions are needed. On the other hand, Cowie et al. (2012) highlight that data on the effects of management practices on soil-carbon stocks in cultivated and natural ecosystems are required, as well as data on the potential of ecosystems to sequester soil carbon. Cowie et al. (2012) also signal that “without LCI data, (i.e. including soil carbon data) […] LCA as a tool for understanding GHG emissions from food cannot be implemented”. Similarly, Koellner et al. (2012) highlight that LCA studies of large scale land-based systems can only provide meaningful results once the detailed data are available.

Regarding the characteristics of the data needed, Sunde et al. (2011) argue that information on soil-carbon stocks and changes must be site specific (see also Section 2.3.3.3). Furthermore, Hillier et al. (2009) explain that these data must relate to the soil and climate

conditions, and represent the short and long term changes. In addition, Follett et al. (2012) states that soil-carbon data must also describe deep soil carbon changes, below the plough layer and beyond. According to Sheehan et al. (2003), these data need to be time dependent (see also Section 2.3.3.4). Bonin and Lal (2012) highlight that a quantification of variability for the area assessed should be included. Finally several authors (Plassmann et al. 2010; Follett et al. 2012) outline the critical need to specify the associated uncertainty of using a particular value (see also Section 2.3.3.2).

Methods to collect these data have been proposed, such as long term experiments, chrono-sequences, and flux measurement networks (Smith et al. 2012), but it is argued that these must also be “rapid and cost effective” (Cowie et al. 2012).

Finally, a number of authors note that data on soil-carbon stock and temporal change need to be expressed with and related to a wider range of environmental site-specific information. These associated data should focus on land characteristics and management, such as crop yield, erosion, nitrogen dynamics (Kim et al. 2009), the fate of above and below ground biomass (Hamelin et al. 2012), and the historical and present management practices (Flynn et al. 2012; van Middelaar et al. 2013).

2.3.3.2. Uncertainty

Uncertainty occurs at all levels of LCA (Bessou et al. 2011) and quantifying uncertainty is essential. It is equivalent to answering the question, “To which extent could this value, choice, result, or interpretation be different?” There is uncertainty in measured data values due to natural and methodological variability, in estimated values due to a lack of data, in natural-processes-modelling choices due to approximation in equations, and in LCA modelling choices due to the numerous assumptions. It is therefore important to quantify uncertainty, in order to know how far estimates are from the true value. Quantification of uncertainty is also important in order to identify where uncertainty is likely to be the highest and to prioritize future data collection..

Several authors characterise soil-carbon stock and change, plus GHG emissions, as a major, if not the most, uncertain parameter in LCA and the CF of land based systems (Styles and Jones 2007; Meisterling et al. 2009; Whitaker et al. 2010; Visser et al. 2011; Malca and Freire 2012). Despite this fact, amongst the 82 LCA and CF case studies[7] reviewed here, only 20 studies (24%) actually quantified the uncertainty related to estimates of soil-carbon stocks and temporal changes. Some 29 more studies simply mentioned uncertainty of soil-carbon stock and change data without qualifying it further.

Uncertainty has been quantified to various degrees. One of the most approximate quantifications of uncertainty was a sensitivity analysis that used unjustified presumed +/- 20% variation of the initial soil-carbon stock (Kimming et al. 2011b). Similarly, van Middelaar et al. (2013) outline that the results of varying by +/- 10% the soil carbon change factors do not necessarily reflect the large uncertainties and variability occurring in natural systems. Conversely, Cherubini and Jungmeier (2010) and Cherubini and Ulgiati (2010) calculated the sensitivity of the total GHG emissions from a bio-refinery system using the extremes of a range of values found in the literature. In the study by Cherubini and Jungmeier (2010), the range extremes were – 66% and + 83% of the initial soil-carbon stock change.

Uncertainty in soil-carbon stock and change has also been expressed in a more detailed way with a range of values accompanying the means presented (Meisterling et al. 2009; Flynn et al. 2012; Koponen et al. 2013). Simple error bars on graphs (without numerical values) have been used (Hillier et al. 2009; Popp et al. 2011; Follett et al. 2012), along with standard errors or standard deviations, (Ciais et al. 2010; Kutsch et al. 2010; Gelfand et al. 2011; Romijn 2011; Siangjaeo et al. 2011; Hergoualc'h et al. 2012; Cameron et al. 2013; Gelfand et al. 2013), and sometimes variation was obtained by Monte Carlo analysis (probability density functions) (Bartlett and James 2011; Malca and Freire 2012).

[7] Excluding the reviews of case studies.

Almost all the studies that quantified uncertainty in soil-carbon stock and change concluded that it could have large consequences for the LCA or CF results. For example, Meisterling et al. (2009) compared organic and conventional wheat cultivation and showed that the uncertainty in soil-carbon sequestration rate could be roughly equivalent to 18 times the difference between the two systems (Fig 2.1). Malca and Freire (2012) calculated that the contribution of soil carbon emissions to the variance in GHG of bioethanol to be more than 68%, and they concluded that this uncertainty could be larger than differences between compared products. Due to this high uncertainty, several authors have urged caution when interpreting the results of their studies. For example, Piemonte and Gironi (2012) warned that it was not possible to use their results as a marketing tool.

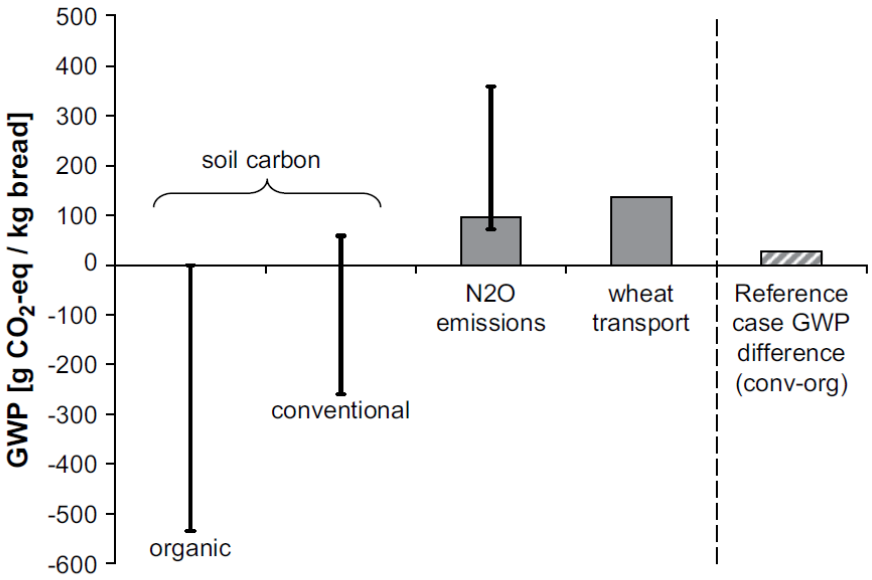

Figure 2. 1 Example of the impact of the large uncertainty in soil carbon data when comparing conventional versus organic wheat production. The uncertainty quantified by the vertical error bars for soil carbon can represent up to 18 times the difference between the systems (diagram bar on the far right). Source: Meisterling et al. (2009, pp 227)).

Quantification of this uncertainty would seem to be a minimum requirement for the transparency and reliability of LCA and CF of land-based systems. Tools exist to assess uncertainty of all types qualitatively (e.g. pedigree matrix[8]) as well as quantitatively (e.g.

[8] A pedigree matrix (Pedersen Weidema and Wesnæs 1996) is a qualitative approach to uncertainty. For each input and output datum, each of six uncertainty indicators receive a score between 1 (good quality data) and 5 (poor quality data). These scores are then computed to calculate a standard deviation.

standard errors and standard deviations) (Bessou et al. 2011). Therefore it is possible to express soil carbon data uncertainty in LCA and CF results. And, as argued by Plassmann et al. (2010), decision-makers need to be informed about these uncertainties in order to interpret results correctly and reach justified conclusions. Furthermore, an emphasis upon representing soil-carbon stocks and change data in study results will encourage further data collection and the implementation of soil carbon change monitoring schemes in the future. As well, these data will have utility well beyond LCA and CF studies, such as a better understanding of the carbon cycle.

2.3.3.3. Site dependency and local specificity

Site dependency can be defined as the effects of the environment in a specific and delimited area that make an estimated or measured variable unique to this area. Often, the term “site specific” is used as equivalent. The quantification or qualification of a variable is then dependent on, or specific to, the particular characteristics of its local context.

Many LCA and CF case studies reported the site dependency of either or both soil-carbon stocks data and the changes in these data values due to the system under analysis. Firstly, some studies highlight the complexity of natural systems, as compared to industrial systems. In other words, the complex relationships between the natural systems variables are seen as a reason for site dependency. For example, Bessou et al. (2011), in an extended review of biofuels production and their impact on climate change, concluded that the complexity of including both temporal and spatial aspects of LUC in LCA and CF imply that accurate estimates, including those related to soil carbon, may be limited to the local level.

Secondly, numerous authors identify the variability of soil-carbon stocks and temporal changes at various scales and within a number of systems. For crops grown for bioenergy, this variability is highlighted at the scales of the field (Follett et al. 2012), the farm (Kimming et al. 2011a), the state (Adler et al. 2007), larger regional (Liebig et al. 2008), the country (Hillier et al. 2009; Kendall and Chang 2009; Cerri et al. 2011) and globally (Bonin and Lal

2012). Also, variability is highlighted in the grassland systems of Europe (Soussana et al. 2004), in a review of GHG emissions from wetlands (Poffenbarger et al. 2011), and globally for feedstock ingredients (van Middelaar et al. 2013).

Furthermore, three types of factors are pointed out to be responsible for this variability in both soil-carbon stocks and the rates of temporal changes. They are climate, soil characteristics, and land management practices (Heller et al. 2003; Cherubini and Jungmeier 2010; Bessou et al. 2011). These factors are detailed in Table 2.1. Indeed, many studies conclude that these factors vary locally, and this implies that the soil-carbon stocks and temporal changes are site specific (Heller et al. 2003; Styles and Jones 2007; Bonin and Lal 2012; Scown et al. 2012).

Combining all the factors listed in Table 2.1 that affect soil-carbon stocks and their changes with time would therefore produce a different outcomes for virtually every single managed piece of land on Earth. To a certain degree, this implies that attempting classifications of managed land according to their stocks and changes in soil carbon "can only give rough estimates" (Sunde et al. 2011). Indeed, the site specificity of soil-carbon stocks and temporal changes increases the uncertainty when extrapolating the results of LCA and CF studies and soil carbon models (Bessou et al. 2011). For example, Hillier et al. (2009) present a dynamic model to estimate the GHG emissions of livestock products and they conclude that the outcome of GHG balances has the potential to change from positive to negative, and vice versa, depending on their location. Similarly, while seeking to improve the reliability and accuracy of data in LCA studies of bio-based products, Benoist et al. (2008) argued that the relevance of the soil-carbon related results in CF studies focusing on large geographical boundaries can be impaired due to this large variability. Therefore, Bonesmo et al. (2013) explained that if the application of mitigation options at the farm level is sought, the focus should be on quantifying the variations within production systems rather than calculating an average for the industry.

Table 2. 1 Examples of factors affecting soil-carbon stock levels and temporal changes in land based systems.

Type	Factor	Reference(s)
Soil	Existing carbon content	Galdos et al. (2010) Styles and Jones (2007)
	Texture (fraction of sand, silt and clay)	Galdos et al. (2010) Adler et al. (2007) Cerri et al. (2011) Popp et al. (2011) Godard et al. (2013)
	Structure	Styles and Jones (2007)
	Bulk density	Galdos et al. (2010)
	pH	Godard et al. (2013)
Climate	Moisture content	Styles and Jones (2007)
	Temperature	Styles and Jones (2007) Godard et al. (2013)
	Rainfall patterns	Godard et al. (2013)
Previous and current land use and management	Land history	Soussana et al. (2004)
	Soil disturbance (e.g. tillage method and intensity)	Venkat (2012) Adler et al. (2007) Godard et al. (2013) Galdos et al. (2010)
	Organic material application	Venkat (2012) Galdos et al. (2010)
	Mineral fertiliser application	Galdos et al. (2010)
	Crop type, crop rotation /sequence	Adler et al. (2007) Godard et al. (2013)
	yield	Adler et al. (2007)

Finally, Gabrielle and Gagnaire (2008) advocated the use of biophysical models when integrating local data to quantify site-specific environmental impacts. The authors proposed that, in the long run, this would allow an environmental rating of various production systems for specific geographical areas. According to the authors, this rating could ultimately result in geographical relocation of production systems.

2.3.3.4. Timing of emissions

The importance of timing of emissions and removals emerged in the climate change literature with the development of Global Warming Potentials (GWPs) to evaluate the climate change effect of greenhouse gases (GHG) emissions. Following the signing of the Kyoto Protocol in 1997, measuring emissions and removals was necessary. The GWP was chosen as the common metric. In 2000, the emphasis was put on removals with tonne-year approaches developed for assessing Land Use, Land Use Change and Forestry (LULUCF) activities, and crediting temporary storage. More recently, with the development of LCA to assess GHG emissions and removals for agricultural systems, the topics of timing of emissions and accounting for temporary removals in LCA led to the development of several methods. Therefore, Section 2.3.3.4.a presents a brief overview of these methods and in Section 2.3.3.4.b, the treatment of the timing of emission in case studies is presented.

2.3.3.4.a. Methods to account for emission timing and temporary carbon storage

The effect of greenhouse gases (GHG) on the atmosphere is related to the lifetime of the GHG in the atmosphere, as well as its radiative forcing capacity (Ramaswamy et al. 2001). The Bern carbon cycle model is used by the IPCC (Joos et al. 2001) to determine future carbon fluxes and their impacts on global climate and ecosystems. The decay of a pulse of carbon dioxide in the atmosphere could be considered as infinite. Following a pulse of CO_2, 17 to 33% of the gas will stay in the atmosphere for about 10,000 years (Archer 2005). Therefore, in order to represent the reality, GHG emissions should be assessed over infinite time to account for the complete Cumulative Radiative Forcing (CRF) of CO_2. However, this is not practical as the size of the impact would be infinite. The assumption that no emission stays in the atmosphere beyond a certain time after a pulse emission (also called “cut off”) allows impacts to be finite and therefore measurable.

However, the longer the time period, the more emphasis is put on CO_2 as opposed to other GHGs whose lifetimes in the atmosphere are shorter. Therefore, there is a balance to find

between the urgency of acting to mitigate climate change associated with the choice of a short time horizon, and the effect of present decisions on future generations which is linked to a longer timeframe of assessment. Fearnside et al. (2000) recommends a time horizon of 100 years, as opposed to Archer (2005) who states that a “better approximation of the lifetime of fossil fuel CO_2 for public discussion might be “300 years plus 25% that lasts forever””. On the other hand the IPCC (2013) provides projections about impacts on our environment and climate that occur less than 40 years into the future. Therefore, the choice of a relevant time horizon has been debated, and three types of methods have been developed to account for the timing of emissions: climate change metrics, tonne-year approaches, and methods developed specifically for LCA. These methods are described and discussed in detail by Brandão et al. (2013), and a brief overview is provided in this section. The global warming potential (GWP) is the most commonly used metric to represent the climatic impact of GHGs. The IPCC reports GWP values for 20, 100 and 500 years for each GHG. When using GWP, it is assumed that all GHG emissions over the chosen time horizon occur as a pulse at the beginning of the accounting period. The timing of emissions is therefore not considered. This has the benefit that all emissions are considered for that time horizon irrespective of the timing of the initial release of the emission. However, when a few years away from the end of the time horizon, it would be easy to delay emissions in order to exclude them from the impact calculation. Recently, several researchers called for different impact metrics in order to represent all the relevant impacts associated with GHG emissions (Shine 2009). For example, Shine et al. (2005) proposed the Global Temperature Potential (GTP), focused on the ratio of future temperature change. The GTP metric was integrated in the Fifth Assessment Report of the IPCC (IPCC 2013), together with GWP. Recently, Kirschbaum (2014) proposed the climate-change impact potential (CCIP) integrating three kinds of impacts: increases in temperature, rate of global warming, and cumulative global warming.

The “tonne-years” approaches include the Moura-Costa and Lashof methods. The Moura-Costa method (Moura Costa and Wilson 2000) calculates the time one tonne CO_2 must be stored in order to compensate for the radiative forcing of an emission of one tonne CO_2 over 100 years according to the Bern cycle model. This permits the calculation of a yearly credit for carbon storage projects. The radiative forcing of an emission is calculated over 100 years, regardless of when it occurs. However, Fearnside et al. (2000) and Brandão et al. (2013) highlight several limitations of the method. The Lashof method (Fearnside et al. 2000) considers that the CO_2 temporary sequestration for a particular time period delays emissions for the same amount of time. Levasseur et al. (2012) highlight several limitations of the method. A linear approximation of the Lashof method for short timeframes developed by Clift and Brandão (2008) is integrated in PAS 2050 (BSI 2011) to assess short term (<25 years) temporary carbon storage. The major drawback of the tonne-years approaches is that a credit is given for delaying emissions that is not consistent with the principle of inter-generational equity, which is an integral part of the concept of sustainable development (Brandão and Levasseur 2010).

Several methods to assess the timing of emissions and temporary storage have been developed for the purpose of LCA. For example, O'Hare et al. (2009) developed the Fuel Warming Potential (FWP) to account for the radiative forcing of a biofuel relative to its fossil fuel equivalent. On the other hand, Kendall (2012) developed the time adjusted GWP (TAWP) which is a hybrid between the GWP and the Lashof methods. Another example is the Dynamic LCA approach (Levasseur et al. 2010) that allows accounting for the temporal distribution of GHG emissions and sequestration. The authors do not recommend a particular time horizon for assessment, as this depends on value choices (Shine 2009).

Within the last 15 years, several methods have been developed to take time into account in climate change impact assessment for LCA and CF. However, a focused workshop (Brandão and Levasseur 2010) and two thorough reviews of proposed methods (Kendall

2012; Brandão et al. 2013) improved the understanding, although there is still no consensus on treatment of emissions timing in LCA and CF.

2.3.3.4.b. Timing of emissions in case studies

In most studies, soil carbon change was simply added to or subtracted from the GHG results, which is equivalent to ignoring the time related aspects of these changes. Three time-related aspects linked to soil-carbon stock and change can be distinguished, and all three can have a big impact on the magnitude of the climate change results of LCA and CF studies.

The first aspect is the short- and long-term timing of the changes in soil-carbon stocks due to land management, or a change in land management. These changes are asymmetric with the rate of soil carbon gain generally being slower than loss rates. Furthermore, they are non-linear over time due to environmental conditions and management practices (Soussana et al. 2004). Therefore whole crop rotations and the entire crop cycle of perennial crops should be considered rather than a single year or season, when performing LCA of land based products (Bessou et al. 2013). For example, in a comparison of long-term (oak) versus short-term (pine) rotation forestry, Vallet et al. (2009) found that a short timeframe of assessment of one pine rotation would favour the short term rotation as carbon stocks would increase faster in the first years of establishment. However, when averaged over the longer oak rotation which is equivalent to several short pine rotations, more carbon would be stored in the oak plantation.

The second aspect is the changes in soil-carbon stocks due to LUC via land conversion. While usually happening in a single year, these changes are often attributed to the new land use for a limited time, sometimes called the “payback period” (Verge et al. 2012) or “amortisation period”. The IPCC guidelines for national GHG inventory recommend distributing these changes over 20 years following land conversion (IPCC 2006). This is due to the assumption that soil-carbon stocks will reach equilibrium within this time period.

Accordingly, some authors present two sets of results Cherubini and Jungmeier (2010) presented results for year 0 to 20, and for year 20 to 100, with changes in soil carbon due to the conversion of set aside land to switchgrass grown for bio-energy only included in the first 20 years of the assessment. In contrast, Knudsen et al. (2011) assessed the sensitivity of accounting for soil carbon change either divided by 20 years, or by 100 years, on the conversion of integrated orange orchard to an organic one. Obviously the authors found a bigger reduction when dividing the soil carbon storage by 20 years (23 to 39%, for large and small farms, respectively) rather than by 100 years (4 and 8% for large and small farms, respectively). Overall, attributing the soil carbon impacts of land use change over different time horizons can lead to very different results.

The third aspect concerns the fact that there is no agreement in LCA on how to account for the impact of carbon emissions, including due to soil carbon loss, on the radiative forcing that drives climate change. As highlighted by Levasseur et al. (2010), a one-time pulse of a GHG does not have the same effect on the atmosphere as emitting the same amount over a long period of time. Several authors (Kendall 2012; Levasseur et al. 2012; Levasseur et al. 2012; Levasseur et al. 2013) show large variations of results depending on the timeframe chosen for assessment, and highlight the important implications if these results are used to support decision making. The method from Levasseur et al. (2010) is the only one so far allowing the consequences of this choice to be graphically displayed and therefore could be a powerful communication tool for LCA practitioners and an essential learning tool for decision makers, as it would push them to clarify and justify their choice of time horizon.

Overall, various authors treat the timing of emissions differently and without a specific standard method applied in all LCA and CF studies, therefore comparing the results of different studies that may have been calculated over different timeframes is difficult.

2.3.3.5. Reference datum

The reference soil-carbon stock datum, that is, the soil-carbon stocks at time zero or the initial soil-carbon stock, is the reference level used to compare the emission or sequestration of soil carbon. The reference datum concerns both LUC and LU. While not often discussed in the reviewed studies, and seldom added to sensitivity analyses, the reference datum can either determine to a large extent the CF results or have a trivial effect, depending on the assumption of what land use type is replaced by another or which land use is modified.

For example, Piemonte and Gironi (2011) found that the assumption of producing bioplastics from annual crops grown after the conversion of natural forest or grassland could make this product “unattractive”, as opposed to producing bioplastics from perennial crops grown on degraded croplands. Similarly, Khatiwada et al. (2012) concluded that the type of land that is converted to sugarcane can affect the GHG emissions results substantially. In the same way, Koponen et al. (2013) identified the definition of a reference land use as a “crucial” assumption that can “significantly influence the results” when they were criticising a European bioenergy directive for the calculation of GHG savings of biofuels. In a case study comparing biofuels crops, Brandão et al. (2011) concluded that there was a negative impact of a willow crop on soil quality, assessed with the indicator soil organic carbon (SOC), despite an increase in SOC. The authors highlighted that this was due to the fact the SOC increase under the willow crop was slower than that of the reference natural system chosen. Mattila et al. (2012) found that the reference SOC has a “key impact on the SOC indicator results” in a case study of beer production.

Most authors use an estimate of the soil-carbon stocks at the beginning of their chosen assessment timeframe as a reference to calculate the impact. However, in accordance with the work of Milà i Canals et al. (2007) that was further developed by Koellner et al. (2013), Kendall and Chang (2009) suggested using the “native ecosystem” as a baseline to calculate soil carbon changes because of their “greater propensity to store carbon than most agricultural systems”. However, Lisboa et al. (2011) argued that “the direct conversion of

native vegetation to sugarcane fields is unlikely to occur in Brazil, whereas for other countries no information is available". Muller-Wenk and Brandão (2010) also use a "native ecosystem" as a reference when assessing cropland carbon stock change. They highlight that there would be a higher climatic impact if native forest was used as reference, as opposed to native grassland. Similarly, Milà i Canals et al. (2012), when studying the land use impacts of margarine, outlined that using an idealistic reference does not consider the short-term effects of land use change. According to the authors, this could lead decision makers to take the wrong decisions, because the focus of the assessment is diverted towards an unrealistic objective of restoring productive land to a near-natural state.

Another way to consider the reference land-use change of a particular system depends on the monetary value of the new crop production. Khanna et al. (2011) provided an example for the growth of biofuel crops across the counties of Illinois, USA. They assumed that as biofuel prices increase, more land is converted to biofuels production. The type of land converted depends on the monetary value of the production on this land compared to the value of producing biofuel crops. In this way, the change in soil carbon stock as a result of LUC was depending on the type of land converted.

Overall, the choice of a particular reference datum to calculate impacts of the change in soil carbon stock is arbitrary and can substantially influence the results of LCA and CF studies.

2.3.3.6. Modelling

A range of types of soil carbon models have been used to calculate data used in LCA and CF studies. However, there is no consensus about the fitness-for-purpose of any one particular model. Variability and uncertainty issues have been highlighted in reviews of these models and generally are directly associated with a lack of data for model calibration and testing.

For example, Liska and Cassman (2008) reviewed studies of biofuels systems to identify issues and propose improvements. They found important differences between the

predictions of change in soil-carbon stock at depth by the CENTURY model (and its daily version, the DAYCENT model) when it was calibrated with topsoil data and more recently measured data on the same land area. Therefore, the authors concluded that there was a high uncertainty associated with model predictions if they were not calibrated with the relevant data.

Similarly large differences were found between the predictions of different models: in a review of the GHG mitigation of managed grasslands in Europe, Soussana et al. (2010) found high variability in estimates by a range of soil-carbon models as well as farm GHG balance models. They concluded that more long term monitoring experiments and GHG fluxes measurements at the farm scale were required. Large variations between different models' results for forest GHG balances, including soil-carbon, were also reported by Cameron et al. (2013).

Additionally, several studies highlighted the arguable assumption of the steady state of soil-carbon stocks at the beginning of the assessments (e.g. Kutsch et al. 2010; Rotz et al. 2010). In order for the soil-carbon stocks to reach equilibrium, the process called "spin-up" consists of running the model for centuries or millennia, following several assumptions for land use change and management, as well as initial soil-carbon stocks (e.g. Kim et al. 2009). As a result, the soil-carbon stocks are regarded as being "at equilibrium" at the start of the assessment. This steady state assumption may be unrealistic because some soils may be accumulating or losing carbon. For example, soils with high carbon stocks originally may lose large amounts of carbon over a long period of time following a disturbance and so may not be "at equilibrium" at the start of an assessment period (Kutsch et al. 2010).

Finally, Popp et al. (2011) pointed out the gap between small (e.g. field, farm) and large (e.g. regional, national or global) scale models. Indeed, due to a lack of data, it is impossible to test the results of large scale models for a large area with a number of small scale

simulations that add up to the large area assessed. Therefore using the results of large scale models to support policy analysis is quite complicated (Popp et al. 2011).

As explained by Smith et al. (2012), the choice of using any particular soil-carbon model should be based on its capacity to represent the change in soil-carbon stock under the range of conditions and variables that are specific to the soil-plant-atmosphere system(s) under study. According to the authors, this involves thorough testing and validation against representative datasets, as well as a quantification of the model's sensitivity and uncertainty.

In conclusion, data on soil-carbon stock and change are absolutely vital if any credible assessment through modelling is to be carried out. It is therefore necessary to set up long term soil carbon monitoring programs and collect data on a range of associated agronomic variables to calibrate, test and validate models for a range of site specific conditions.

2.3.3.7. Indirect Land Use Change

The link between Indirect Land Use Change and soil-carbon stocks has mainly been raised in case studies assessing the GHG emissions of biofuels. This is due to the possibility that planting biofuels crops on food producing land would lead to a decrease in food supply that would then need to be compensated, leading to the clearing of native ecosystems in other areas. Yet, iLUC was not integrated in the biofuels LCA until 2010 (Whitaker et al. 2010). Many studies highlight the huge uncertainty associated with the assumption of a change in Land Use elsewhere (iLUC) due to the change in direct Land Use (LU) being assessed (Whitaker et al. 2010; Sunde et al. 2011; Bonin and Lal 2012). These studies and others also recognise the large impact that such assumptions could have on their results. For example, Kendall and Chang (2009) described the potential impact of iLUC emissions on the CF of biofuels as "outstanding". Furthermore, Cederberg et al. (2011) describe the impact of iLUC emissions from deforestation as far greater than the CF of exported Brazilian beef. Several authors advocate that iLUC emissions should not be treated at project level (e.g. Cowie et al. 2012) but rather they "need to be modelled on a global scale by coupling complex economic

and biophysical models" (Monti et al. 2012). And Cowie et al. (2012) suggested the establishment of "discount factors" based on the regional or national rate of deforestation, that could be applied to all biofuels projects in the area.

2.3.3.8. Permanent impact

Several authors have highlighted the fact that the long-term impacts, beyond the timeframe of assessment, are ignored in LCA and CF studies (e.g. Hamelin et al. 2011; Kimming et al. 2011).

The permanent impact of a change in the soil-carbon stock is very much dependent on the assumption of what happens beyond the timeframe considered in the assessment. After some time of consistent land management, the gain rate as a function of inputs may reach zero. Some authors argue that soil-carbon stock reaches a maximum level that depends on the soils' unique physicochemical characteristics (Six et al. 2002; Stewart et al. 2007). This phenomenon is called "steady state" or "equilibrium". However, as explained by Soussana et al. (2004), such a state can be sustained only if the land management stays the same, and any change in land management may result in a change in the soil-carbon stock. Similarly, Adler et al. (2007) highlight that the specific soil, the type of crop and its management will determine soil carbon sequestration in the long term. In addition, it is possible that methods such as application of biochar to the soil can increase carbon sequestration (Macías and Camps Arbestain 2010), perhaps beyond the saturation levels in soils.

2.4. Conclusions

This review has identified many outstanding issues in the treatment of soil-carbon stock and change in LCA and CF studies. Despite their potentially huge impact on the climate-change impact assessment values for land based production systems, the assessment of soil carbon change suffers from a crucial lack of data. Most studies have used data that are not site-specific despite the fact that soil-carbon stocks and their changes over time are governed by site-specific factors related to the local soil, climate and past and present management practices. This site specificity is due to the complexity and variability of natural systems at all spatial and temporal scales. Therefore, in the vast majority of cases, soil carbon related results in LCA are characterised by a huge uncertainty, which is rarely quantified despite readily available statistical methods. Some studies used various dynamic or biophysical models to predict changes in soil-carbon stocks, although these models suffer from the same general lack of site specific data for testing and validation, and therefore show similar levels of uncertainty as other estimates.

Additionally, several methodological assumptions further reduce the reliability of soil carbon related results. The time-related aspects of land-based production systems such as the influence of crop rotations, and the timing of emissions and removals and their impact on radiative forcing, are in most cases omitted. When considered, a variation in the timing aspects of the changes in soil-carbon stocks could lead to large variations in the climate change results, and increase the complexity of interpretation when comparing similar land based production systems. Furthermore, the choice of a reference situation is arbitrary and contentious, and iLUC depends on complex economic and environmental factors. Finally, the permanent impact of current changes in soil-carbon stocks depends on what happens to the land in the future, beyond the assessment timeframe, and is therefore highly uncertain.

In conclusion, there is a clear need for research to focus on collecting data on soil-carbon stock and change, including the effect of various land management practices. Ideally these

data should be collected in all land based systems, include deep soil carbon estimates and should be site specific, geo-localised and time dependent. They should be representative of the particular area under study, should quantify the inherent variability, and should express the uncertainty of averages of soil-carbon stock and change. Finally, these soil carbon data should be accompanied by data sets describing the environmental and management conditions in which they were collected. Such data would allow the testing and calibration of soil carbon models and therefore reduce the uncertainty surrounding future soil-carbon stock and change predictions. As highlighted in this review, integrating data on soil-carbon stock and change into LCA and CF studies of land-based production systems can have a large impact on the climate-change impact-assessment results with critical implications for the interpretation of these results and subsequent decision-making processes. Therefore, whenever data on soil-carbon stock and change are used in LCA and CF studies, ideally all the above characteristics of soil carbon data should be included. In particular, the statistical uncertainty of the soil carbon estimates should be quantified and clearly expressed, in order to improve the transparency and reliability of LCA and CF results.

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Chapter 3:

Variability of bulk density, carbon content and carbon stock in an apple orchard block, and implication for measuring and monitoring

Table of Contents

3.1. Introduction

Robust evidence of changes in the atmosphere, the oceans, the cryosphere, and the land surface of planet Earth have been recorded over the last century, and result primarily from the radiative forcing of anthropogenic Well Mixed Green House Gases (WMGHG) (IPCC 2013). Regarding the future, the latest IPCC report (IPCC 2013) explains that "societal choices can still have a very large effect on future radiative forcing, and hence on climate change".

As discussed in section 1.5.1, increasing the soil's carbon content could constitute an efficient tool but only represents a short term climate change mitigation measure, because of carbon saturation in soils (Mondini and Sequi 2008). Additionally, Smith and Olesen (2010) identified soil carbon sequestration as the most prominent option providing synergy between climate change mitigation in agriculture and enhancing resilience to future climate change.

Furthermore, as highlighted in section 1.5.2, higher levels of soil carbon are generally beneficial for soil functioning and biodiversity. Therefore increasing soil carbon has diverse benefits. These are economic through more stable yields, increased resilience to extreme weather events, as well as societal by enhanced food and water security, less damage to infrastructure through reduced flooding and water run-off, plus environmental through erosion and desertification mitigation, and the reduction of water pollution (FAO and CTIC 2008; Victoria et al. 2012).

However, standardized methods for assessing the potential environmental impacts of production systems, such as the carbon footprint and Life Cycle Assessment (LCA), exclude this substantial global carbon cycle component. This has significant implications for the results of studies employing these methods, as explained in Section 1.3.2 and illustrated with a review of case studies in Section 2.3.

Strikingly, the potential relevance of soil carbon in such assessments contrasts with the limited availability of data on soil carbon stocks at all spatial scales (see Section 2.3.3.1).

This can be explained by the difficulty of measuring a change in soil carbon stocks over time. The high spatial variability of soil carbon stocks (Post et al. 2001; VandenBygaart et al. 2007) results from natural factors such as soil mineralogy, historic vegetation successions and climate conditions, as well as anthropogenic traits such as current and past land use and management. Most studies have focused on the top 30 cm layer, as suggested by the (IPCC 2006), or even shallower depth increments. But it is now clear that, as noted by Schmidt et al. (2011), “there is a lot more deep soil carbon than we once thought”.

In order to compensate for the lack of site specific data expressed earlier in this section, scientists and LCA analysts have sometimes used biophysical models to simulate the evolution of carbon stocks in soils (see Section 2.3.3.6). However, data about soil carbon stock and change are required to calibrate models, and sustainably monitor soil carbon stocks. Furthermore, a good understanding of the variability is required. To do so, it is preferable to sample and analyse the soil profile in several increments corresponding preferably to the various soil horizons. Indeed, Kravchenko & Robertson (2011) emphasise the higher variability of the soil carbon stock at deeper depth and the importance of statistical power (see also section 3.2.6.1). They conclude that whole profile soil carbon stocks should be sampled by soil horizons, to reduce the variability.

So far, many studies focused on soil carbon stocks and changes in croplands, grasslands and forests worldwide e.g. Conant et al. (2001); Bellamy et al. (2005); Don et al. (2007); Meersmans et al. (2009) but also in New Zealand (Tate et al. 2005; Schipper et al. 2007; Schipper et al. 2010; McNeill et al. 2014) In contrast, as noted by Kirschbaum et al. (2009) “very few international studies have examined soil carbon stocks and change under horticulture”. For example, in the soil carbon inventory model for New Zealand developed by McNeill et al. (2014), the category “perennial croplands”, of which horticultural land would be a sub-category, was validated by 76 soil carbon samples, against 481 samples for the “forest” categories, and 1231 samples for the “grasslands” categories (McNeill et al. 2014).

Nevertheless, while horticultural systems with perennial trees represent less than 1.6% of the 28 or so Million hectares of land in New Zealand[1], they can sequester substantial amounts of carbon in the soil (Jobbagy and Jackson 2000). Soil carbon originates primarily from below-ground inputs (Kong and Six 2010; Schmidt et al. 2011) through root growth and turnover, and exudation. Indeed, (Rasse et al. 2005) reviewed the contribution of roots to soil carbon to be on average 2.4 times that of shoots, and suggest that this ratio is likely to become higher for the deeper soil horizons. Furthermore, Kong and Six (2010) reported that after less than one year, around 52 % of root derived carbon remained in the soil versus only 4% of shoot derived carbon.

At the same time, growing concerns worldwide about the sustainability of food production systems are particularly disadvantaging far-away producers, such as New Zealand (McLaren 2007). Additionally, global supermarkets, such as Tesco's are asking their suppliers to reduce emissions of their products; this could have implications for shelf access for products - as well as potential price premiums for the best environmentally performing products. Therefore, if the ongoing increase and/or maintenance of soil carbon stocks can be demonstrated for perennial fruit crops in New Zealand, this could lead to a positive demarcation of New Zealand products (Deurer et al. 2010).

In order to estimate soil carbon stocks and change in an apple orchard block (see the definitions in section 3.2.1), an assessment of the horizontal and vertical variability of carbon stocks is an imperative. Indeed, information about this variability is required to design a sampling protocol that allows detection of soil carbon-stock changes with a sufficient level of statistical significance and power (Garten and Wullschleger 1999). Two parameters are required to calculate soil carbon stocks at any particular depth: the carbon concentration and the bulk density of the soil (Batjes 1996; Grigal and Berguson 1998).

The objectives of this chapter are therefore:

[1] http://www.mfe.govt.nz/more/environmental-reporting/land/land-cover-indicator/land-cover Accessed on 5.02.2015.

- To quantify the spatial variability, both horizontally and with depth, of the soil's carbon content, bulk density and carbon stock both at the tree and the apple orchard - block scale.
- To define, using the variability estimates, the minimum sampling requirements to measure and monitor the soil carbon stock at the orchard block scale and to infer the cost of such monitoring.

3.2. Materials and methods

3.2.1. Definitions

An "orchard block" is the management unit of apple (*Malus domestica*) growers, being a sub-unit of an orchard). A block is defined as equally spaced rows of equally spaced trees of the same age, variety and rootstock that are all managed in the same way and at the same time, through practices such as pruning, spraying, and irrigation.

The Allocated Tree Area (ATA, in m^2/tree) was defined as the sampling unit and represents the area equivalent to the space taken by one tree in the orchard block (Fig. 3.1). The ATA is the smallest systematically repeated structure of the orchard block, and can be calculated from tree and row spacing:

$$ATA\ (m^2/tree) = Tree\ spacing\ (m) \times Row\ spacing\ (m)$$

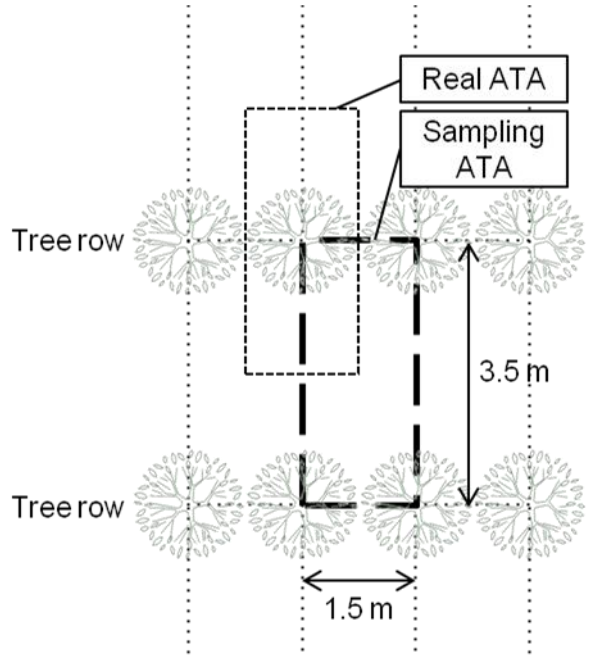

Figure 3. 1 Schematic representation of the Allocated Tree Area (ATA) in an orchard block viewed from above. Tree and row spacings can vary widely between orchard blocks depending on many factors.

The bulk density of the soil is a measure of the oven-dry weight of soil for a particular (undisturbed) volume, and is expressed in grams per cubic centimetre (g/cm^3) of dry soil.

The carbon content or carbon concentration of the soil is a measure of mass of carbon in a particular mass of soil. It is expressed as percentage carbon (% C).

3.2.2. Experimental site description and recent history:

In 2008, an orchard block of apple trees of approximately 0.3 hectares, variety Jazz, were grafted on a M.9 (dwarfing) rootstock, was planted at a spacing of 3.5 m (between rows) by 1.5 m (between trees) on a Hastings silty clay loam soil (soil class: Typic Recent Gley Soil (GRT), New Zealand soil classification (Hewitt 1998)) in a commercial orchard (integrated management system) located near Hastings (Long. 176.800417, Lat. -39.586380), Hawke's Bay, New Zealand. A typical soil textural profile of the orchard block is presented in Table 1.Two generations of apple trees had previously been grown in this orchard block, which had never been irrigated: Previously, apple trees of the cultivar (variety) Pacific Rose had been planted in 1996 on the semi-vigorous rootstock M.M.106, and these were preceded by

vigorous apple trees planted in the 1960s.Tile drains in the form of clay pipes had been installed when the land was first converted fifty or so years earlier from grazed pasture to an apple orchard, So there has been very little soil disturbance after the first tree planting. Under the current land use, irrigation consists of four (normal year) to five (dry year, e.g., 2012-2013 season) applications of 40 mm of water per year using a portable sprinkler. The water table was measured on 1st September 2011 at 108 cm depth.

Borders, including 10 trees (approx. 15 metre) at both ends of each row, and 1.5 rows on each “side” of the orchard block, were excluded from the investigation. Because this research focuses on defining minimum sampling requirements, it was important to ensure the overall homogeneity of the studied orchard block. First, homogeneity in tree vigour (tree height, stem size) across the orchard block was verified by visual observation. Subsequently, soil texture was assessed by feel, following the method of Thien (1979), at five locations in the orchard (four corners + centre). For this purpose the soil was sampled in 10 cm-depth increments to one metre depth using a Purckhauer single gouge auger for hard soils (Eijkelkamp, P.O. Box 4, 6987 ZG Giesbeek, NL. www.eijkelkamp.com). This assessment led to exclude an additional ten trees (total of 20 trees, or approx. 30 metres) from the northern end of each tree row, due to the deep sandy layer starting at a shallower depth in this area.

At a later stage, one representative soil texture profile was sampled in 10 cm-depth increments to one metre depth and each sample was analysed using the pipette method (Claydon 1989). In addition soil horizons were identified. Results are presented in Table 3.1

Table 3. 1 Representative soil texture profile of the top metre of soil in the apple orchard block, in 10 cm depth increments.

Depth (cm)	% Sand	% Silt	% Clay	Soil texture	Soil profile	Soil horizons
0-10	12.8	57.8	29.6	Silty clay loam		**A**: 0-26 cm weak medium granular structure, dark brown (7.5YR 3/2), many fine roots
10-20	12.1	55.9	31.3			
20-30	7.3	55.2	36.6			
30-40	6.5	56.7	36.1			**Bt_1***:26-72 cm moderate fine subangular blocky structure, brown (7.5R 5/3), few fine roots, fine mottles
40-50	9.8	60.0	29.9			
50-60	12.9	63.4	23.6	Silt loam		
60-70	27.1	54.6	17.8			
70-80	64.1	27.9	7.5	Sandy loam		**Bt_2**:72-100 cm weak subangular blocky structure, gray (7.5R, 5/1), medium mottles
80-90	58.8	32.8	8.1			
90-100	63.9	28.8	6.6			

*On rare occasions, the soil profile was showing a Bs inclusion between the A and Bt1 horizons, of 5 to 25 cm width. This inclusion was of weak fine granular structure, yellowish brown (10YR 5/6).

3.2.3. Sampling procedure

Within the orchard block, two experiments were conducted:

- "Pit" sampling was carried out to estimate soil carbon variability at the tree scale, both horizontally and with depth, and between the tree row and the grass alley (Fig 2). In November 2011, one location was randomly selected to dig a pit (width 1.4m, length 1.65m, depth 1m) adjacent to the tree row.

  The carbon content (%C) and bulk density (BD) profiles to one meter depth were obtained by sampling 10 increments of 10 cm. Five sample locations per depth increment were taken in both areas: the "tree row" (between two trees) and in the middle of the "grass alley" (Fig 3.2). In the middle of each depth increment, an

undisturbed soil sample was taken with a 100 cm^3-stainless steel cylinder for bulk density determination. Additionally, a slice of soil (approx. 1 cm thick and 8 cm wide) was taken from the entire depth of each 10 cm-increment for % C analysis. All samples for the "pit" experiment were collected and processed between 1/11/2011 and 30/11/2011.

- "Site" sampling (or "cluster" sampling) was carried out to explore further the variability of soil carbon content at the tree scale, but mainly to describe the variability at the orchard scale (Fig. 3.3). Within the orchard block, 10 sampling sites (i.e. clusters, each equivalent to one ATA) were randomly selected. When a sampling site was not available (e.g., missing or diseased tree), the next available ATA was sampled.

  For each sampling site, one bulk density profile was sampled in the middle of the ATA. Samples were collected in 10 cm increments to one metre depth, following the same method as above.

  Furthermore, in order to cover the whole area that could be sampled within each ATA, 16 one metre soil samples were taken on a 4 m by 4 m systematic grid. Individual one meter soil core samples were extracted using an engine driven drill core sampler (engineered by Plant and Food Research, Hamilton, see Appendix A3.1 for soil corer characteristics and validation). The grid spacing was as close as practically feasible, to avoid disturbance between samples thereby maintaining at least 30 cm between sampling locations. The resulting 1 meter soil samples were cut in half for total carbon content (% C) analysis of the 0-50 cm and 50-100 cm depth increments. All % C and BD samples were collected between 16/04/2012 and 26/05/2012.

  For the purpose of testing and validating the soil core sampler used in the "site" sampling experiment, five soil core samples (1 m length) were collected immediately beside the sampling location "grass alley" (see Appendix A3.1).

A slight compaction (usually <5%) of the 1 metre soil samples was observed, and it was decided that samples shorter than 95 cm would be discarded, because it was not possible to determine precisely at what depth compaction occurred. Furthermore, a stone occasionally blocked the coring procedure. In order to minimise the reduction of the number of samples due to sample compaction and practical difficulties, two extra sampling locations were used to replace up to two missing samples per sampling site (E1 and E2 in Fig.3.3).

3.2.4. Processing and analysis of samples

Following collection, all samples were kept in a cold room below 4^{o}C until further processing. The % C samples were oven dried overnight at 60^{o}C before being forced by hand through a sieved of 2 mm mesh in order to separate the fine earth fraction from stones, pumice rocks and roots. Total carbon content was determined by a LECO TruSpec CN analyser (LECO Corporation, St. Joseph, Michigan, USA) following overnight drying at 60^{o}C. Sub-sampling was carried out using a riffle splitter, a tool that provides the least inaccuracy among 5 sub-sampling methods (see Gerlach et al. (2002)). Only 4 grams of soil are required for %C analysis, and the collected soil samples weighed up to 1.6 kg (dry).

No distinction was made between the organic and inorganic fractions of soil carbon, since only small quantities of calcium carbonate are present in New Zealand soils (Tate et al. 1997). Furthermore, both carbon fractions, if sequestered in the soil, are relevant for climate change mitigation and for carbon footprinting purposes, since they both originate from capturing atmospheric CO_2. They result either from photosynthesis (organic fraction) and subsequent decomposition of organic material in, and on the soil, either through infiltration of dissolved organic carbon (DOC), from dissolution of atmospheric CO_2 in water followed by infiltration and re-precipitation as calcium carbonate at depth.

The BD samples were oven dried at 105^{o}C until they reached a constant weight. Subsequently, stones, roots and pumice rocks were removed and weighed separately for correction of soil BD estimates. The BD of stones was assumed to be 2.65 g/cm^3 (Tate et al.

1997) and the BD of pumice was assumed to be 0.48 g/cm^3. This value was derived by measuring the BD of a subsample of pumice rocks using Archimedes' principle and is similar to the average value of 0.51 g/cm^3 found by Yagi et al. (1962). However, in order to allow comparing bulk density samples of the "pit" experiment with the five core samples taken for the drill soil corer testing and validation (see Appendix A3.1), the bulk density samples of the "pit" experiment were first oven dried at 60^{o}C, sieved, weighed and then oven-dried at 105^{o}C until they reached a constant weight.

3.2.5. Calculation of total carbon stocks

The total carbon stock of the fine earth fraction ($C\ stock$) in tonnes of carbon per hectare (t C/ha) was determined for each depth increment according to the following formula:

$$C\ stock = BD_{fine\ earth} \times \%\ C_{fine\ earth} \times depth \qquad \text{Eq. 3.1}$$

The $BD_{fine\ earth}$ and the $\%\ C_{fine\ earth}$ are the bulk density (g/cm^3) and the carbon content (%) of the fine earth fraction of the soil. The $depth$ is the sampling-depth increment (cm). All BD samples were collected for increments of 10 cm, including in the site experiment. Therefore, $BD_{fine\ earth}$ for the 0-50 cm and 0-100 cm soil layers was calculated by averaging the BD in all relevant depth increments within each sampling site.

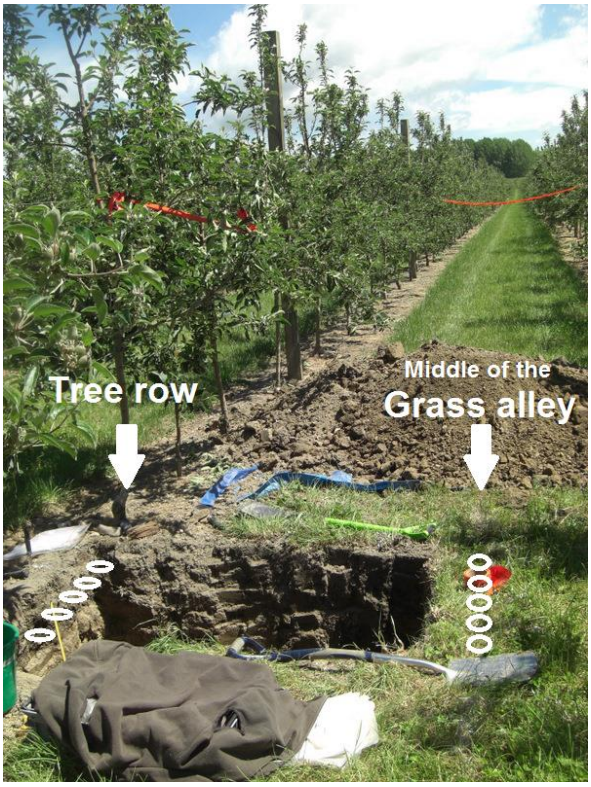

Figure 3. 2 Photo of a pit dug in the apple orchard under study. The white circles represent the sampling locations in the tree row and in the grass alley. Sampling for carbon content and bulk density was carried between 0 and 100 cm depth by 10 cm increments. The photo was taken after the samples in the tree row were collected.

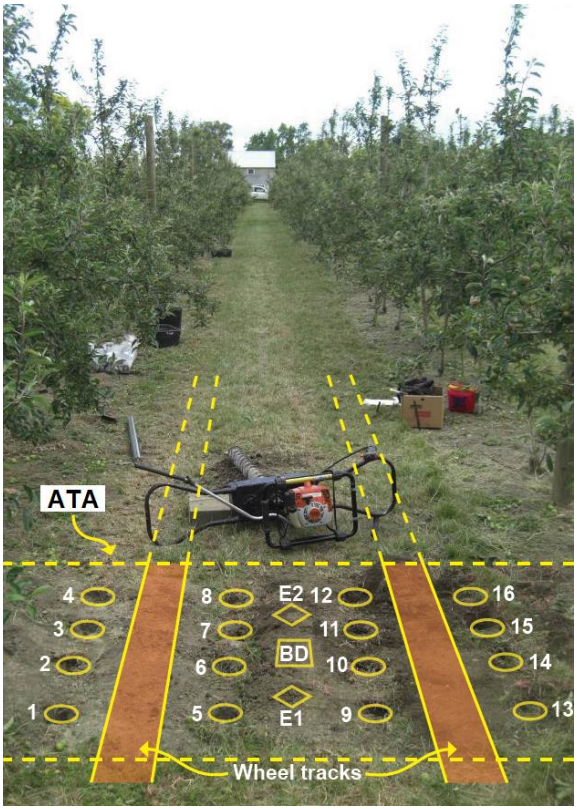

Figure 3. 3 Photo of a sampling site covering the entire Allocated Tree Area (ATA). The %C samples are numbered from 1 to 16. Samples 1 to 4 and 13 to 16 are "outside the wheel tracks". Samples 8 to 12 are "between the wheel tracks". In case samples could not be taken (e.g. because a stone blocked the corer) two extra sampling locations, E1 and E2 were available. One bulk density (BD) profile was sampled in the middle of each sampling site.

3.2.6. Statistical analyses

Descriptive statistics were used to characterise all measured variables. Standard deviations (SD), expressing the variation in the samples set, in the same unit as the mean, and standard errors (SE), describing the error associated with the sample mean, relative to the population mean. Both are estimated according to Webster (2001). Furthermore, coefficients of variation (CV) are sometimes used to allow an easy comparison of means of the same unit and order of magnitude. An example of this is Table 3.2 for average carbon contents of the various sites for the 0-50cm depth increment.

To avoid confusion, the word “significant” and its derivatives are *always* used in a statistical context in this paper. The statistical significance of differences between averages of the various treatments was tested using either the Student’s t-test, or the Welch’s t–test, used for independent variables, equal or unequal sample sizes and unequal variances. An F test was used to determine if the equality between the variances of the compared means could be assumed. Differences were interpreted to be statistically significant at the 5% level and a “tendency for a difference” was highlighted when significant differences at the 10% level were detected. A statistical power analysis (Barker Bausell and Li 2002) was conducted when no significant difference was found between treatments. Furthermore, a paired t-test was used to analyse the differences across the orchard block between two groups of samples located within each site, since the individual samples were selected according to a systematic grid within each site, rather than at random.

Linear regression analysis was carried out with Genstat (VSN International 2012) to determine the effect of the distance of a sampling site from a tree on the soil’s carbon content (Section 3.2.3 and Fig. 3.10). Genstat was also used to observe the change in the mean’s variance following the pooling of several samples for each sampling site. Subsequently, contour plots were created to assess the minimum number of samples required to detect a particular change in soil carbon stocks in the orchard block (Section 3.3, Fig 3.17, 3.18, 3.19 and 3.20).

3.2.6.1. Importance of statistical power

Knowing statistical power is essential for the design of experiments and when concluding about statistical significance of a difference between two means. The statistical significance (conventionally at the 5% level) is the probability that the observed difference between two means happened by chance alone. If this statistically significant difference between two means exists in reality, then the statistical power, conventionally superior to 0.8, represents the probability of detecting this significant difference. Therefore, if no statistically significant

difference is observed between two means, it could be due to the sole fact that the experiment has a low statistical power (Barker Bausell and Li 2002).

3.2.6.2. Number of samples calculations

In order to calculate the minimum number of samples, n, to observe a given change, δ, in soil carbon stocks , and assuming that the same variance is found when re-sampling, the following formula from Steel et al. (1997) was used:

$$n = \frac{(Z_{\alpha/2} + Z_{\beta})^2 \sigma_D^2}{\delta^2}. \quad \text{Eq. 3.2}$$

Here $Z_{\alpha/2}$ and Z_{β} are the values from the Z table with α the Type I error (statistical significance, $\alpha = 5\%$) and β the Type II error ($statistical\ power = 1 - \beta = 0.8$), respectively. Here σ_D^2 is the variance of the difference between the two sample sets.

3.2.7. Geostatistical methods

Geostatistical analyses were carried out using R software (R Development Core Team 2012). Pairs of soil-carbon stocks samples were grouped sequentially according to their spacing in the orchard block. Semi-variograms were produced by plotting the group variance of the pairs as a function of the distance between samples within these pairs. Semi-variograms presented a maximum distance of 60 metres. The spatial dependency of soil carbon stocks was described using the model parameters fitted to the data:

- The "**nugget**" is the y origin of the modelled semi-variance as a function of distance between samples, and represents the natural variability, or the non-spatial variability. A high nugget value therefore indicates a large natural variation that is independent of the distance between samples.
- The "**sill**" is the constant maximum value of the semi-variance. It expresses that from a certain distance, the variance between two samples does not increase further.

- The “**nugget/sill ratio**” can be used to indicate the level of spatial auto-correlation. The higher the nugget/sill ratio, the weaker the spatial auto-correlation.
- The “**range**” is the distance at which 95% of the sill is achieved, and indicates the maximum distance at which samples are auto-correlated. In other words, beyond the distance indicated by the range, increasing the distance between samples will only increase the variance of the sample set by a small amount (5%).

3.3. Results & discussion

3.3.1. Variability at the tree scale

3.3.1.1. Bulk density of the fine earth

The bulk density ranged from 1.04 g/cm^3 (SE = 0.03 g/cm^3) to 1.46 g/cm^3 (SE = 0.01 g/cm^3) for 10 cm depth increments and was higher in the grass alley than in the tree row for all depths, except below 80 cm depth (Fig 3.4). For both treatments, the lowest BD was found for the 30-40 cm depth increment. Standard deviations per treatment and soil layer varied between 0.02 and 0.12 g/cm^3. This results in coefficients of variation of 1.8% and 9.7%, respectively, which indicates quite small variations within datasets.

A statistically significant difference in bulk density between tree row and grass alley was detected for seven depth increments out of 10 ($p<0.05$), and a tendency for a difference ($p<0.1$) was present for the 90 to 100 cm depth increment. There was no significant difference for depths increments 0-10 cm and 40-50 cm between tree row and grass alley. Although the between-sample variation for these depths for the grass alley was high (CVs are 9.7% and 6.8% of the mean, respectively) and the difference between the means is small. This reduces considerably the statistical power (<0.4 in both cases). However, for the 40-50 cm layer, the difference between tree row and grass alley is quite small (0.06 g/cm^3), which implies that a significant difference, if it exists, would be harder to detect. More

samples at these depths would therefore be required to conclude about the statistical significance of the observed differences between tree row and grass alley for these depth increments.

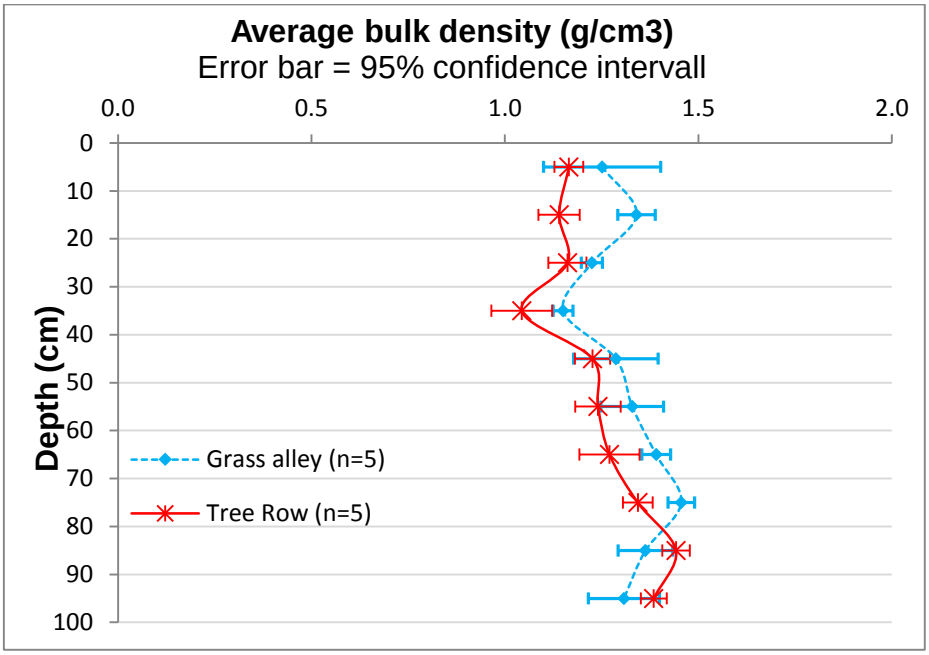

Figure 3. 4 Bulk density as a function of depth under the tree row and in the middle of the grass alley in an apple orchard block. The number of samples (n) is 5 per treatment for each depth increment.

The BD for each 1 metre column per treatment was obtained by averaging the ten depth increments of that column. This BD for the top metre averaged 1.24 g/cm^3 (SE= 0.008, n=5) in the tree row, and 1.31 g/cm^3 (SE= 0.004, n=5) in the grass alley. A statistically significant difference was detected between tree row and inter-row ($p<0.001$). Coefficients of variation between one metre columns of each treatment were as low as 1.5% in the tree row and 0.7% in the grass alley. This indicates quite small variations in bulk density within datasets.

3.3.1.2. Carbon content

Carbon content decreased rapidly with increasing depth and ranged from 3.27% (0-10 cm depth, tree row, SE=0.04%) to 0.25% (90-100 cm depth, grass alley, SE=0.04) (Fig.3.5). Carbon content was higher in the tree row than in the grass alley for all depth increments

between the soil surface and 40 cm depth, and for the 70-80 cm and 90-100 cm depth increments. The opposite was true for the other depth increments. A clear shift of the carbon content from more than 1.5 % above 40 cm depth to less than 1% for deeper soil layers was observed. For all but the 20-30 cm depth increment, no significant difference in carbon contents was observed between tree row and grass alley. The soil layers 50-60 cm and 70-80cm showed a tendency for a difference in carbon content between the tree row and grass alley. No statistically significant difference between tree row and grass alley was observed for the average %C of 1 metre profiles, and the carbon contents averaged 1.34 %C (SE=0.012, n=5) in the tree row versus 1.30 %C (SE=0.032, n=5) in the grass alley. However, again, the statistical power was low for all these comparisons, allowing at best a 52% chance of detecting significant differences. However, these differences were quite small. More samples are therefore required for this depth increment.

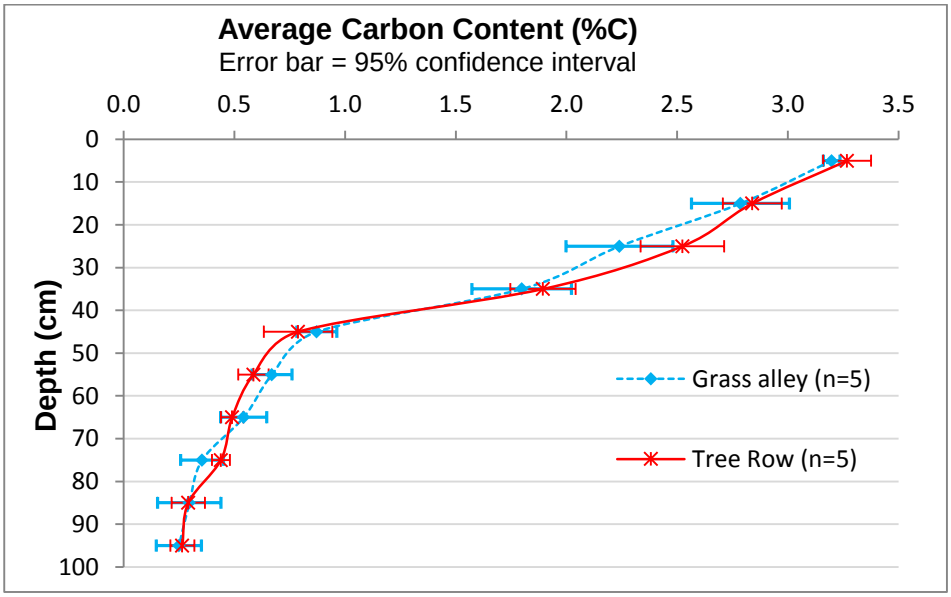

Figure 3. 5 Carbon content as a function of depth under the tree row and in the middle of the grass alley in an apple orchard block (n=5 per treatment for each depth increment).

As already noted in other studies (Kravchenko and Robertson 2011; Syswerda et al. 2011), there was a tendency for the carbon content to be more variable with depth (Fig 3.6). The CVs are the highest for both tree row and grass alley for the two deepest soil layers. They

were generally higher in the grass alley compared to the tree row, although the opposite was true for the 0-10 cm and 40-50 cm depth increments.

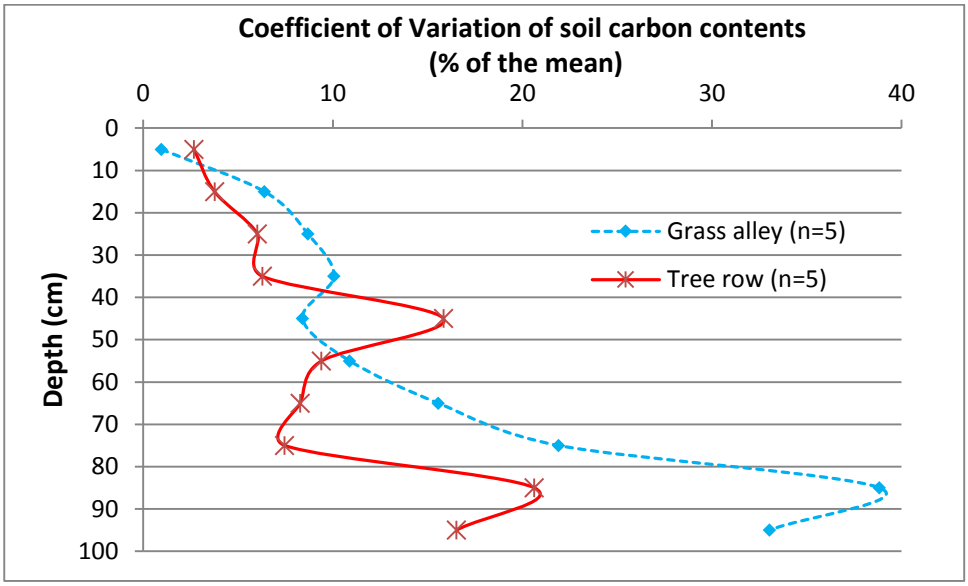

Figure 3. 6 Coefficients of Variation (CVs) of the soil carbon content as a function of depth under the tree row and in the middle of the grass alley in an apple orchard block. (n=5 per treatment for each depth increment).

3.3.1.3. Carbon stock

Carbon stocks were calculated according to Eq. 3.1. As with carbon contents, carbon stocks decreased rapidly with increasing depth, and ranged between 40 t C/ha (0 to 10 cm layer, grass alley, SE=1.9 t C/ha) and 3.2 t C/ha (90 to 100 cm layer, grass alley, SE=0.5 t C/ha), as shown on Fig. 3.7. A significant difference between the tree row and grass alley was detected for the 10-20cm, 50-60 cm and 60-70 cm depth increments ($p<0.05$). A tendency for a difference was detected between tree row and grass alley for the 40-50 cm depth increment ($p<0.1$). However, these statistically significant differences could be driven by the differences in bulk density between tree row and grass alley for these depth increments. This was noted by Ellert and Bettany (1995) and Gifford and Roderick (2003). For example, for the 10 to 20 cm depth increment, the bulk density of the grass alley was 115% of the BD in the tree row, while for carbon contents the equivalent figure was 102%.

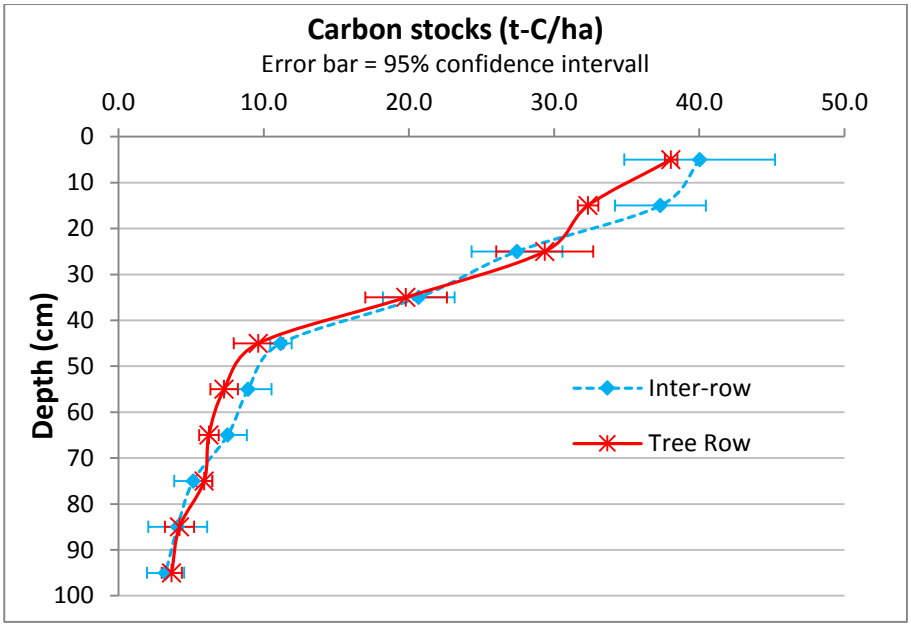

Figure 3. 7 Carbon stocks as a function of depth under the tree row and in the middle of the grass alley (inter-row) in an apple orchard block. (n=5 per treatment for each depth increment).

The CVs per depth increment ranged from 1% (10-20 cm depth increment in the tree row) to 40% (80-90 cm depth increment in the inter-row). The CVs tended to increase with increasing depth, and were higher in the grass alley compared to tree row for most depths, except for two depth increments: 30-40 cm and 40-50 cm.

For both the row and alley in the "pit" sampled (see Fig 3.2), we considered what fraction of the 1 m carbon stocks were in the top 50 cm of soil. The minimum required depth of sampling is further discussed in section 3.3.2.4. On average for the pit, only 64% of the carbon stock of the top metre was present in the top 30 cm of soil. Sampling the top 50cm at least was necessary to account for 80% of the carbon stock present in the top metre of soil. Therefore, measurement and analyses at the orchard scale were carried out for the 0-50 cm and 50-100 cm for both carbon contents and carbon stocks. An analysis of the whole profile (0-100 cm) was included when assessing soil carbon stocks. Further discussion of these results is presented in section 3.3.3. However, generalising these proportions is not possible due to the spatial variations in soil types, texture profiles, and other characteristics affecting soil carbon dynamics. For example, within 500 m of the sampling site, there are two very

different soil types[2]: a “Recent Gravelly”, and a “Humic Organic” for which the properties, including soil carbon, may vary greatly with depth compared to the “Orthic Gley” soil sampled in this study. Furthermore, even within the same soil type, there is important variability of soil carbon at depth (Syswerda et al. 2011).

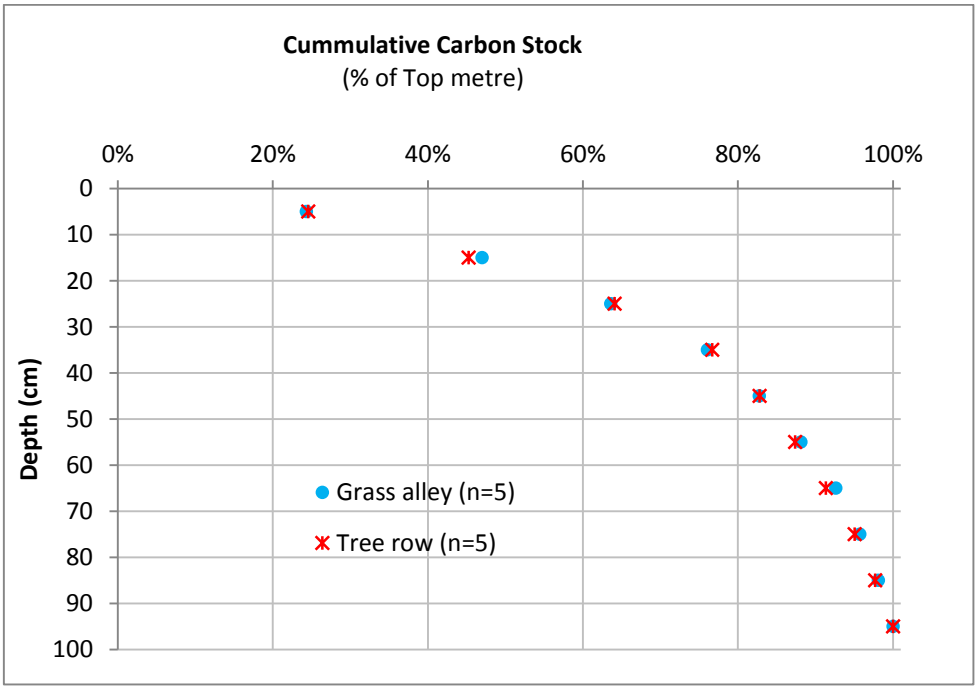

Figure 3. 8 Cumulative soil carbon stock as a function of depth for the tree row and the grass alley in one sampling location in the orchard block (pit). Sampling to 50cm depth at least is necessary in order to account for 80% of the carbon stock present in the top metre of soil.

3.3.2. Variability at the orchard scale (10 sites /orchard)

The soil-core sampler available for the experiments could not provide reliable bulk density measurements (see Appendix A3.1) due to compression. It was therefore decided to sample one bulk density profile per sampling site in the orchard.

3.3.2.1. Bulk density

The bulk density per depth increment across the orchard block varied from 1.16 g/cm^3 (20-30 cm layer, SE=0.02 g/cm^3) to 1.33 g/cm^3 (50-60 cm layer, SE=0.02 g/cm^3). Figure 3.9 shows the average BD profile for the orchard block. Coefficients of variation per depth

[2] Maps of New Zealand soil types, soil carbon to 20 cm depth and many other soil characteristics are available at http://soils.landcareresearch.co.nz/contents/SoilData_FSL_Maps.aspx?

increment varied from 3.4 to 9.2% of their respective means. The soil layer showing the highest variation between samples was 30 to 40 cm depth (Average: 1.18 g/cm^3, SD= 0.11 g/cm^3), although this variation could be the result of just one sample in this layer being different from the mean by more than two standard deviations (Site 6, $BD_{30\text{-}40cm}$= 0.95 g/cm^3). Another noticeable source of variation was around 70 cm depth, which corresponds to the change in soil texture from silt loam to sandy loam (see Fig. 3.1).

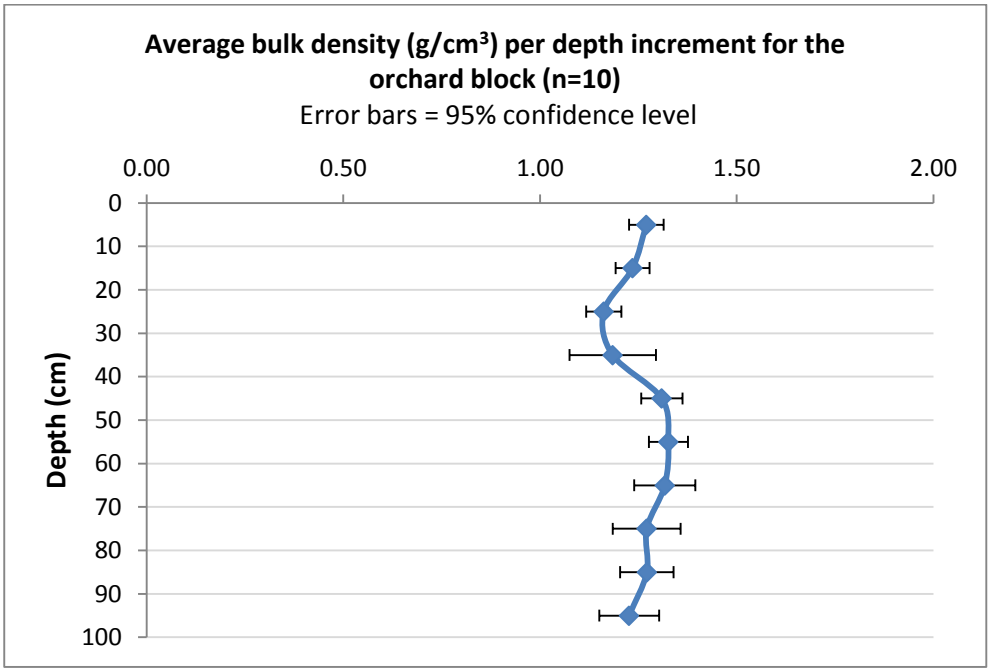

Figure 3. 9 Average bulk density as a function of depth in the middle of the grass alley in an apple orchard block. (n=10 for each depth increment).

The BD for the top meter of soil for the orchard block averaged 1.26 g/cm^3 (SE=0.011 g/cm^3, range: 1.21 to 1.31 g/cm^3). This average BD value was similar to the average BD of the grass alley of the pit site (i.e. 1.31 g/cm^3, SE= 0.004).

3.3.2.2. Carbon content

The minimum and maximum soil carbon contents in the top 50 cm of soil across the 147 samples (out of 160) for the orchard block were 1.94%C and 3.47%C. Equivalent figures for the 50 to 100 cm depth increment were 0.23%C and 0.8%C. Additionally, 95% of cores were within the 2 to 2.8%C range in the top 50 cm, and 95% of cores were between 0.23 and 0.65

%C in the 50-100 cm layer. Carbon content results for the 10 sampling sites across the orchard are presented in Table 3.2.

Table 3. 2 Carbon content (% or g carbon/ 100g soil) for the 0-50cm and 50-100cm soil layers. (n: number of samples, Avg: Average, SD: Standard Deviation, SE: Standard Error, CV: Coefficient of Variation)

Depth:		0-50 cm			50 -100 cm		
Site	**n**	**Average**	**SD**	**CV**	**Average**	**SD**	**CV**
1	16	2.39	0.18	7.5%	0.37	0.07	18.5%
2	14	2.39	0.15	6.1%	0.53	0.08	15.5%
3	16	2.41	0.17	6.9%	0.40	0.05	12.6%
4	13	2.51	0.23	9.0%	0.54	0.06	10.9%
5	16	2.33	0.19	8.3%	0.34	0.04	13.1%
6	12	2.37	0.24	10.2%	0.40	0.05	13.8%
7	16	2.53	0.33	13.0%	0.37	0.07	19.8%
8	14	2.56	0.31	12.2%	0.64	0.09	14.4%
9	15	2.36	0.21	8.8%	0.36	0.07	18.3%
10	15	2.16	0.14	6.7%	0.33	0.03	10.4%
Avg	14.7	2.40			0.43		
SE		0.04			0.03		
SD		0.11			0.10		
CV		4.7%			24.3%		

Within each sampling site in the orchard, the variation as a percentage of the mean (CV) in carbon content was always higher in the lower part of the profile (50-100 cm depth) than in the 0-50 cm soil layer. For the whole orchard block, the variation between sampling sites was relatively low in the top 50 cm of soil, as shown by the SD of 0.11 %C. However, the SDs are similar for both depth increments, while the average carbon content of the 50-100 cm layer was only 14% of the %C of the top 50 cm layer. Furthermore, it is interesting to note that the variability between sites for the top 50 cm depth (4.7%) was lower than the variability within sites (6 to13%). The opposite was true for the 50-100 cm part of the profile (24% vs 10- 20%, respectively). Overall, these variability estimates are well within the range reported by Zhang et al (2011), who reviewed the coefficient of variation (CV) of soil organic carbon concentrations in croplands from 117 studies. They found a CV less than 35% in 100 studies, which included 43 studies with a CV under 15%. However, this study did not take the depth of sampling into account.

3.3.2.3. Variation of carbon content within sampling sites according to their spatial position in the ATA

As shown in Figure 3 for all sites, samples number 5 to 12, as well as E1 and E2, were collected from between the wheel tracks. That is the area on either side of the middle of the grass alley. Samples number 1 to 4 and 13 to 16 were collected outside the wheel tracks on the edges of the grass alley and towards the herbicide strip. Differences in carbon contents were observed between samples from between and outside the wheel tracks for the whole orchard block, and are presented in Table 3.3.

Table 3. 3 Difference in carbon contents outside versus between the wheel-tracks for the orchard block and their statistical significance

Soil depth	Average %C between wheel tracks	Average %C outside wheel tracks	Average difference (n=10)	Standard Deviation of the average difference	t value calculated	p value (paired t test)
0-50 cm	2.32	2.48	-0.16	0.08	-6.18	<0.001
50-100 cm	0.42	0.43	-0.004	0.05	-0.21	0.84
0-100 cm (Average)	1.37	1.45	-0.08	0.06	-4.03	0.003

A statistically significant difference ($p<0.001$, paired t-test) was observed between samples situated between and outside the wheel tracks in the top 50 cm of soil ($p<0.001$, $df=9$). However, this difference was not observed for the bottom part of the profile (50-100 cm depth).

Furthermore, the carbon contents of the 0-50 cm and 50-100 cm depths were averaged at the sample level, in order to obtain an estimate of the 0-100 cm depth for each sampling location. Next, an average for each area (between wheel tracks, outside wheel tracks) within each sampling site was calculated. A statistically significant difference ($p=0.003$, paired t-

test) was found between samples situated between and outside the wheel tracks for the top 100 cm of soil.

Due to the statistically significant difference between samples situated between and outside the wheel tracks in the top 50 cm of soil at the orchard scale, the variation of carbon content as a function of the distance to the nearest tree for all sites was investigated. A three-step procedure was carried out. Firstly one linear regression model was fitted to all data (step 1). Secondly one linear model fitted to each sampling site with different intercepts but maintaining a common slope (step 2). Thirdly one linear model with different slopes and intercepts was fitted to each sampling site (step 3). For each of these steps, the proportion of the variance accounted for by the model was observed.

Step 2 significantly improved the modelled regression ($p<0.001$) over step 1. This indicated that different sampling sites show different intercepts. However, step 3 did not significantly improve the modelled regression ($p=0.84$) over step 2. The slopes of the regressions were thus similar between sampling sites. The resulting model (step 2) gave an average negative slope of -0.29 (SE=0.65) which is significantly different from zero ($p<0.001$). The data and fitted regressions lines are presented on figure 3.10.

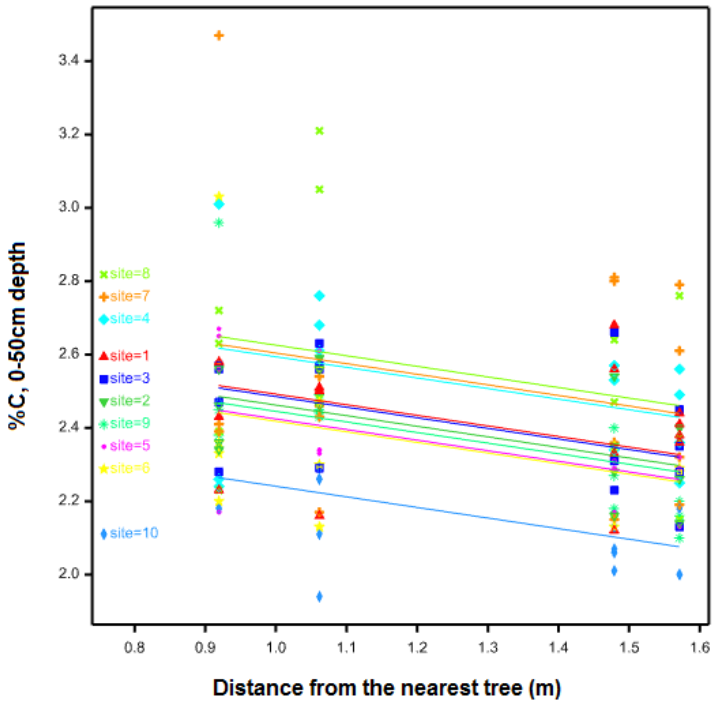

Figure 3. 10 Trend in soil carbon content as a function of the distance to the nearest tree for the 0-50cm depth. Each sampling site is represented by a different symbol and colour.

In conclusion, the carbon content in the top 50 cm of soil decreased at a rate of 0.29% C/m with increasing distance away from a tree. This trend is consistent with the results of the pit experiment, where a tendency for a difference in soil carbon contents can be observed between tree row and grass alley for the top 50 cm of soil (p=0.06, data not shown). This trend is, it is considered, attributed to the tree roots rather than the grass roots, because no samples were taken in the herbicide strip, and grass was present on the surface at all sampling locations. However, the difference between tree row and grass alley found in the pit experiment (0-50 cm, difference =0.08% C, SE= 0.04% C) is smaller than would be expected at this spatial decrease rate of 0.29% C/m. According to these results, the carbon content of the top 50 cm is lower in the tree row and in the grass alley, and higher half way between the two areas, that is, outside the wheel tracks. A combination of the effects of the tree roots and the grass roots could have increased soil carbon contents outside the wheel tracks.

Overall, these findings suggest a correlation between soil carbon contents and the planting pattern in the orchard block. This means that ideally, all areas representing the various distances to the nearest tree within a sampling site should be sampled in order to represent the carbon stock of the soil of an orchard block. However, practical difficulties exclude some areas of the ATA for sampling purposes. For example, a few (one to three) years after planting, it is not possible to sample at depth in the herbicide strip using a soil core sampler, because of overhanging tree branches. Furthermore, sampling close to the trees may damage the tree roots, making them more susceptible to disease infections and potentially delaying tree growth. However, in order to take into account the variability within an ATA, it is necessary to sample evenly between and outside the wheel tracks.

3.3.2.4. Carbon stock

On average for the orchard block, 84% of the carbon in the top meter was in the top 50 cm of soil (range: 81% to 87% for individual sampling sites). The results reported here suggest that the 0-30 cm minimum default sampling depth suggested by the IPCC to account for changes in soil carbon stocks would not consider 80% of the soil carbon embedded in the first metre of soil in the sampled apple orchard block. This level of accountability was set as minimum for general inventory in kiwifruit orchards (Deurer et al. 2010). This highlights, for soil carbon stocks measurements, the necessity to sample apple orchard soils at least to a depth of 50 cm, in order to consider at least 80% of the carbon stock in the top metre of soil.

However, Deurer et al. (2010) suggested sampling to "[...] 1 m if the temporal or spatial dynamics of soil carbon stocks are of interest". Indeed, various researchers have demonstrated the necessity to sample deeper than 30 cm (e.g. Syswerda et al. 2011; VandenBygaart et al. 2011). Clothier et al. (2010) recommended sampling to a depth of 70 cm in order to account for 80% of the carbon in the top metre of soil, following a study of duplex soils in two Australian apple orchards. Some researchers even argue that soil carbon should be sampled to one meter depth as a minimum (Schmidt et al. 2011). Jobbagy and Jackson (2000) estimated global soil organic carbon (SOC) stocks to a depth of 3 m in

perennial systems and observed that the 1-3 m soil layer contained 56% of the amount of carbon found in the 0-1 m soil layer. They also found that root/shoot allocation and vertical root distribution were essential factors controlling the SOC distribution in the soil profile, although SOC was distributed even deeper than the roots. Another striking example is the comparison of soil carbon stocks to 9 metres depth under a 30 year old kiwifruit orchard and adjacent long term pasture field (ZESPRI and MAF 2012). In this study, the top 30 cm of soil accounted for only 34.5 % of the 9 meter SOC stock in the kiwifruit orchard. For pasture, the top 30 cm accounted for 60.6% of the 9 metre SOC stock. Another recent study (Harper and Tibbett 2013) considered the entire depth of several soils to bedrock, from 5m to 38m from the surface. The authors highlighted that the top 50cm of soil only accounts for 20% to 50% of the carbon stock for the whole soil depth. For deep soils, it was necessary to consider 5 meter depth to account for 50% to 75% of the stocks. In view of these results, samplings should at least use 1 metre as a minimum sampling depth, while investigating the top 5 metres of soil would be preferable, even if requiring more effort. In this Chapter, the main focus is on investigating the variability horizontally and with depth, therefore the results for all layers are presented and analysed.

Soil carbon stocks of the various sampling sites are presented in Table 3.4; it can be seen that they ranged between 133.45 t C/ha to 157.12 t C/ha, between 22.23 t C/ha and 38.03 t C/ha, and between 155.69 t C/ha and 194.54 t C/ha for the 0-50 cm, 50-100 cm and 0-100 cm depth increments, respectively. Within-site variability, expressed as a CV, of soil carbon stocks in the 0-50 cm (part A, Table 3.4) and 50-100 cm (part B, Table 3.4) layers was exactly the same as for the carbon content results, since there was only one bulk density profile for each sampling site within the orchard block. The variability (CV) within sites for the whole one metre profile (part C, Table 3.4) was between 7% and 13% of the mean, and was higher than the variability of carbon stocks between sampling sites (CV=6.2%).

Table 3. 4 Soil carbon stock for the 0-50cm, 50-100cm and 0-100cm depth layers. (n= number of samples; Avg= average; SD= standard deviation; SE= standard error; CV= coefficient of variation).

Depth:		A: 0-50 cm		B: 50 -100 cm		C: 0-100 cm	
Site	**n**	**Avg carbon stock**	**SD**	**Avg carbon stock**	**SD**	**Avg carbon stock**	**SD**
1	16	150.39	11.32	25.28	4.69	175.67	13.69
2	14	145.84	8.95	33.34	5.18	179.18	11.71
3	16	141.29	9.78	24.80	3.12	166.08	11.47
4	13	151.27	13.60	33.28	3.62	184.55	13.72
5	16	147.60	12.31	22.25	2.92	169.85	13.73
6	12	150.37	15.40	26.00	3.58	176.37	17.52
7	16	157.12	20.43	23.57	4.68	180.69	23.59
8	14	156.51	19.05	38.03	5.46	194.54	20.64
9	15	145.64	12.77	23.03	4.21	168.68	16.15
10	15	133.45	8.91	22.23	2.32	155.69	10.16
Avg	14.7	147.95		27.18		175.13	
SE		2.22		1.77		3.41	
SD		7.03		5.60		10.77	
CV		4.8%		20.6%		6.2%	

Several authors (Kravchenko and Robertson 2011; Syswerda et al. 2011) have suggested that including more variable deeper depths may reduce the chance of observing significant differences over time. The greater variability found in the 50-100 cm layer both within and between sampling sites affected the variability of the whole profile soil carbon stocks (0-100 cm). The CV increased from 4.8% to 6.2%, even given the small contribution of this layer (only around 20%) to the whole profile carbon stocks.

3.3.2.5. Spatial characteristics of soil carbon stocks at the block scale

A spatial analysis of soil carbon stocks was carried out in the orchard block for the 0-50 cm, 50-100 cm and 0-100 cm depth increments using semivariograms.

In the top 50 cm soil, the total semi-variance of the model[3] (sill) was 221. The nugget was 143. The nugget/sill ratio was 0.65, which implies a low spatial autocorrelation, and low

[3]The “sill” is the maximum value of the modelled semi-variance.
The “nugget” is the y origin of the modelled semi-variance as a function of distance between samples.
The “nugget/sill ratio” indicates the level of spatial auto-correlation.

variability at the small scale. In other words, the non-spatial variation between samples accounts for 65% of the total variance across the orchard block, while the variance due to an increasing distance between samples accounts for some 35% (=100%-65%) of the total.

For the top 50 cm of soil, most of the variance was therefore independent of the spatial position of the samples. Two reasons can be suggested for this non spatial variability: The measurement error, which is the sum of the observer error and the instrumental error, plus the natural variations at a smaller scale than the smallest distance between two samples. While the nugget semi-variance is considered as a 'black box', and cannot be separated into the various sources of error, the observer and instrumental errors can be quantified separately. The observer error includes the sampling and sub-sampling errors and was estimated by repeating three times the sub-sampling process of one sample for each of the 0-50 cm and 50-100 cm layers. The 0-50 cm layer triplicates showed a mean of 2.26% C with a standard error of 0.017, and a coefficient of variation of 1%. The instrumental error was given by the laboratory performing the analysis on the LECO CN analyser, and equals +/- 0.03%C. Thus, it seems that the observer and instrumental errors for this soil layer are small. However, three replicates (of one sample) is a very small number to estimate the observer error, and more replicates should be analysed in order to obtain a realistic and reliable error estimate.

Additionally, it was noted that one outlier is present at the top right of Fig.3.11 (as well as Fig 3.13 and 3.15). However, the number of paired samples for this group was low, as shown by its red colour, which explains its low impact on the modelled semi-variance curve.

Overall, there was very little spatial correlation beyond the range distance of 13.6 m between samples. This suggests that a systematic sampling grid with a minimum grid cell size of 13.6 m would be best suited to account for the variability of soil carbon stocks in the top 50 cm of soil of the orchard block studied in this Chapter. However, the fit of the modelled semi

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The "range" is the distance at which 95% of the sill is achieved.
(see section 3.2.7)

variance to the data is poor and does not allow confidence in the value of 13.6m. Furthermore, it is important to note that systematic sampling embeds the risk of missing repetitive patterns within the area under study. Alternatively, it is possible to implement a "block sampling"[4] design. In this case, the area under study is divided into equal sampling blocks, and the total number of sampling sites for the area under study is equally distributed between these sampling blocks. Within each sampling block, the sampling sites are randomly distributed, in order to enable observation of repetitive patterns. In this chapter, no repetitive pattern at the orchard block scale was observed; a "block sampling" grid would therefore be suitable.

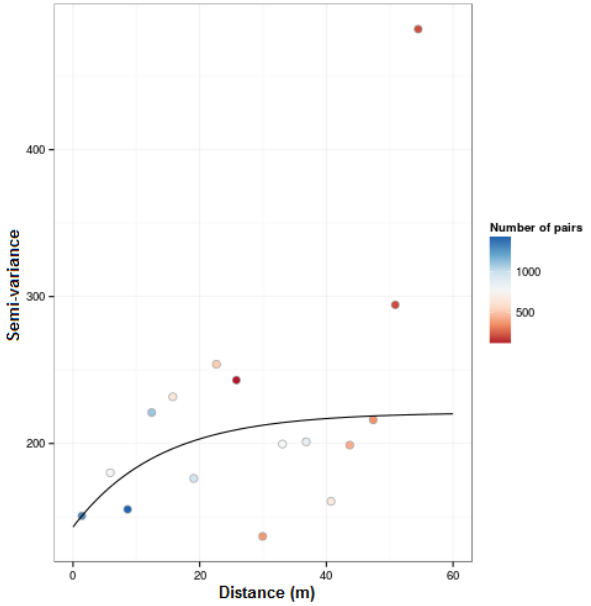

Figure 3. 11 Semi-variogram of experimental data (points), and the fitted exponential model (line) for the top 50 cm of the soil profile, over the entire orchard block (n=147). The colours of the dots indicate the number of samples paired according to their spacing for which the variance is calculated (see scale "Number of pairs" on right of graph).

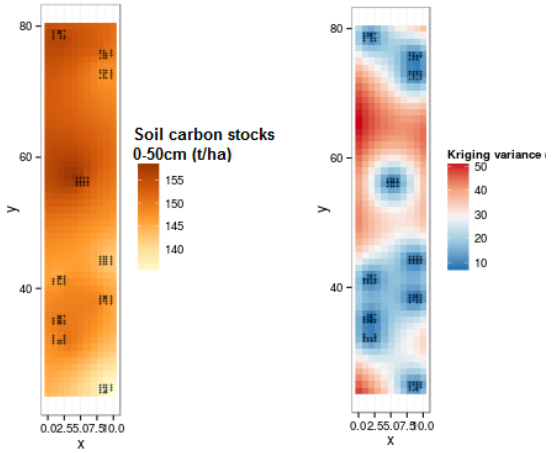

Figure 3. 12 Kriging of soil carbon stocks (left) and its variance (right) to a depth of 50 cm. Black dots represent individual soil samples locations on the orchard block.

In the 50-100 cm depth layer, the sill of the total semi-variance of the model could not be defined, as the modelled variance does not plateau (Fig 3.12). Qualitatively, the sill could be

[4] To avoid confusion, the terms "block sampling" and "sampling blocks" are only used in this paragraph and designate the sampling design.

defined as “very high” The nugget equals 17.2. The nugget/sill ratio was therefore “very small”, as opposed to the top 50 cm. This implies an important spatial autocorrelation for this depth increment. In other words, the variance between samples was almost only dependent of the distance between them. The 50-100 cm layer triplicates showed a mean of 0.33% C with a standard error of 0.014, and a coefficient of variation of 7%. The instrumental error derives from the laboratory analysis using the LECO CN analyser, and this equals +/- 0.05%C. Thus, it seems that the observer and instrumental errors (relative to the mean) for this soil layer are more important here than compared to the 0-50 cm layer. It is therefore conceivable that the natural variations at a scale that is smaller than the smallest distance between two samples are small.

Therefore, it is recommended to adapt a systematic sampling grid covering the whole area of the orchard block to account for the variability of soil carbon stocks in the 50-100 cm layer of soil. Moreover, a trend of the soil carbon stocks being higher towards one end of the orchard block can be observed on the kriging map (Fig. 3.14) This pattern could be due to the texture variation observed (qualitatively) at the northern end of the orchard block, which had already forced a wide border of 20 trees to be excluded from the sampling area (see Section 3.2.2). In this case, this may imply a limitation of the method of soil texture assessment by hand, which would be suitable to observe large texture variations, but not small ones.

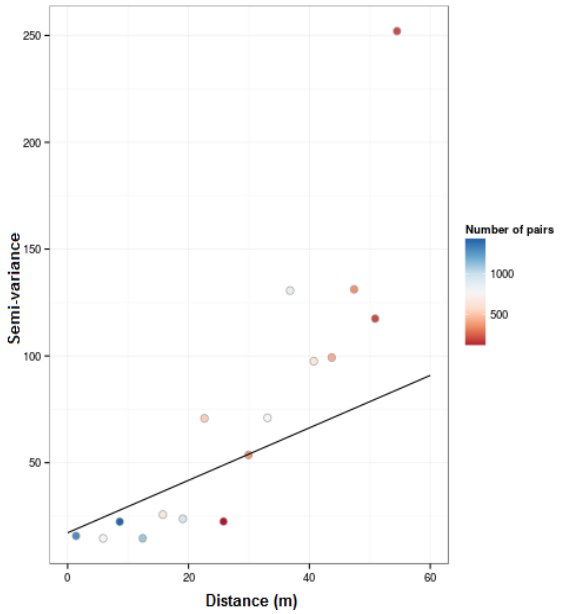

Figure 3. 13 Semi-variogram of experimental data (points), and the fitted model (line) for the 50-100 cm depth, over the entire orchard block (n=147). The colours of the dots indicate the number of samples pairs for each spacing group.

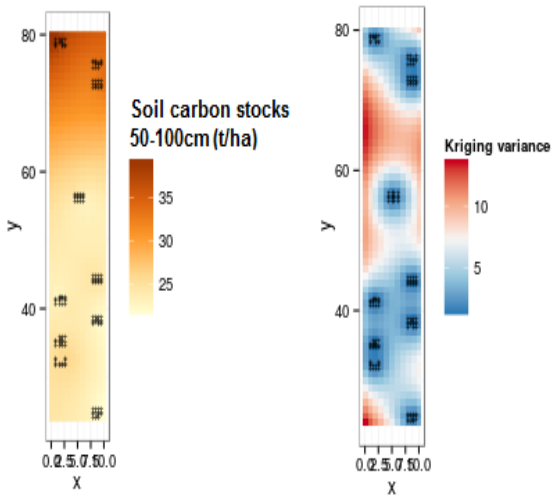

Figure 3. 14 Kriging of soil carbon stocks (left) and its variance (right) for the 50-100cm depth layer. Black dots represent individual soil samples locations on the orchard block.

The semi-variogram of the whole 100 cm depth layer shows characteristics of both the semi-variograms of the 0-50 cm and 50-100 cm layers. Again, the sill of the total semi-variance of the model could not be defined, as the modelled variance did not plateau (Fig 3.15). The nugget equals 203, indicating a high non-spatial variability. A high spatial autocorrelation can be observed. In other words, the variance was partly non spatial, and partly dependent of the distance between the samples. But without further sampling it was impossible to quantify the sill and the nugget/sill ratio.

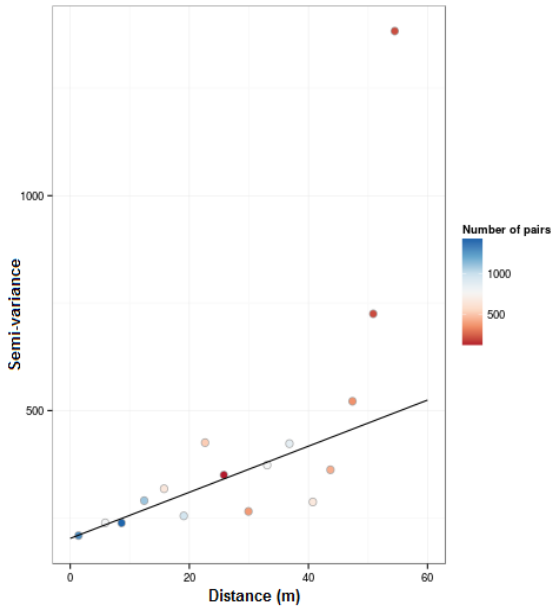

Figure 3. 15 Semi-variogram of experimental data (points), and the fitted model (line) for the 0-100 cm depth, over the entire orchard block (n=147). The colours of the dots indicate the number of sample pairs for each spacing group.

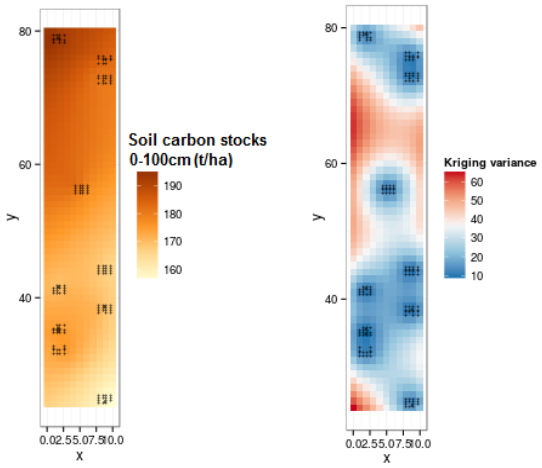

Figure 3. 16 Kriging of soil carbon stocks (left) and its variance (right) for the 0-100cm depth layer. Black dots represent individual soil samples locations on the orchard block.

Overall, to sample for soil carbon stocks in the top 100 cm an orchard block, a block sampling grid would allow for both covering the whole area of the orchard block, and accounting for the spatial correlation of soil. Indeed, using a total random sampling design would not be suitable. This is because of the risk of not covering the entire orchard block.

3.3.3. Towards the minimum requirements to measure changes in soil carbon stocks at the scale of the orchard block

Due to the large variations in soil carbon contents within an ATA, and as a result of the dominance of the non spatial variability, repeating sampling at the tree scale would appear essential. Therefore, the minimum number of soil samples required to estimate the carbon stock at the tree scale was calculated by pooling randomly selected samples within each site. This was done for both the 0-50cm and 0-100cm depth layers.

Given the significant difference between carbon stocks situated between and outside the wheel tracks, it was assumed that equal numbers were to be taken for each area, for example, 4 pooled samples comprising 2 between and 2 outside the wheel tracks.

For each number of pooled samples (2, 4, 6, …, 16), the within-site random selection of samples was repeated 1000 times, and these results were used to obtain an average variance of the mean soil carbon stock for the orchard block, as well as the upper and the lower 95% confidence intervals of this variance for each number of pooled samples (Figure 3.17)

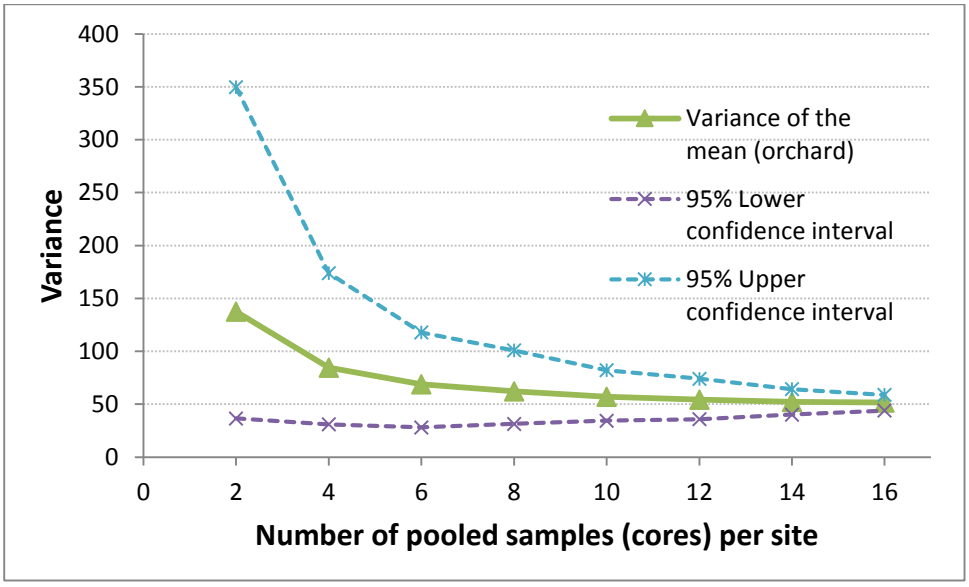

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Figure 3. 17 Evolution of the variance of the mean carbon stock and the 95% confidence interval of this variance for the 0-50cm layer as a function of the number of pooled core samples per site.

The pooling of four samples within each site reduced the variance of the mean carbon stock of the orchard by 38%, and reduced the confidence interval around this variance estimate by more than half (54%). The pooling of six samples per site reduced the variance by a further 11%, and the confidence interval by a further 20%. However, increasing the number of pooled samples per site from 6 to 8 or 10 only reduced the mean variance and its confidence interval by further amounts smaller than 10%.

Therefore, a minimum of 4 to 6 samples per site is required in order to estimate reasonably the mean soil carbon stock for each site.

Using these estimates of variance allowed the calculation of the number of sites required to observe a change in the mean soil carbon stocks for the orchard. This assumes the minimum statistical requirements of a 95% confidence interval (α=0.05) and an 80% chance of observing a statistically significant difference (Power = 0.8). The results are presented in Figure 3.18.

A typical change in soil carbon under apple orchards is difficult to predict at this stage, due to a lack of data in the literature and the site specificity of soil carbon stocks and changes. However, yearly changes in soil-carbon stock are small when compared to the size of the stocks (Post et al. 2001). For example, Schipper et al. (2007) re-sampled 31 soil profiles across seven soil orders in New Zealand pastures and found yearly changes to about 1 m depth between -2.4% and +1% of the historical carbon stocks. Apple orchards are composed of tree rows and grass alleys. It is therefore plausible that changes in soil carbon stocks in apple orchards and under pastures are of the same order of magnitude. Furthermore, there is now evidence that soil carbon is mostly composed of root derived carbon (Schmidt et al., 2011), and in addition to grass roots, tree roots are present in orchard systems and contribute to soil carbon changes over time. In this study, conservative changes inferior or equal to 1% of the soil carbon stock per year are considered. Therefore a potential change of 10% implies an interval of 10 years or more between two soil-carbon measurement campaigns.

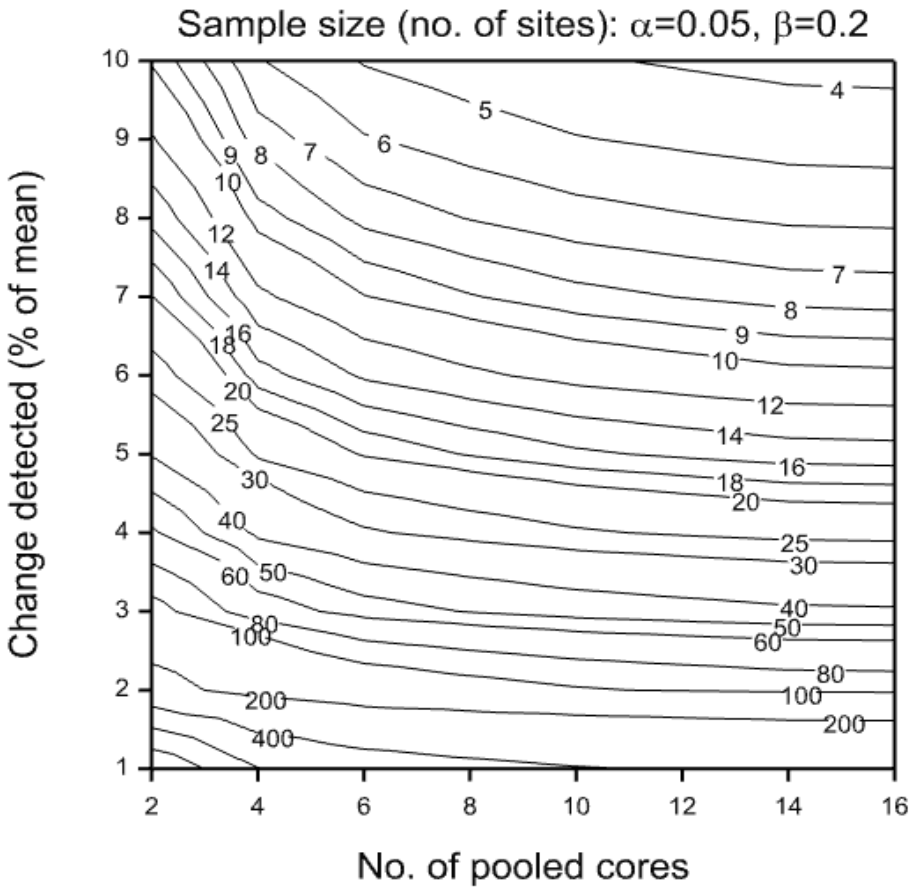

Figure 3. 18 Contour plot expressing the minimum number of sites required within an orchard as a function of the number of pooled samples (cores, 0-50 cm depth) per site (X axis) and the change detected as a % of the mean carbon stock for the orchard (Y axis). Here α is the statistical significance level and β = 1-statistical power.

In general, taking less than four to six pooled cores (0-50 cm) per site increases the number of sites to be sampled that allows observing a given change. The maximum, practically achievable number of samples per site for the research purposes presented in this study using 10 sites, with an average of 14.7 samples per site, enables detection of a change in carbon stocks of about 6.5% of the mean. This assumes that (1) the same sampling intensity would be repeated at a later time, and (2) the same overall variation was observed for that second sampling campaign.

In contrast, sampling ten sites at a rate of eight samples per site enables detection of a change in carbon stocks of about 7% of the mean, which here is equivalent to 10.4 t C/ha. This indicates that reducing the total number of samples by half provides only a small increase in the detectable change. In addition, a change of 5% could have been observed by

sampling 18 sites at a rate of eight samples per site, resulting in a total of 144 samples, or slightly less than that collected in this study.

In conclusion, sampling more sites with fewer samples per site enables detection of smaller changes. However, the fewer samples per site, the more uncertain the variance estimate is. This uncertainty is related to assumption (2), used to estimate the number of samples for the second sampling campaign.

As deduced in Section 3.3.2.4, sampling to 1 metre depth instead of only the top 50 cm is important. Therefore, the analysis carried out at the beginning of Section 3.3.3 was repeated for the top metre of soil.

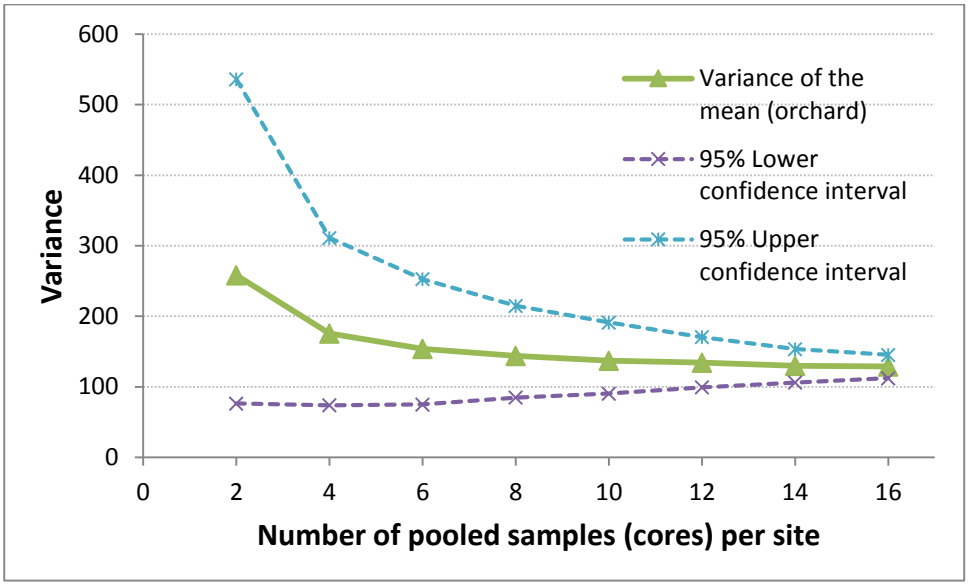

Figure 3. 19 Evolution of the variance of the mean carbon stock and the 95% confidence interval for the 0-100cm layer as a function of the number of pooled core samples per site.

In the 0-100 cm soil layer, as for the top 50 cm, the pooling of 4 samples within each site provides an important reduction of the variance of the 95% confidence interval of the mean carbon stock of the orchard block. However, increasing the number of cores per site from 4 to 6, 8 or 10 provided a smaller but relatively steady reduction of the variance of the orchard mean.

Again, a minimum of 4 to 6 samples per site is required in order to estimate reasonably the mean soil carbon stock for each site.

These estimates of variance were used to calculate the number of sites required to observe a change in the mean soil carbon stocks for the orchard, when assuming the same minimum statistical requirements as those used for the analysis of the top 50 cm. Results are presented in Figure 3.20.

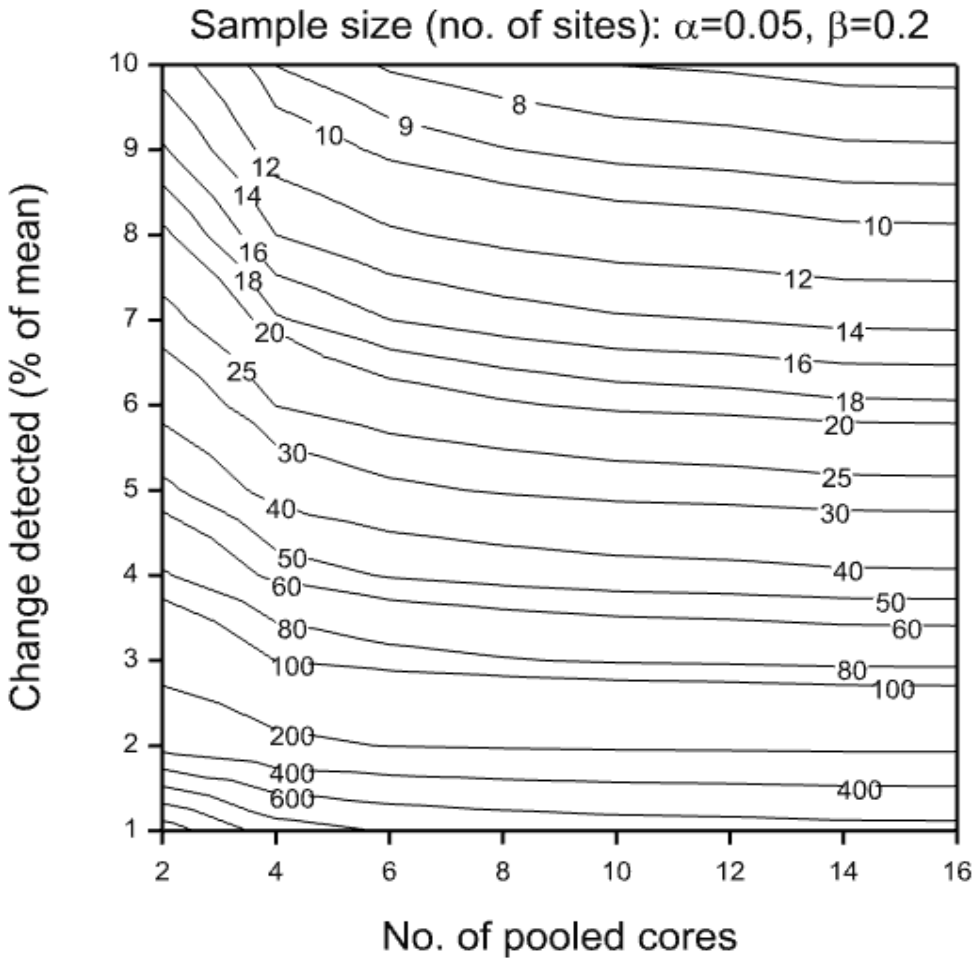

Figure 3. 20 Contour plot expressing the minimum number of sites required within an orchard as a function of the number of pooled samples (cores, 0-100 cm depth) per site (X axis) and the change detected as a % of the mean carbon stock for the orchard (Y axis). Here α is the statistical significance level and β = 1-statistical power.

As shown in Figure 3.20, taking less than 4 to 6 samples over 0-100 cm per site increased the number of sites to be sampled in the orchard required to observe a given change. The sampling regime presented in this study, enables detection of a change in carbon stocks of

about 8.5% of the mean for the top metre of soil, which is equivalent to 14.89 tC/ha. In contrast, reducing the number of samples per site to 6, and sampling 10 sites within the orchard enables detection of a change in carbon stocks of about 9% of the mean.

However, as opposed to the top 50 cm, now 30 sites at a rate of 8 samples per site would be needed to observe a change of 5%. This would be 240 samples in total. This assumes as well that the same sampling intensity would be repeated again, and that the same overall variation would be observed for that second sampling campaign.

3.3.4. Costs involved in sampling.

The costs of collecting, processing, and analysing samples are often the limiting factor in quantifying soil attributes. In order to determine the most cost-effective approach, the costs of the minimum sampling regime can be calculated as a function of the change that can be observed for various combinations of sites and samples per site. These combinations follow the calculations in section 3.3. However, for defining the costs of sampling, several assumptions have to be made. For example, the simplest assumption would be to consider a constant cost for each sample taken. In this case, for a given total number of samples, taking fewer samples per site and visiting more sampling sites would always lead to quantification of the smallest detectable change. However, assuming a constant cost per sample is not realistic. This is because one bulk density profile is required for each sampling site regardless of the number of core samples. This assumption raises several questions (such as, “What are the variability, and financial benefits of pooling several sampling sites together?)”. Therefore, more realistic assumptions have been made here, possibly reflecting the various constraints that an individual land owner, or primary producer, faces, when intending to measure and report changes in soil carbon stocks over time.

Several items and tasks are needed to measure soil carbon stocks (Table 3.5). The cost of each item was set and associated with minimum unit and a certain number of samples to be taken and processed. A minimum unit is the minimum-set period of time or number of

samples required for a task. For example, it is not possible to hire a hydraulic core sampler for less than one unit, that is half a day, and returning it one hour late incurs the payment of another unit. However, only 40 samples can be taken in half a day. Therefore if 42 samples have to be collected, the hydraulic core sampler will need to be hired for two units, that is a full day.

The cost assumptions are described in Table 3.5. The subsequent cost results for the 0-50 cm layer and 0-100 cm layer are shown in Figure 3.21 and 3.22, respectively.

Table 3. 5 The cost assumptions for sampling.

Item (& task)	Cost (NZD)	Minimum Unit	Number of samples taken and processed
Hydraulic core sampler hire (%C sampling)	400	1/2 day	40
Specialised technician (%C sampling)	200	1/2 day	40
Processing %C sample (drying + sieving (2mm) + sub-sampling)	20	1 hour (30 min/sample)	2
Laboratory analysis %C sample (LECO)	20	1 sample	1
Specialised technician (BD sampling – whole profile)	50	1 hour	1

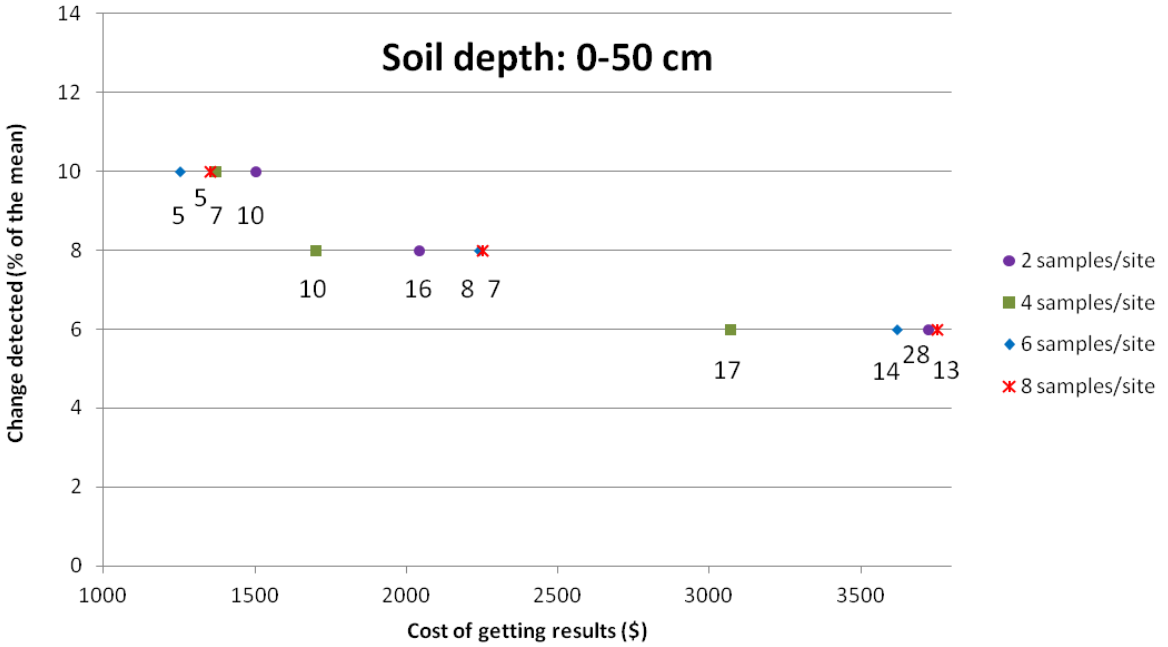

Figure 3. 21 The observable change of the mean soil carbon stock of the orchard block as a function of the cost of obtaining the results, for the 0-50 cm layer, for different sampling regimes that have to be repeated in order to observe a change. The numbers situated above the data points are the number of sampling sites required within the orchard block for a particular number of samples per site. The costs have been calculated using the data in Table 3.5 and the results of the contour plots in Section 3.3.3. An example is provided in the text.

An example from Figure 3.21 is as follows. In order to detect a change of 8% of the mean soil carbon stock in the top 50 cm of the orchard block (ordinates axis), several combinations of sites and samples per site are possible: (10*4), (16*2), (8*6), (7*8). However, the combination (10*4) is the cheapest sampling regime, assuming that one bulk density profile per site is obtained.

Prior to drawing conclusions, it is important to highlight that this part of the analysis is illustrative and illuminating. Obviously the results will change depending on the cost assumptions and the degree of variability in soil carbon stocks for a particular orchard block. Nevertheless, the cost assumptions can be considered as being realistic. The degree of variability of this orchard block is most likely at the lower end of the range, since the orchard block has been chosen for its homogeneity. Overall, these cost results can be considered to represent the “minimum”. Furthermore, these results are for one sampling campaign only, and this will have to be repeated later in order to observe changes in soil carbon stocks.

In our specific site conditions, if it were decided to sample the top 50 cm of soil, and assuming that one bulk density profile was sampled per site, then taking 4 samples per site (times the number of sites required to observe a given change) would be the least expensive way of measuring soil carbon stocks to observe up to a 10% change of the mean. However, for the particular conditions of the orchard block assessed, in order to observe a change of 10% of the mean, a sampling with a minimum of 5 sites at a rate of 6 samples per site is required. The associated cost for such a sampling campaign is $1250 (NZD).

Sampling to one meter depth seems to be a minimum, although it may increase the variability, and therefore require more samples, as discussed in Section 3.3.2.4. The costs results for the 0-100 cm layer are provided in Figure 3.22.

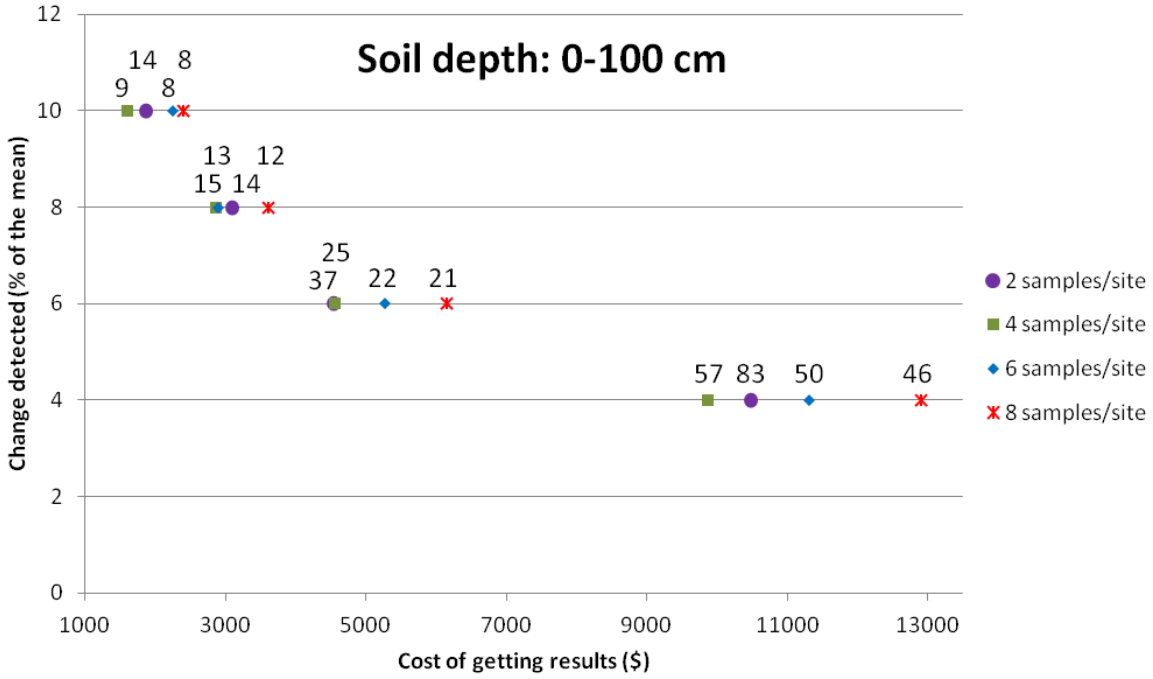

Figure 3. 22 The change of the mean soil carbon stock of the orchard block as a function of the cost of obtaining the results, for the 0-100 cm layer, for different sampling regimes. The numbers above the data points are the number of sampling sites required within the orchard block for a particular number of samples per site. The costs have been calculated using the data in Table 3.5 and the results of the contour plots in Section 3.3.3.

For the specific site conditions of this study, if it were decided to sample the top 100 cm of soil, and assuming that one bulk density profile were sampled per site, a change of 10% of the mean could be observed by sampling a minimum of 9 sites at a rate of 4 samples per

site is required. The associated cost for such sampling campaign is $1590 (NZD). As two sampling campaigns are required to observe a change, this cost would have to be doubled.

Now, it is possible to relate these cost estimates to their implications in terms of an incentive for measurements. However, more assumptions necessarily need to be made. For the specific conditions of this study, it is assumed that:

- A 1 ha orchard block has a soil stock of 150 t C to one metre depth at the beginning of the measuring period, and the variability of these stocks is the same as in the present study.
- A substantial and constant increase of 0.5% per year in the mean soil carbon stock is observed in that orchard block, and
- The cost of getting the results to observe a change of 10% in soil carbon stocks to 1 meter depth is, as in our study, $1590 per sampling campaign (9 sites, 4 samples per site).
- Two sampling campaigns are performed, one at the beginning and one at the end of a 20 year period, although for simplicity inflation is ignored.
- Sampling is performed by a trusted independent organisation, and there are no costs for verifying the results.

The price of carbon in the carbon market would have to be greater than $212 per tonne at the time of the second measurement campaign in year 20 in order to provide an incentive to measure this change. Even the most optimistic forecasts of the price of a tonne of carbon do not exceed $100 per tonne.

However, let us assume that the orchard block (1ha) consistently produces 35 tonnes[5] of export quality apples per year. During the first three years after planting, apple production is assumed to be nil. To compensate for the cost of measuring a change of 10%, NZ$ 5.35 per

[5] On average, New Zealand apple orchards produced 35 tonnes of export apples per hectare on average over 2011 and 2012. http://freshfacts.co.nz/file/fresh-facts-2013.pdf.

tonne of exported apples over the 20 years is required. In New Zealand, the yield of apples is often expressed in “carton equivalent”. A carton equivalent corresponds to 18 kg of apples. Approximately NZ$ 0.1 per carton of apples is required to compensate for the cost of the sampling campaigns. This provides a somewhat more realistic incentive, considering that the price of a carton of export apples at the ship side is currently around NZ$ 20.

In conclusion, it seems unrealistic to rely on the carbon market to provide measurement and monitoring incentives for soil carbon stocks in apple orchard systems. In contrast, speculating that in the near future, global supermarkets give price premiums for the best environmentally performing products, a price premium equivalent to 0.5% of the value of NZ apples would compensate for the cost of monitoring soil carbon stocks.

3.4. Critical Analysis

Two limitations of this study can be critically considered:

3.4.1. Bulk Density

Only one BD profile was sampled for each sampling site.

The BD varies spatially too. This is shown by the comparison between the tree row and grass alley (Fig.3.4). It is possible that these variations are correlated with the distance to a particular tree, as well as management practices, such as wheel tracks. The BD sampling design of this study, while being the maximum that was possible practically, does not fully account for the variability within ATAs. This has implications when calculating soil-carbon stocks in the site experiment. One could argue that the soil-carbon stocks for each core sample should be adjusted according to the differences between tree row and grass alley of the pit experiment (Fig. 3.4). However, it was not possible to determine how these should be corrected, because no BD information was available between the tree row and the grass alley. Less time- and energy-consuming bulk density measurement methods need to be developed. This could involve the utilisation of soil core samplers and sensors that allow reliable bulk density estimate as well as carbon content measurements.

3.4.2. Stocks: Depth or Mass Equivalence

There is a difference in accounting for soil carbon stocks per equivalent depth rather than equivalent mass.

As noted in Section 3.3.1.3 of this Chapter, estimating the changes of soil carbon stocks on an equivalent depth basis embeds the risk of mistaking the difference in the quantity of soil measured for a difference in carbon stock, when two means are compared. In other words, are any measured changes in soil carbon stocks the result of more carbon in the soil or simply more soil mass being measured? This point is important for the determination of a change in soil carbon stocks which involves a comparison between two (or more) soil carbon

stock estimates. When this is the case, it is necessary to apply an appropriate correction to the carbon stocks results, as discussed by Lee et al. (2009) and further commented by McBratney and Minasny (2010) and Lee and Six (2010). However, in this study, the objectives were to estimate the variability of the soil's carbon content, bulk density and carbon stock, and to estimate, from these variability figures, the minimum sampling requirements in order to observe a hypothetic change. No soil-carbon stocks means were compared with the aim of observing a change over time. These corrections were therefore not necessary.

3.5. Conclusions & perspectives

This chapter presents the first detailed inventory of the variability of soil carbon contents, bulk density and the carbon stocks in an apple orchard block. Furthermore, no equivalent study of this intensity of sampling in a small management unit, an orchard block of 0.3 ha, has been reported in the literature. Several conclusions have been reached in this chapter:

- At the tree scale, for the 0-100 cm soil layer, BD was significantly different between tree row and grass alley and BD variation were low within each of these area. No significant difference was found between tree row and grass alley for the %C and the carbon stock and their variability increased with soil depth.
- The carbon content in the top 50 cm of soil decreased at a rate of 0.29% C/m with increasing distance away from a tree, possibly due to both the tree and grass roots.
- At the orchard scale, the increased variability of BD at depth was related to the change in soil texture. The variation of %C between sampling sites was relatively low (CV= 4.7%) in the 0-50 cm soil layer, while it was relatively high (CV=24.3%) in the 50-100 cm layer.
- Overall, the planting pattern at the tree and the orchard block scales affected the soil's bulk density, carbon content and carbon stock. It is therefore essential to adapt the sampling design to take into account the spatial layout of the crop. Sampling evenly between and outside the wheel tracks within sampling sites was necessary.
- For both the tree and orchard-block scales, sampling the top 50 cm at least was necessary to account for 80% of the carbon stock present in the top metre of soil.
- However, sampling soil-carbon stocks to one meter depth instead of the top 50 cm increased the variability relative to the mean by 30%, despite the small contribution of the 50-100 cm layer to the whole profile carbon stocks.
- In the 0-50cm soil layer, the variance between samples seem to increase with distance although it was mostly non spatial. In contrast, in the 50-100cm layer, the variance between samples was almost only dependent of the distance between

them. As a result, in the top meter, the variance was partly non spatial, and partly dependent of the distance between the samples.

- A block sampling grid would be best suited to account for the variability of soil carbon stocks in both the top 50 cm and the top 100 cm soil layers in the orchard block assessed in this chapter. In addition, repeating sampling at the tree scale would appear essential to obtain measures of the temporal variation in soil carbon stock at the orchard scale.
- In order to detect a change in soil carbon stocks, sampling more sites with fewer samples per site enables detection of smaller changes. However, a minimum of four to six samples per site is required.
- For the specific site conditions of this study, observing a change of 10% of the mean in the top 50 cm requires sampling five sites at a rate of six samples per site, for a cost of NZ$1250 per sampling campaign. In contrast, observing a change of 10% of the mean in the top meter requires sampling nine sites at a rate of four samples per site, for a cost of NZ$1590 per sampling campaign.
- To illustrate the feasibility of monitoring, while it seems unrealistic to rely on the carbon market as an incentive, a price premium equivalent to 0.5% of the value of apples at the New Zealand ship side would compensate for the cost of measuring and monitoring soil carbon stocks in New Zealand apple orchards.

In conclusion, while the variability of the soil-carbon stock horizontally and with depth is important, it seems feasible, both practically and economically, to measure and monitor this stock on a routine basis. However, these results are based on the assessment in one young apple orchard block in one particular year, and further research is needed to confirm these results in other orchard blocks of different ages, and to determine if there is a change in the soil-carbon stock over time in apple orchards.

In Chapter 4, the same investigative sampling strategy as that used in this Chapter was used to study three additional apple orchard blocks of different ages. The four orchard blocks,

aged between one to twelve years, constitute a chrono-sequence and the potential to estimate a change in soil-carbon stocks is investigated. The possibility to define a standard protocol to monitor the changes in soil carbon stocks that is applicable to all apple orchard blocks is investigated. Finally, the practical and economic implications of measuring and monitoring the changes in soil carbon stocks in apple orchard blocks are presented.

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Chapter 4:

Monitoring soil-carbon stocks in apple orchards: practical and financial feasibility considering incentives through carbon footprinting

"In the best of all worlds, dedicated field experimentalists with guidance from modellers and quantitative ecologists could have several dozen new high-impact field studies with two decades of observational data by the year 2035. Instead of confining our understanding largely to soil C dynamics in the temperate region, by 2035, scientists could substantially increase the certainties about soil C changes across a wide range of ecosystems and land uses, from the boreal zone to the tropics, from contemporary agricultural systems to urban and residential influences." (Smith et al. 2012)

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4.1. Introduction

Monitoring soil-carbon stocks is desirable for many reasons, including its potential impact for climate change mitigation and the enhancement of soil functioning and biodiversity (see sections 1.3 and for example Suddick et al. (2013))

However, choice of an appropriate soil-carbon monitoring protocol is critical in order to obtain representative results. This requires consideration of both the practical and economic aspects of carbon monitoring.

Chapter 3 presented a detailed inventory of the variability of soil-carbon content, bulk density and carbon stocks in one apple orchard block. This variability implied that measuring and monitoring soil-carbon stocks should be implemented using a block sampling grid at the orchard block scale. In addition, sampling more sites, equivalent to one ATA and fewer samples per site would increase the chance of observing statistically significant differences over time. Sampling deeper than 30cm in the soil of apple orchards was also highlighted in Chapter 3 and sampling to one meter depth was preferable, even if requiring more efforts, as discussed in section 3.3.2.4 and in accordance with international literature (Clothier et al. 2010; Deurer et al. 2010; Schmidt et al. 2011; Syswerda et al. 2011; VandenBygaart et al. 2011)

Moreover, the conclusions of Chapter 3 were specific to one orchard block and depended on soil-carbon stocks being measured at one point in time. Therefore it is necessary to test these findings on other orchard blocks, and at different points in time, in order to assess the potential for development of a “standard” method that is applicable to different orchard blocks at different points in time.

The sustainability of an orchard block also depends, amongst other things, on the change in its soil-carbon stocks over time. Studies assessing these changes in orchards are rare. For example, Holmes et al. (2015) found a sequestration rate of 0.64 t C/ha/year to 1m depth when comparing a 10 year old and neighbouring a 25 year old kiwifruit orchards.

However, an apple orchard is composed of grass alleys and tree rows and it is possible to estimate the trends of carbon dynamics along the life of an apple orchard, from orchard development to the end of life, from other similar systems, such as grasslands and land afforestation. For example, Jones and Donnelly (2004) reviewed measured and modelled soil carbon changes in grasslands and show that while most grassland sites worldwide are sequestering soil carbon, changes are generally small (<2 t C/ha/year). Schipper et al. (2010) re-sampled 83 grassland sites in New Zealand to 1 m depth some 27 years (on average) after their initial sampling, and found changes between -1.21 and +1.0 t C/ha/year, representing less than 2% of the soil carbon stock. Therefore, it seems that changes in soil carbon stocks in grasslands are small and could equally be positive or negative.

On the other hand, land afforestation tends to be beneficial in the way of soil carbon stocks, depending on species. For example, Paul et al. (2003) found that afforestation with deciduous species (e.g. apple trees) resulted in changes in soil carbon stocks to 1m depth between -0.07 and 0.55 t C/ha/year while changes after afforestation with conifers ranged from -0.85 to 0.58 t C/ha/year. However, 7 years after afforestation of a walnut orchard, Lu et al. (2015) found lower soil carbon stocks to 50cm depth compared to a traditional cropland and a walnut orchard with intercropping (crops planted in the inter-row). Similarly, Mendham et al. (2003) found no significant difference between pasture and afforest soils to 1m depth after 7-10 years, however their statistical power is very low due to a very small number of samples (4 samples/ site) and highly variable soil carbon stocks between sampling sites. Finally, over longer time periods of 15 years or more, the apple trees' root-growth and turnover could result in an increase in soil carbon stocks, given the general high correlation of roots location with soil carbon stocks in the soil profile (Jobbagy and Jackson 2000).

Overall, the re- establishment of an apple orchard should therefore lead first to a decrease in soil carbon stocks due to the initial disturbance of orchard establishment, followed by an accumulation and stabilising slightly above the initial soil carbon stock. This scenario (see Fig 4.1) of soil carbon dynamics is similar to shape of the Covington curve (Covington 1981)

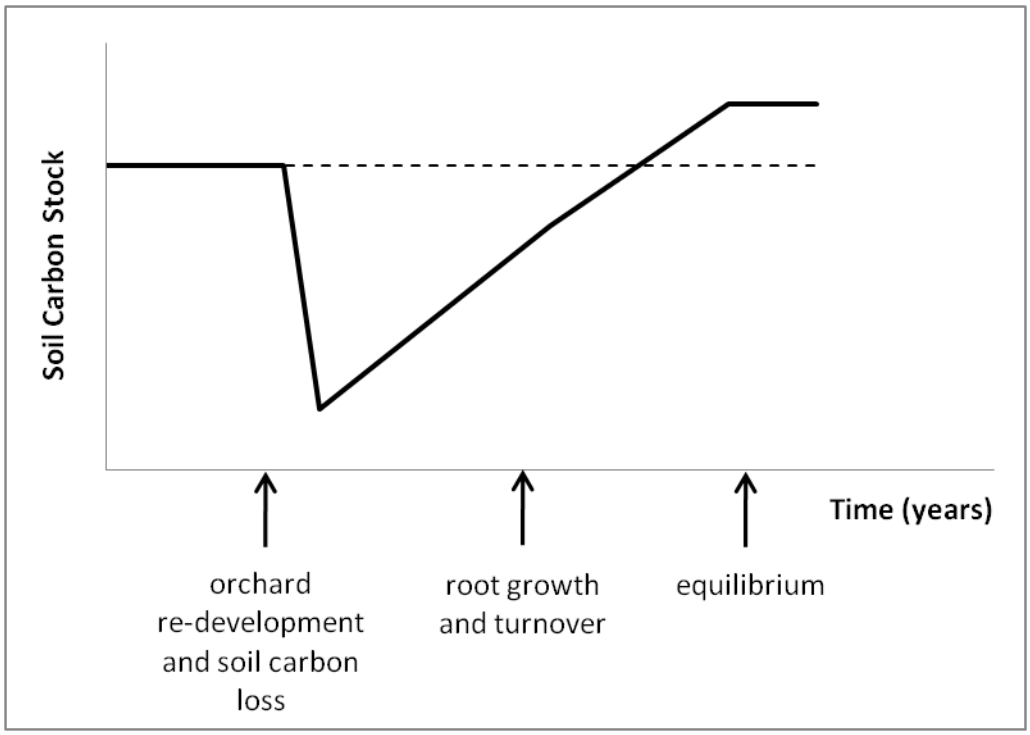


Figure 4. 1 Expected trend in the change in soil carbon stocks following re-development of an apple orchard.

This change in soil carbon stock can be measured in a particular field by direct sampling over intervals of several years, although this option has the disadvantage of having to wait long enough for a change to take place and to be statistically observable.

In this research, due to the limited time available, it was decided to use a chrono-sequence instead (see Stevens and Walker (1970)). In a chrono-sequence, soil-carbon stocks are measured within the same year and season in several orchard blocks that represent an age sequence. Effectively, the time necessary for a change to take place is substituted by space. The disadvantage of this "space-for-time" substitution is that, except for the orchard block's age, all other variables affecting the changes in soil-carbon stocks, also called "soil forming factors" by Stevens and Walker (1970), need to be similar in order to maximise the likelihood that the changes observed are due to the age of the orchard block alone. An example of potential mis-use of the chronosequence is presented by Yanai et al. (2003) The main assumption in a chrono-sequence is that each orchard block of the chrono-sequence has

been or will be at one time in the exact same state as the other orchard blocks of the sequence.

Regarding economic aspects, in line with the conclusions of Chapter 3, and due to the interests of global supermarkets in selling “greener products” (see Section 1.4.2 of Chapter 1 and Section 3.1 of Chapter 3), there may be incentives to monitor changes in soil-carbon stocks in order to reduce the carbon footprint of apple production. However, careful consideration needs to be given to who pays for the cost of monitoring, and who organises and implements such monitoring systems.

The objectives of this chapter are therefore:

- To verify if the spatial variability in soil-carbon stocks within a single orchard that was reported in Chapter 3 is observed in similar apple orchards of different ages.
- To investigate the suitability of a chrono-sequence to observe a statistically significant change of soil-carbon stocks over time in apple orchard blocks.
- To determine whether it is possible to define a standard protocol to measure and monitor soil-carbon stocks in all apple orchards.
- To determine whether it is practically and economically feasible to monitor soil-carbon stocks at the orchard block level.

4.2. Methods

4.2.1. Description of the orchard blocks

For this experiment, a twelve year chrono-sequence was adopted that consisted of four orchard blocks with similar characteristics (see Table 4.1). The four blocks were respectively planted one year, four years, six years and twelve years prior to sampling and were all located near Hastings (Longitude: 176.800076, Latitude: -39.588125), Hawke’s Bay, New Zealand. The blocks were chosen to be as similar as possible in order to minimize non-age differences between these blocks. They were all planted with an early fruiting apple variety,

used the semi-dwarf M.9 rootstocks, had a similar soil texture to at least 70cm depth, and the water table was at the same depth. The soil is classified as Hastings silty clay loam soil (soil order: Orthic Gley Soil, New Zealand soil classification, Hewitt, 1998 Insert WSR-soil type classification).

Furthermore, the management of the orchard blocks was very similar. All the blocks utilised integrated fruit production (IFP) techniques and required little irrigation, and the soil in orchard blocks was left bare for one year following the removal of the previous trees and prior to planting new trees. In all the orchard blocks, tile drains in the form of clay pipes had been installed at a soil depth of 90cm when the land was first converted from grazing pasture (sheep and cattle) to apple orchards, and so there had been very little soil disturbance after the first tree planting.

Furthermore, all except the one year old block belonged to a single orchardist, who represented the second generation of growers owning the orchards. Finally, the previous land use was similar for the four orchard blocks. All blocks had been converted from grazed pasture and planted with apple trees at least 20 years ago (and more than 30 years ago for the four year old block). For all orchard blocks, headlands of approximately 15 metre at both ends of each row, and borders of 1.5 rows on each “side” of the orchard block were excluded from the investigation.

Table 4. 1 Main characteristics of the four apple orchard blocks of the chrono-sequence.

Tree age (years)	Variety	Rootstock	Soil Texture	Depth of the water table (Approx.)	Orchard block Management	Previous Land Use
1	/	/	Similar, at least to 70 cm depth (see Fig. 4.1)	100 cm	- Integrated Fruit Production (IFP) - Low irrigation - 1 year of bare soil before replanting	Apple orchards for 20+ years
4	Jazz	M.9 (semi-dwarf)				Apple orchards for 30+ years
6	Jazz	M.9 (semi-dwarf)				Apple orchards for 20+ years
12	Royal Gala	M.9 (semi-dwarf)				Apple orchards for 20+ years

The one year old block was planted in 2011. The cultivar “Pacific Queen” was planted on a semi-vigorous MM.116 rootstock at a spacing of 4.2 m (between rows) by 2.3 m (between trees). However, this block could be considered to be at the initial state of planting in the chrono-sequence because it was sampled in 2012. The previous trees were of the cultivar “Braeburn” planted on a vigorous MM.793 rootstock, and were at least 20 years old when removed (Ross Wilson, pers. comm.), although the exact year of planting could not be determined because the current orchard manager started working on the orchard within the last 20 years. Under the current land use, irrigation consists of applications of less than 100mm of water per year using micro-sprinklers. The water table was not measured in this orchard block, and during sampling in winter, the wettest period, no water was observed at the bottom of the sample holes, indicating that the water table was always deeper than 1m at sampling times. However, it should be noted that the orchard block was never accessible following several days of rain because the orchardist was usually spraying his orchard at these times for disease control.

The four year old orchard block is described in detail in Section 3.2.2.

The six year old block was planted in 2006. The cultivar “Jazz” was planted on a dwarfing M.9 rootstock at a spacing of 3.5 m (between rows) by 1.5 m (between trees). The previous trees were of the cultivar “Royal Gala” planted on a semi-vigorous MM.106 rootstock in 1986. Under the current land use, irrigation consists of eight to ten applications of 15 to 20 mm of water per year using micro-sprinklers. The frequency depends on the weather patterns during each year. This corresponds to an amount equivalent to that applied in four year old orchard block but with the application being more spread out over time. The water table was measured on 31st August 2011 at a depth of 94 cm.

The twelve year old block was planted in 1999. The cultivar “Royal Gala” was planted on a dwarfing M.9 rootstock at a spacing of 3.5 m (between rows) by 1.5 m (between trees). The previous trees were of the cultivar “Braeburn” planted on a MM.106 rootstock in 1986. Under the current land use, irrigation is similar to the six year old block and also uses micro-sprinklers. The water table was measured on 31st August 2011 at a depth of 100 cm.

4.2.2. Selection of suitable orchard blocks

The process of seeking and selecting the orchard blocks took approximately eight months in total. Firstly, meetings were organised with Pipfruit New Zealand, the pipfruit-industry body, in order to access the registry of orchard blocks which provided information on the identification number (PIN) of the orchard, the cultivar, the year of planting, the type of management (Integrated or organic), the spacing between trees and between rows, the rootstock, the total number of trees and the area of the orchard block.

Secondly, the software ArcGIS was used to cross reference this information with the soil type by using the Fundamental Soil Layers developed by Landcare Research[1]. However, it was necessary to visit the Hawke’s Bay Regional Council mapping department in order to

[1] Available at: https://lris.scinfo.org.nz/#layer/79-fsl-new-zealand-soil-classification accessed on 16 June 2014.

obtain a map at a scale of 1:25000[2]. A number of criteria were then defined for choosing the orchard blocks. These were the cultivar Royal Gala planted on an M.9 rootstock, IFP management, homogenous tree vigour, and a single soil type across the block[3]. However, while the PIN was specific to the orchard, it did not indicate where the orchard block of interest was situated in the orchard. Therefore the initial list of orchards included some that were later removed from this list because many orchards included several soil types, and it was determined on a subsequent site visit that the sought-after block was not on the required soil type.

Thirdly, the selected orchards were visited in order to present the project to the orchard manager, and to find out about the physical location, management and history of the block. These meetings were organised with large companies owning or managing a large number of orchards, companies buying apples from individual orchard managers, and orchard managers of one, or several of the orchards. The main goal of these meetings was to obtain the approval from the manager of the orchard to check first the orchard block(s) for homogeneity above the ground. If this was the case, then approval was sought to come back at a later date to assess five (four corners of the block and centre) detailed profiles of soil texture every 10 cm down to 1 m depth using the soil texture assessment by feel (Thien 1979).

At the site visits, important variations in the soil textural profiles were found between orchard blocks on different properties across the Hawke's Bay, even though theses properties showed the same soil type according to the soil maps, as well as having the same rootstock, same cultivar and similar management. These soil-texture variations occurred mainly in the lower part of the soil profile, generally the more sandy layers (more than 50% sand), starting anywhere between 30cm and more than 1m depth. These variations are probably due to the

[2] Information about these maps are available at:
http://www.hbrc.govt.nz/Services/Environment/Land/Soil%20Information/Pages/Soil-Maps.aspx
[3] Although there was no restriction of the soil type, in order to increase the chances of finding similar orchard blocks of different ages.

generally alluvial and relatively recent nature of the Heretaunga Plains in the Hawke's Bay, which have been built-up over decades by rivers that changed paths and due to the various floods in the area. Furthermore, large variations in tree vigour were observed within some single orchard blocks. In the end, the only chance of finding four orchard blocks of an age sequence that were similar for the other characteristics was the proximity of the blocks. In other words, within the same soil type, soil texture variations with soil depth were so large that if the blocks were to be similar, they would have to be within a few hundred meters of each other. Therefore, compromises were made on the cultivar to find the four suitable blocks. This selection criterion changed from "Royal Gala" to "early harvested cultivars", including the cultivar Jazz, for example.

In the Pipfruit NZ database, properties with already one candidate orchard block were checked for other blocks with similar criteria. Following further investigations, the four, six and twelve year old blocks were defined as potential candidates, because they were in close proximity and showed similar criteria. While the orchard included many blocks with these similar criteria, only the blocks in immediate close proximity showed a similar soil texture profile. Furthermore, a gradient of decreasing upper depth of the more sandy layers was found the closer the sampling to the Ngaruroro River situated at the North Western end of the orchards.

The soil texture profiles of the twelve, six and four year old blocks were assessed by feel. Further discussions with the orchard manager as well as managers of neighbouring orchards ended in finding the one year old block across the road from the 6 year old block. Figure 4.1 is a map of the four orchard blocks of the chrono-sequence.

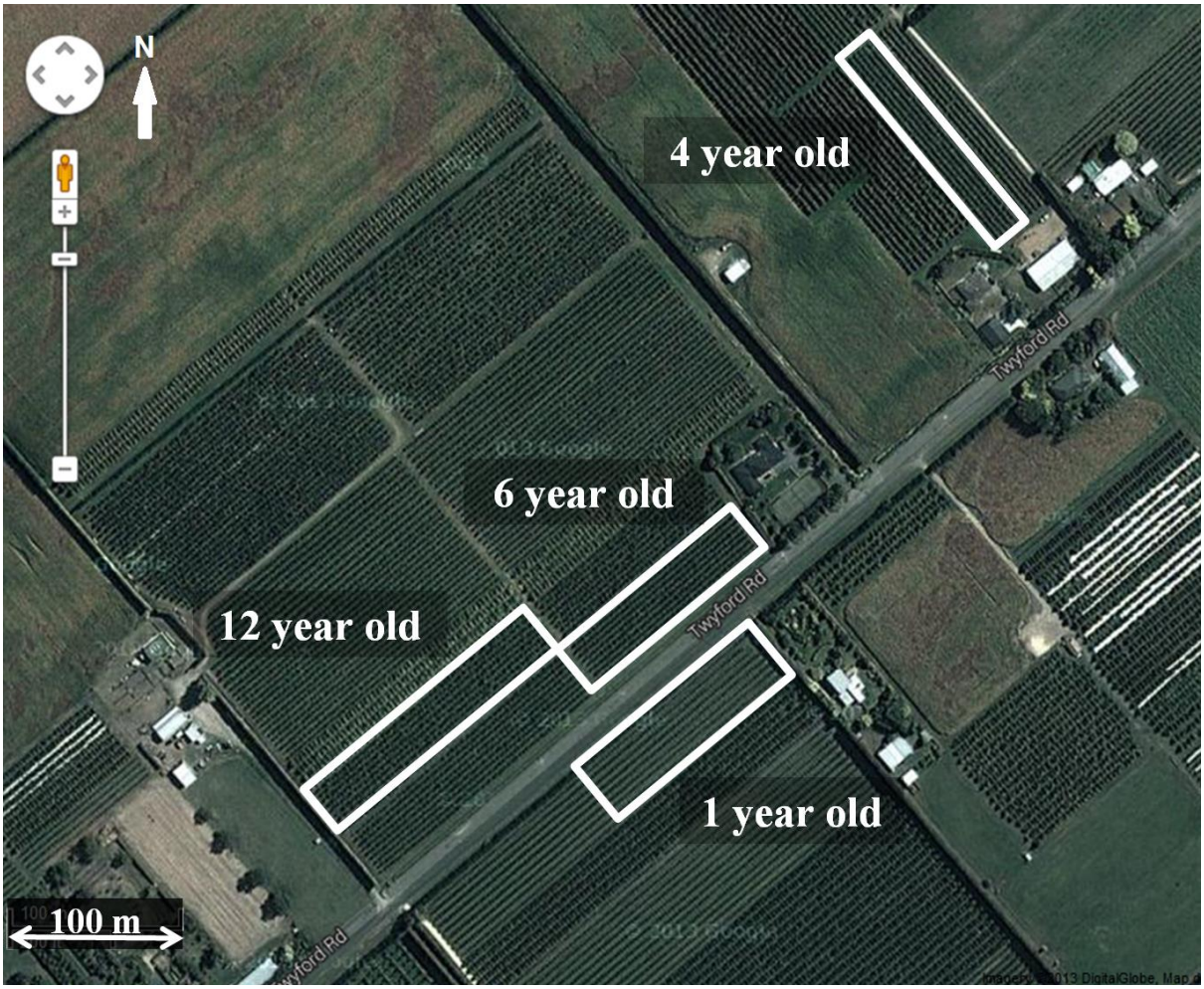


Figure 4. 2 Map showing the proximity of the four orchard blocks of the chrono-sequence. All blocks are within 500m of each other. Latitude: -39.588125, Longitude: 176.800076. Source: Adapted from maps.google.co.nz.

In conclusion, selection criteria were reduced to a minimum at the start of the search for potentially suitable blocks, and an assessment of the concentration of potential blocks in space was carried out. Pipfruit New Zealand, irrigation consultants, as well as large companies owning numerous orchards or buying apples from individual growers were important in the search process. Additionally, discussion with these various industry actors as well as individual orchard managers was extremely valuable in order to learn about the industry and the concerns of orchards managers.

4.2.3. **Sampling and sample processing**

The sampling procedure described in Section 3.2.3 was carried out on each of the three additional orchard blocks. All carbon content samples were collected between 16/04/2012

and 24/08/2012. The sampling was carried out for the four-year-old block first, and then for the three other blocks depending on accessibility to the orchard.. Associated bulk density samples were collected over the next 15 months for the 1 year old orchard block and over the next 12 months for the other blocks. The delay in collecting bulk density samples was due to difficulties in accessing the orchard blocks outside of the winter months because of spraying in the orchards. It was assumed that bulk density did not change during this period. The same total amount of samples (i.e. 160) in each orchard block was targeted, although with various level of success. The six year old orchard block had the largest number of missed samples and resulted in a total of 132 samples of one metre depth being taken, with the least represented site comprising 11 samples instead of the 16 targeted. The high number of missed samples in this block may be due to the high moisture content of the soil as sampling was carried out in a particularly wet period. This resulted in the drop-out of the bottom 5 to 10 cm of soil of core samples when pulling the soil core sampler out of the sampling hole. In the one, four and twelve year old blocks, some 146, 147 and 157 intact carbon-content samples were successfully collected, respectively.

Furthermore, one typical soil texture profile was collected in each of the one, six and twelve year old orchard blocks. Three layers were defined on the basis of the texture profiles assessed by feel in each orchard block and of the texture profile of the four year old block assessed soon after the start of sampling. The three layers were: 0-50 cm, 50-70 cm and 70-100 cm. Figure 4.2 shows a summary of the soil texture profiles for each orchard block. In addition, Table 4.2 shows the soil profile description for each orchard block.

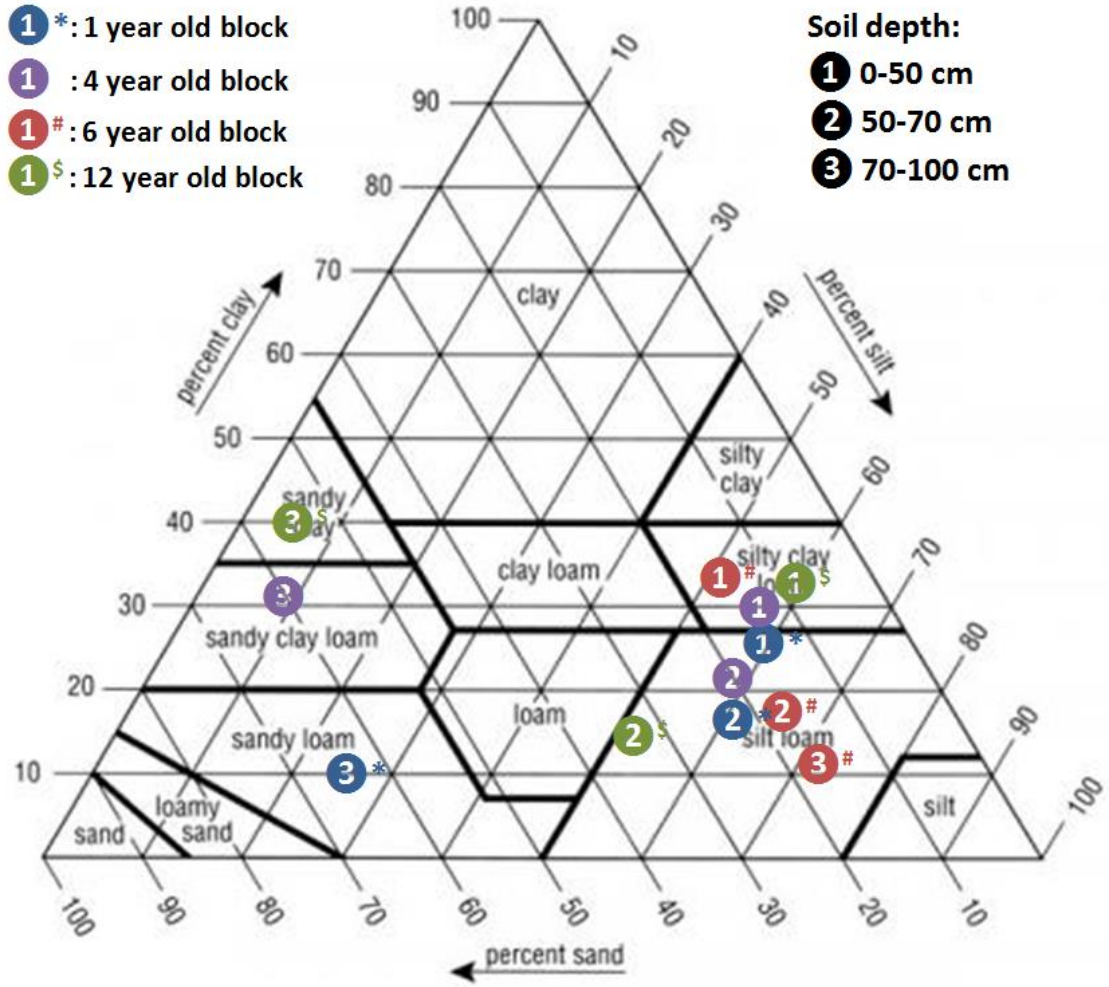


Figure 4. 3 The soil texture chart showing the texture results[4] of one soil textural profile to one meter depth for each of the four orchard blocks. When the four orchard blocks are compared, small differences in soil texture can be observed for the top 70cm of soil (❶ + ❷), while larger differences exist below 70cm soil depth (❸). Source: adapted from Thien (1979).

[4] Figure 4.3 presents the soil texture triangle originally designed by (Thien 1979). It details the various textural classes of the soil depending on the proportion of the particles of different sizes that compose the soil. These particles are divided in three groups. Sand particles have a size range of 0.05 to 2 mm, clay particles, a range of 0.002 to 0.05 mm and silt particles have a size smaller than 0.002 mm.

Table 4. 2 Soil profile descriptions of the four orchard blocks

<table>
<tr><th>1 year old</th><th>4 year old</th><th>6 years old</th><th>12 years old</th></tr>
<tr><td>A: 0-25 cm
weak medium granular structure, dark brown (7.5YR 3/2), many fine roots</td><td>A: 0-26 cm
weak medium granular structure, dark brown (7.5YR 3/2), many fine roots</td><td>A: 0-24.5 cm
weak medium granular structure, dark brown (7.5YR 3/2), many fine roots</td><td>A: 0-26 cm
weak medium granular structure, dark brown (7.5YR 3/2), many fine roots</td></tr>
<tr><td>Bt₁:25-69 cm
moderate fine subangular blocky structure, brown (7.5R 5/3), few fine roots, fine mottles</td><td>Bt₁*:26-72 cm
moderate fine subangular blocky structure, brown (7.5R 5/3), few fine roots, fine mottles</td><td>Bt₁:24.5-75 cm
moderate fine subangular blocky structure, brown (7.5R 5/3), few fine roots, fine mottles</td><td>Bt₁:26-43cm
moderate fine subangular blocky structure, brown (7.5R 5/3), few fine roots, fine mottles</td></tr>
<tr><td>Bt₂:69-89 cm
weak subangular blocky structure, gray (7.5R, 5/1), fine mottles</td><td rowspan="2">Bt₂:72-100 cm
weak subangular blocky structure, gray (7.5R, 5/1), medium mottles</td><td rowspan="2">Bt₂:75-100 cm
weak subangular blocky structure, brown (7.5R, 5/2), fine mottles</td><td>Bt₂:43-91 cm
weak subangular blocky structure, gray (7.5R, 5/1), few small to medium pumice rocks</td></tr>
<tr><td>C: 89-100 cm
weak coarse granular structure, gray (7.5, 5/1)</td><td>C: 91-100 cm
weak coarse granular structure, gray (7.5, 5/1)</td></tr>
</table>

*On rare occasions, the soil profile was showing a Bs inclusion between the A and Bt1 horizons, of 5 to 25 cm width. This inclusion was of weak fine granular structure, yellowish brown (10YR 5/6).

4.2.4. Soil-carbon data modification and comparison

The soil-carbon stocks of sites with different bulk density characteristics need to be standardized to an equivalent mass of soil, in order to avoid confounding a difference in soil quantity assessed with a difference in soil-carbon. Therefore, the minimum Equivalent Soil Mass (ESM_{min}) method developed by Lee et al. (2009) was used to correct the soil carbon stocks of each soil sample based on the smallest soil sample mass in all soil samples in the four orchard blocks. According to Mikha et al. (2013) the equivalent soil masses for each soil layer and the soil carbon stock on a fixed depth basis (without correction) are also presented for future reference. Unless indicated otherwise, the ESM_{min} based carbon stocks are used in the analyses.

In order to compare the average carbon stocks in the top meter of the soil between the four orchard blocks, the carbon stock of the 0-50 cm and 50-100 cm layers were added at the

single core sample level. Subsequently, an average for each of the ten sampling sites in each orchard block was calculated. For each orchard block, these site specific figures were averaged to calculate the average soil-carbon stock in each orchard block.

4.2.5. Statistical analysis

The statistical methods and assumptions described in Section 3.2.6 were employed in this Chapter. Descriptive statistics are shown to compare the soil-carbon stocks between orchard blocks and display their embedded variability.

Additionally, a mixed-model analysis was carried out with Genstat (VSN International 2012) in order to compare the variance components of the four orchard blocks. This analysis allowed investigating, for each orchard block, how much of the variance was due to either the variability between sampling sites, or the variability between single core samples within sampling sites. Subsequently, orchard blocks were compared according to their respective variance components.

4.2.6. Geo-statistical analyses

The geo-statistical analyses presented in Section 3.2.7 were repeated for each of the four orchard blocks separately. Semi-variograms were produced in order to determine the spatial dependency of soil-carbon stocks in each of the four orchard blocks of the chrono-sequence.

4.3. Results and discussion

4.3.1. Characteristics of soil-carbon content and bulk density in four orchard blocks

The four orchard blocks showed different carbon contents, bulk density and variability patterns. Table 4.2 and 4.3 present, for the 0-50 cm and 50-100 cm soil layers, respectively, summaries of the carbon content (%C) and bulk density (BD) characteristics of the four

orchard blocks included in the chrono-sequence. The detailed results of the bulk density and %C within sampling sites for each orchard block are displayed in Appendix 4.1.

4.3.1.1. Soil layer 0-50cm

The carbon content of the 0-50 cm soil layer varied between 1.45 %C and 2.56 %C across the four orchard blocks (Table 4.2).

The four year old orchard block showed the highest average carbon content, as well as the lowest associated standard deviation compared to the other blocks. The lowest average carbon content was observed in the twelve year old block with 1.7 %C. The average carbon contents of the four year old block were significantly different compared to the other blocks ($p<0.01$).

Table 4. 3 Carbon content (% or g carbon/ 100g soil) and bulk density (BD, g/cm^3) for the 0-50 cm soil layer in each of the orchard blocks of the chrono-sequence.
Different letters beside the %C averages indicate that values are significantly different at the 5% level. (min: minimum, max: maximum, Avg: Average, SD: Standard Deviation, SE: Standard Error, CV: Coefficient of Variation)

Tree age (years):	1		4		6		12	
Parameter	%C	BD	%C	BD	%C	BD	%C	BD
min	1.51	1.21	2.16	1.17	1.45	1.16	1.45	1.25
max	1.94	1.30	2.56	1.27	2.35	1.35	2.15	1.36
Avg (n=10)	**1.74 a**	**1.25**	**2.40 b**	**1.23**	**1.85 a**	**1.23**	**1.70 a**	**1.31***
SE	0.04	0.01	0.04	0.01	0.09	0.02	0.07	0.01
SD	0.14	0.03	0.11	0.03	0.28	0.05	0.21	0.04
CV	8.1%	2.2%	4.7%	2.4%	14.9%	4.4%	12.3%	2.8%

***The bulk density of the twelve year old block is significantly different from the three other blocks with $p<0.01$ in all three cases.

The bulk density of the 0-50 cm soil layer varied between 1.16 g/cm^3 and 1.36 g/cm^3 across the four orchard blocks. The twelve year old orchard block showed a significantly higher average bulk density compared to each of the other blocks. Bulk density showed a typically

low variability of less than 5% CV, although the six year old block showed a slightly higher CV compared to the other blocks.

In all but the four year old block, the variability between sites is within the range of the variability within sites. The four year old block therefore stands out by displaying a smaller variability between sites than within sites.

4.3.1.2. Soil layer 50-100 cm

The carbon content of the 0-50 cm soil layer varied between 0.22 %C and 0.64 %C across the four orchard blocks (Table 4.3). For this layer, the six year old orchard block showed the highest average carbon content (0.47 %C). However, the four year old block showed the highest standard deviation of the carbon content compared to the other blocks. Similar to the 0-50 cm layer, the lowest average carbon content was observed in the twelve year old block with 0.27 %C. This average carbon content was significantly different compared to that of the other blocks. Overall, large variations within each block were observed in the 50-100 cm soil layer.

Table 4. 4 Carbon content (% or g carbon/ 100g soil) and bulk density (BD, g/cm^3) for the 50-100cm soil layer in each of the orchard blocks of the chrono-sequence.
Different letters beside the %C averages indicate that values are significantly different at the 5% level. (min: minimum, max: maximum, Avg: Average, SD: Standard Deviation, SE: Standard Error, CV: Coefficient of Variation)

Trees age (years):	1		4		6		12	
Parameter	%C	BD	%C	BD	%C	BD	%C	BD
min	0.27	1.14	0.33	1.19	0.27	1.13	0.22	1.15
max	0.43	1.30	0.64	1.35	0.57	1.37	0.32	1.30
Avg (n=10)	**0.36 a**	**1.20**	**0.43 ab**	**1.28***	**0.47 b**	**1.21**	**0.27 c**	**1.23**
SE	0.02	0.02	0.03	0.02	0.03	0.02	0.01	0.02
SD	0.05	0.05	0.10	0.05	0.09	0.07	0.03	0.05
CV	15.1%	4.2%	24.3%	3.8%	19.5%	5.5%	12.3%	4.1%

*****The bulk density of the four year old block is significantly different from the three other blocks with $p<0.05$ in all three cases.

The bulk density of the 50-100 cm soil layer varied between 1.13 g/cm^3 and 1.37 g/cm^3 across the four orchard blocks. This bulk density range is about the same as found for the 0-50 cm layer. The four year old orchard block showed a significantly higher average bulk density compared to each of the other blocks. Bulk density showed a slightly higher variability than the 0-50cm layer, although coefficients of variation were between 3.8% and 5.5%. Again, the six year old block showed a slightly higher CV compared to the other blocks.

In all but the four year old block, the variability between sites is within the range of the variability within sites. The four year old block therefore stands out by displaying a larger variability between sites than within sites for the 50-100 cm layer. Potential reasons for this difference are discussed in Section 4.3.2.

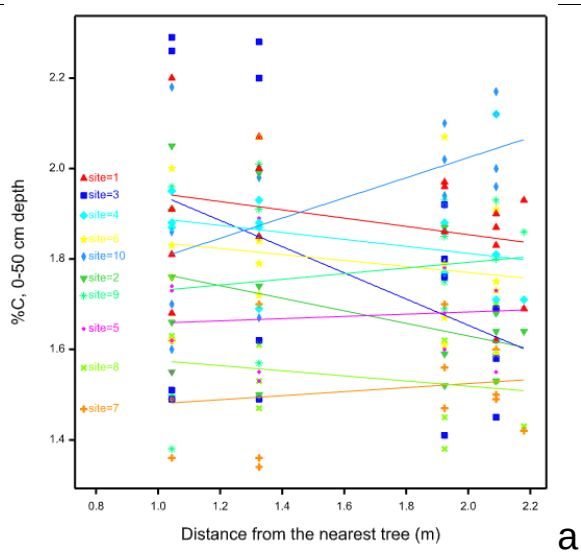
Overall, important efforts to seek homogeneity both above and below ground (except for tree age) within each of the four orchard blocks generally resulted in low levels of variation. In particular, the carbon contents of the 0-50 cm layers showed coefficients of variation lower than 15% for all blocks. The six year old orchard block is the most variable for this layer compared with the other blocks. However, the 50-100 cm soil layer was more variable, with coefficient of variations between 12.3% and 24.3%. Finally, the variability pattern of the four year old block contrasts with that of the other blocks. Potential reasons for this difference are discussed in Section 4.3.3.

4.3.2. **Carbon changes as a function of the distance to the nearest tree**

This section repeats, for the four blocks of the chrono-sequence, the analysis of the variation of carbon content within sampling sites, either relative to the wheel track or as a function of the distance to the nearest tree that is presented in Section 2.3.2.3 for the four year old orchard block.

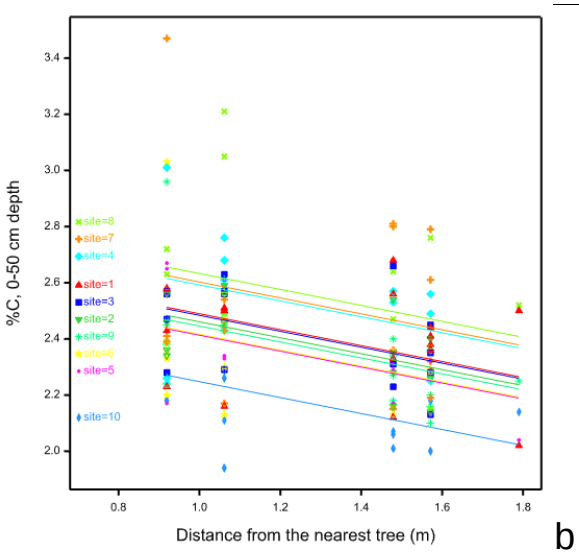
Firstly, for all but the four year old orchard block, no statistically significant difference was found between samples taken between and outside the wheel tracks. Furthermore, for all sites in all orchard blocks, the change in soil-carbon content as a function of the distance to the nearest tree was investigated using the same linear regression model approach as in Section 3.3.2.3. The same three steps of the procedure were repeated for each orchard block. Figure 4.3 shows the linear regressions for the top 50 cm of each of the four orchard blocks. While Fig 4.3b was already presented in Chapter 3, it is repeated here for comparison and convenience.

For each orchard block, the results are shown in Fig. 4.3 for the 0-50 cm layer. The step of the procedure presented depends on the statistical significance of its improvement of the explained variance compared to the previous step. For example, when the third step (different intercepts and slopes) was not significantly improving the fit of the model to the data, which is materialised by a statistically-significant-from-zero increase in the % variance explained by the model, the second step (different intercepts and common slopes) is presented, such as in Fig. 4.3b and 5.3c. In this particular case, the common slope of the regression lines is given below the figure (Fig. 4.3b and 5.3c), as well as, in brackets, the p value related to the statistical significance of the difference of the slope from zero. No trend was observed for the 50-100cm layer and so the data are not presented).



a

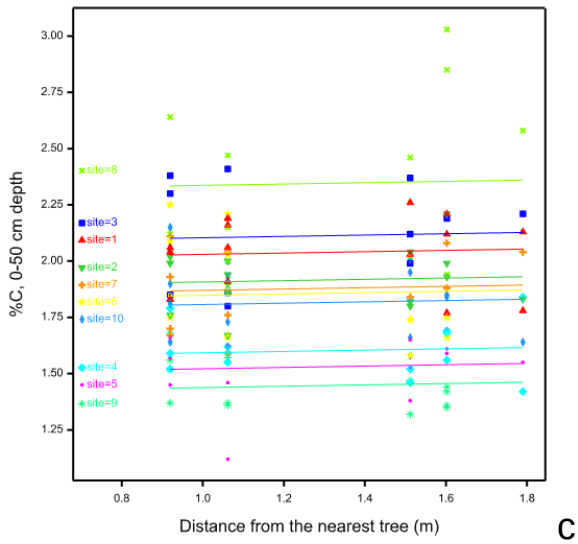
Model explains 35.4% of variance.



b

Model explains 26.5% of variance.

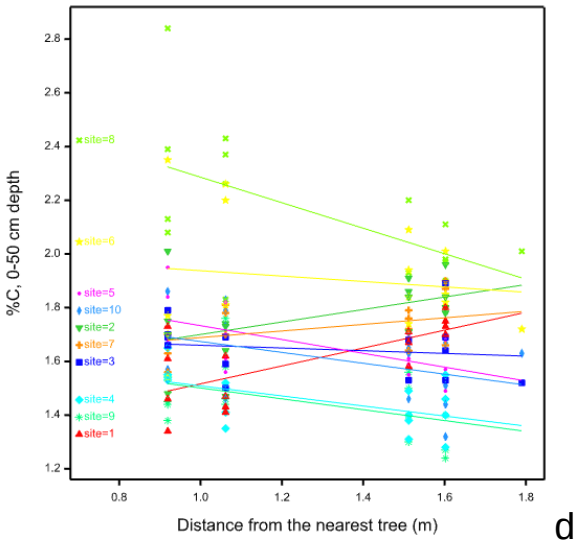
Slope = - 0.28 %C/m ≠ 0 (p<0.001)



c

Model explains 62.1% of variance.

Slope = 0.03 %C/m =0 (p=0.59)



d

Model explains 67.9% of variance.

Figure 4. 4Trend in soil-carbon content as a function of the distance to the nearest tree for the 0-50 cm depth layer. (a) 1 year old block, (b) 4 year old block, (c) 6 year old block, (d) 12 year old block. Each sampling site is represented by a different symbol and colour. The pattern of decreasing soil-carbon content with distance to the nearest tree was only found in the 4 year old orchard block. Note that the scale of both axes is specific to each orchard block.

The model's predictions were improved when allowing different slopes for each of the sampling sites' regressions for the one year old and the twelve year old blocks. Within each

of these blocks the correlation between soil carbon content and distance to the nearest tree varied between sampling sites and no general rule for this relationship can be determined.

On the other hand, the models' predictions were best for regressions with common slopes in the four year old and the six year old blocks. However, in the six year old block, the common slope was not significantly different from zero. This shows that soil carbon content does not change as a function of the distance to the nearest tree, as opposed to the four year old block.

Overall, these results indicate that a decreasing trend of carbon content as a function of the distance to the nearest tree found in the four year old orchard block does not occur in the other orchard blocks. Therefore in general, soil-carbon content is not necessarily correlated to the distance to the nearest tree in apple orchards.

However, as discussed in section 3.1, given the importance of roots for the origin of soil carbon (Rasse et al. 2005) and its distribution in the soil profile (Post and Kwon 2000) it is possible that the pattern found in the four year old block could be found in orchard blocks of a similar age. This hypothesis could be explained by the growth of tree roots closer to the tree during the first four years following tree planting, whereas this trend might then disappear after due to further exploration of the entire ATA by the tree roots. This could explain why the 6 year old orchard block shows trends, even though it is not statistically significant from zero. However, these results would need to be repeated to determine if a similar pattern is found in other orchard blocks of a similar age. If this were the case, a fixed age range might be necessary to stratify sampling between and outside the wheel track. For younger or older orchard blocks, samples would only need be taken randomly within each sampling site. Until these results are confirmed, taking the same number of sample between and outside the wheel tracks is necessary when measuring soil-carbon stocks in apple orchard blocks.

4.3.3. **Characteristics of the carbon stocks in the four orchard blocks**

The soil carbon stocks for the four orchard blocks, using both the fixed depth (FD) and the minimum equivalent soil mass (ESM_{min}) methods, are presented in Table 4.4. For clarity, only their respective standard deviations are also presented. In order to obtain the soil-carbon stocks of the 0-100 cm soil layer, the soil-carbon stocks 0-50 cm and 50-100 cm layers were added at the individual core sample level[5].

Table 4. 5 Soil-carbon stocks (in tons of carbon per hectare, t C/ha) for the four orchard blocks, for both the 0-50cm and 50-100cm soil layers.
Different letters indicate statistically significant differences at the 5% level within each individual column separately. ESM_{min} (0-50 cm) = 5806 tons of soil/ha. ESM_{min} (50-100 cm) = 6076 tons of soil/ha. (FD: Fixed Depth method, ESM: Equivalent Soil Mass method, SD: Standard Deviation).

Tree age (years)	0-50 cm layer				50-100 cm layer			
	Carbon stock FD (t C/ha)	SD (±)	Carbon stock ESM (t C/ha)	SD (±)	Carbon stock FD (t C/ha)	SD (±)	Carbon stock ESM (t C/ha)	SD (±)
1	108.7 a	8.8	101.0 a	8.2	21.2 a	2.6	28.9 a	1.3
4	147.9 b	7.0	139.4 b	6.6	27.2 b	5.6	33.8 b	0.6
6	113.9 a	14.8	107.6 a	16.0	28.5 c	5.3	38.9 bc	1.3
12	110.9 a	12.7	98.5 a	12.1	16.8 ad	2.4	26.3 d	0.8

Soil-carbon stocks across the chrono-sequence varied between 98.5 ±12.1 and 139.4 ±6.6 t C/ha when calculated on an equivalent soil mass basis. There was no statistically significant difference at the 5 % level between 0-50 cm layers of the 1-year-old, the 6-year-old and the 12-year-old orchard block. However, the four year old block was significantly different from the other blocks for this layer. Furthermore, the six year old block showed the highest standard deviation compared to the other blocks. These findings are true regardless of the method employed for the calculation of soil-carbon stocks.

[5] While these layers have been added, the standard deviations of the 0-100 cm soil layer are not the result of applying the usual formula: $\mathrm{SD}_{0-100} = \sqrt{(\mathrm{SD}_{0-50}^2 + \mathrm{SD}_{50-100}^2)}$ because the addition of the soil-carbon stocks of the 0-50cm and 50-100cm soil layers happened at the individual soil sample level.

In the 50-100 cm layer, soil-carbon stocks across the chrono-sequence varied between 26.3 ±0.8 and 38.9 ±1.3 t C/ha when calculated on an equivalent soil mass basis. There was no statistically significant difference between the four and six year old blocks for this layer. However, there were statistically significant differences between all other orchard blocks for this layer.

Calculating soil-carbon stocks based on equivalent mass (Lee et al. 2009) as opposed to the fixed depth method importantly decreased the carbon stocks in the 0-50 cm soil layer, and increased the carbon stocks of the 50-100 cm layer. This is because the minimum ESM method recalculates carbon stocks based on the lowest soil mass for each layer. Furthermore, the standard deviations of the 50-100 cm layers were importantly decreased as a result of a decrease in the variation in soil masses compared within each orchard block. This suggests that important variations in soil masses occur within orchard blocks. Therefore, the soil-texture variations observed between orchard blocks for the lower part of the 50-100 cm soil layer (Fig. 4.2) could also occur within each of the orchard blocks. This is consistent with the higher variability at depth observed by Syswerda et al. (2011).

Soil carbon stocks of the 0-100c m layer were between 127.7 ±14.7 and 175.1 ±10.8 t C/ha. The same statistically significant differences were observed regardless of the carbon stock calculation method. Only the soil-carbon stock of the four year old orchard block was significantly different from the other blocks. This is similar to the results for the 0-50 cm layer, most likely because the 0-50 cm layer embeds on average 79 ± 3% of the soil-carbon stocks of the 0-100 cm layer for all samples. In a similar way to the 0-50 cm layer, the six year old block showed the highest variation compared to the other blocks.

Table 4. 6 Soil-carbon stocks (t-C/ha) of the 0-100 cm soil layer for the four orchard blocks. Different letters indicate that values are significantly different at the 5% level within each individual column separately. (FD: Fixed Depth method, ESM: Equivalent Soil Mass method, SD: Standard Deviation).

Tree age (years)	0-100 cm depth			
	Carbon stock FD (t-C/ha)	SD (±)	Carbon stock ESM (t-C/ha)	SD (±)
1	130.0 a	9.9	128.7 a	9.9
4	175.1 b	10.8	172.4 b	11.1
6	142.4 a	19.2	140.9 a	19.7
12	127.7 a	14.7	125.5 a	14.1

The four-year-old orchard block had a much higher soil-carbon stock than the three other blocks. The associated statistically significant difference at the 5% level could mean that soil-carbon stocks in soil of the same soil type and texture and within a maximum distance of 500 meters show an important natural variability. However, this is unlikely, because soil texture is one of the major controls of carbon stocks in soils (Jobbagy and Jackson 2000; Lutzow et al. 2006; Schmidt et al. 2011). Therefore, this difference suggests that something different happened to either this orchard block or the three other blocks. After discussion with the orchard manager of the four, six and twelve year old blocks, it became clear that two potential events could have increased the soil carbon stock of the four year old block. First, this block was converted from grazing pasture to an orchard at least 10 years earlier than the three other blocks. Due to the fact that root turnover in the soil represents the main input of carbon into the soil, especially at depth (Schmidt et al. 2011), it is possible that having trees on the land for a longer time period favoured soil-carbon sequestration. However, if this is the case, the large increase in soil-carbon stocks could have occurred in the first ten years after the conversion to orchard. This is not consistent with the fact that the three other blocks with lower soil-carbon stocks were all converted to apple orchard at least 20 years before planting of the current trees.

Secondly, a flood occurred in the area in the mid 1980s, and the deposition of alluvial sediments that might have been rich in carbon could have modified the carbon content of the soil, and therefore increasing the soil-carbon stock. Additionally, this flood could also explain the unusual variability pattern found in the four year old block compared to the other blocks, at least in the 0-50 cm layer. The lower variability between sites than within sites there could have been the result of a higher level of homogenisation of the soil by the flood waters, while within site variability would be governed by tree scale phenomena. Furthermore, the standard deviations between sites for the 0-50 and 50-100 cm layers are similar (0.11 versus 0.10 tC/ha, respectively). This would suggest a similar effect of the flood on both soil layers. Therefore, if the tree scale phenomena were to have had little effect on the soil-carbon stock variability in the 50-100 cm layer, there would be little reason for the within-site variability to be higher than between sites. However, it is important to note that these flooding effects remain uncertain, as the orchard manager is not sure which parts of the orchard block were most affected.

Moreover, the levels of variation in soil-carbon stocks can be very different for different orchard blocks, even though the same sampling procedure was carried out for all orchard blocks. This indicates that generalizing a particular level of variation to any orchard block, from the four orchard blocks in this study, is not possible. In other words, the results here suggest that each individual orchard block has its own specific level of variation. In this case, sampling at the level of the orchard block is necessary in order to monitor soil-carbon stocks in apple orchards. Alternatively, variations in soil-carbon stocks could occur on different scales than the orchard block; for example according to the area affected by floods. More investigations would be needed to test this hypothesis.

However, the one, six and twelve year old blocks were not significantly different at the 5 % level. This conclusion is also valid at the 10% statistical level. Therefore, the carbon stock of the 0-50 cm as well as the 0-100 cm soil layers did not follow a particular trend with regards to the time since the establishment of the contemporary orchards. This can be interpreted in

several ways. First, one can deduce that the differences between soil-carbon stocks over 12 years are too small and the rate of change is too slow compared to the sampling campaign carried out in order to detect a statistically significant difference between them. In other words, either not enough samples were taken or the samples were not arranged in an optimal way that allowed reaching a high enough precision of the average soil-carbon stock for each of the orchard block. Secondly, it is possible that current management practices in these apple orchards achieve the maintenance of the soil carbon stocks over time in these three orchard blocks without change. This could be explained by the fact that there is an equilibrium between soil carbon inputs and soil carbon outputs and therefore that this soil-climate-land-use combination could have reached soil carbon saturation, the upper limit of soil carbon sequestration (Six et al. 2002; Stewart et al. 2007; Stewart et al. 2008).

The current sampling regime does not allow deciding which is the most likely interpretation because either the level of variability is too high such as in the six year old block, or the difference between means is too small compared to the change observable, such as between the one year old and the twelve year old blocks.

Finally, despite the sampling effort, it was not possible to observe a statistically significant change in soil-carbon stocks over 12 years along the chrono-sequence. This would imply that more samples need to be collected, or that more time should be allocated for a bigger change to take place, in order to observe a statistically significant change over this time period. Alternatively, it is possible that there was no change within this time period, and therefore that the current orchard-management practices, maintain the soil-carbon stocks in a stable state. Therefore, for the verification of this maintenance, the soil-carbon stocks should be sampled once at the beginning and once at the end of the orchard cycle, which is usually equivalent to 15 to 20 year intervals.

4.3.4. Spatial characteristics of carbon stocks

A spatial analysis of soil-carbon stocks was carried out in the four orchard blocks using semivariograms. Only the 0-100 cm soil layer was assessed, because it is the most relevant layer to assess changes in soil carbon stock, as discussed in section 3.3.2.4. In Chapter 3, the spatial correlation of soil carbon stocks extended to more than 60 meters for the 0-100 cm soil layer. Therefore, for both soil layers, a block sampling grid was best suited to account for the spatial and non spatial variations in the soil of the four year old block.

However, as highlighted in Section 3.4.2, the soil carbon stock data used for the analyses in Chapter 3 were not presented on an equivalent soil mass basis. In the present Chapter (See section 4.2.4), this correction has been applied to all soil carbon stocks data of the four orchard blocks. The results of the spatial analysis are presented in Figure 4.4

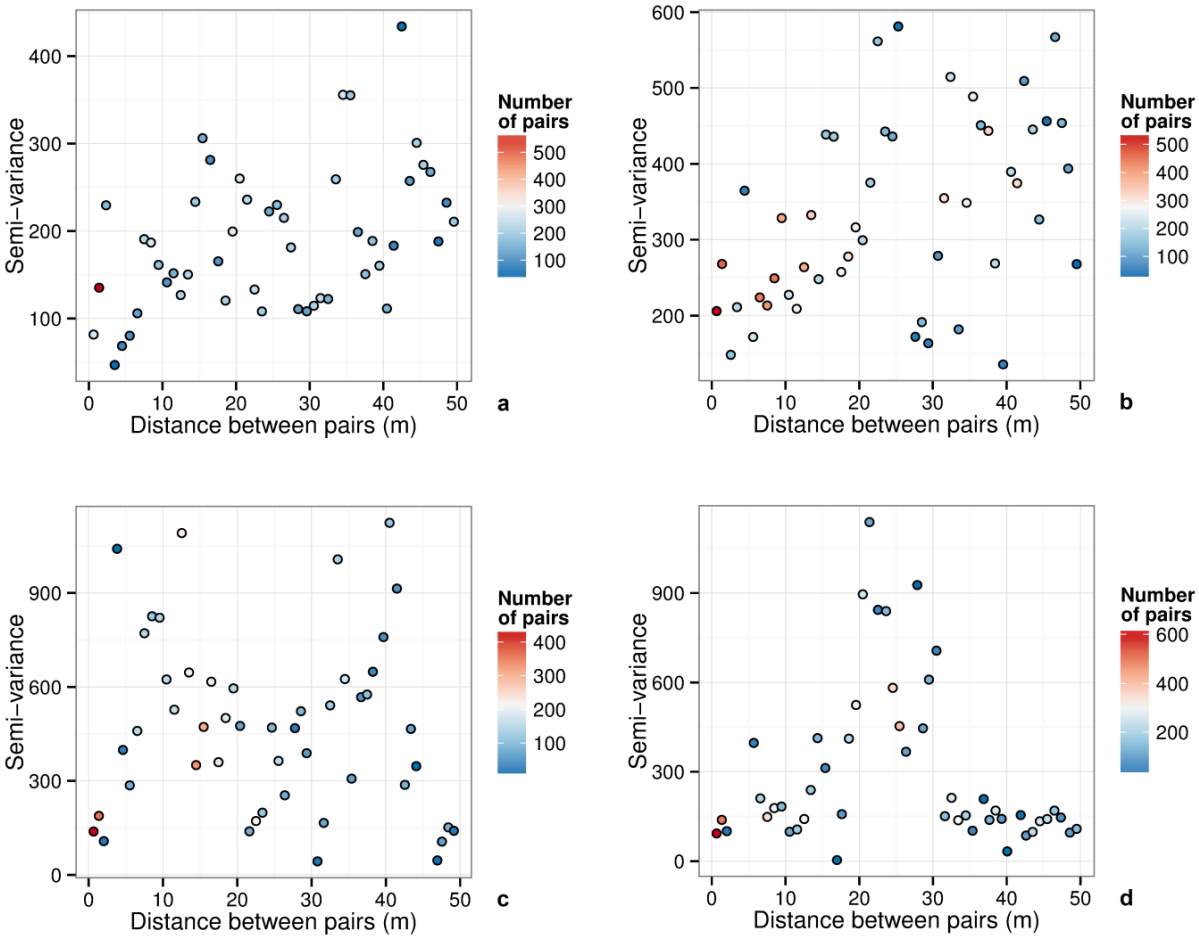


Figure 4. 5 Semi-variogram of experimental data (points) for the 0-100 cm depth for the one year old (a), the four years old (b), the six year old (c) and the twelve years old (d) orchard blocks . The colours of the dots indicate the number of sample pairs for each spacing group. No model with sufficient representativeness could be fitted to the data.

For all orchard blocks, it was generally not possible to fit a representative model to the data. This indicates that the soil carbon stocks are not noticeably spatially auto-correlated. In other words, the variability in soil-carbon stocks in the 0-100 cm layer of the four orchard blocks of this Chapter depends on many factors but the distance between the samples.

However, in the one year old block (Fig 4.4a), there is a weak tendency for spatial structure, with a range[6] ≈ 5 m. This could be due to the homogeneity of the soil of this newly planted orchard block. Indeed, after old trees were pulled out, the soil was homogenised through root ripping as well as light ploughing to prepare the soil for tree planting. This

[6] The “range” is the distance at which 95% of the maximum semi-variance is reached.

homogenisation would then reduce the influence of other factors on the overall variability of soil carbon stocks, and this would reveal the spatial influence on this variability.

In the four-year-old orchard block (Fig 4.4b), the correction of soil carbon stocks for equivalent soil mass modified the pattern of the semi-variogram. This highlights the importance of reporting soil carbon stocks data for equivalent soil mass rather than fixed depth, as highlighted in Section 4.2.4.

It is interesting to note that for the twelve-year-old orchard block (Fig. 4.4d), two structures seem to appear. Up to a distance of approximately 30 meters, the variance seems to increase with the distance between samples. However, beyond this distance of 30 meters, the variance is low and stable. This could indicate the presence of a spatial structure within the orchard block. For example, an area of a different soil texture could be present in the middle of the orchard block. Further investigations are however required to determine the reasons for this phenomenon.

In view of these results, a “block sampling” grid (see Section 3.3.2.5) would be best suited to account for the variability in soil carbon stocks in apple orchard blocks.

4.3.5. Measuring changes in soil-carbon stocks at the orchard block level

In Chapter 3 the minimum sampling requirements to observe a statistically significant change over time in the carbon stock of the soil were calculated for the four year old orchard block. However, the carbon stocks of other orchard blocks investigated in this Chapter proved to be more variable. Therefore, this Section presents an evaluation of the minimum sampling requirements in order to observe a statistically significant change over time in the most variable block of the chrono-sequence. As explained in Section 4.3.4, the 0-100 cm soil layer is the relevant layer for measuring and monitoring soil carbon stocks. However, the analysis of the 0-50 cm soil layer is also presented for illustration and comparative purposes.

The six year old orchard block presents the most variable carbon stock for both the 0-50 cm (Table 4.4) and the 0-100 cm (Table 4.5) soil layers. The variability of the six year old block stands out both in an absolute way, as shown by its highest standard deviation compared to the other orchard blocks (Table 4.5), as well as in a relative way, when the standard deviation is expressed as a proportion of the carbon stock mean.

As presented in Section 3.3.3, for both the 0-50 cm and 0-100 cm depth layers, the minimum number of soil samples required to estimate the carbon stock at the tree scale was calculated by mathematically pooling a certain (even) number of randomly selected samples within each site. For the reasons discussed in Section 4.3.2 equal numbers of soil samples were selected from between and outside the wheel tracks. For each number of pooled samples, an average variance of the mean soil-carbon stock for the orchard block was calculated based on 10 000 simulations, accompanied with the associated upper and lower 95% confidence intervals. The results are presented in Figure 4.4.

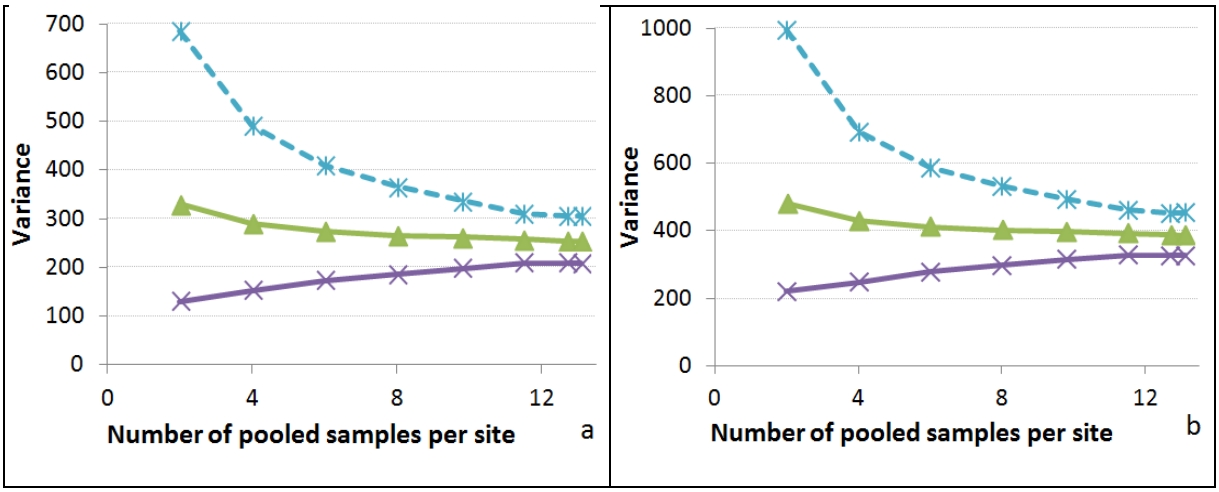


Figure 4. 6 Evolution of the variance of the mean carbon stock (green triangles) and 95% confidence interval (lower: purple crosses, upper: turquoise stars) for the 0-50cm (a) and 0-100cm (b) layer as a function of the number of pooled core samples per site for the 6 year old orchard block. NB: Scales of variance axes are different.

Analogous to the results in Chapter 3, the pooling of four samples within each site instead of two provides a reduction of the variance of the mean for the orchard block. However, this decrease in variance is much smaller, relative to the mean of the block, than that observed for the four year old orchard block (15% versus 32%). It is therefore possible that pooling two

samples per sampling site is enough when sampling the 0-100 cm layer in this orchard. However, it should be noted that for two samples pooled per sampling sites, the 95% confidence interval of the variance is large, with an upper limit more than double the variance estimate. Therefore, assuming that such variance will occur every time the orchard block is sampled is highly uncertain. In order to reduce that uncertainty, more core samples could be taken and pooled within each site.

Additionally, these estimates of variance were used to calculate the number of sites required to observe a particular change over time for both the 0-50 and 0-100 cm soil layers (Fig. 4.5), in the same way as presented in Section 3.3.3. However, while the average variance is used in this Chapter to calculate the number of sites required, a conservative approach would be to carry out the same analysis using the upper limit of the confidence interval rather than the average variance. The subsequent results would then express the absolute maximum number of sampling sites required to observe a given change in the 6 year old orchard block. Because of the precursory nature of the analysis presented here, it was decided simply to use the average variance.

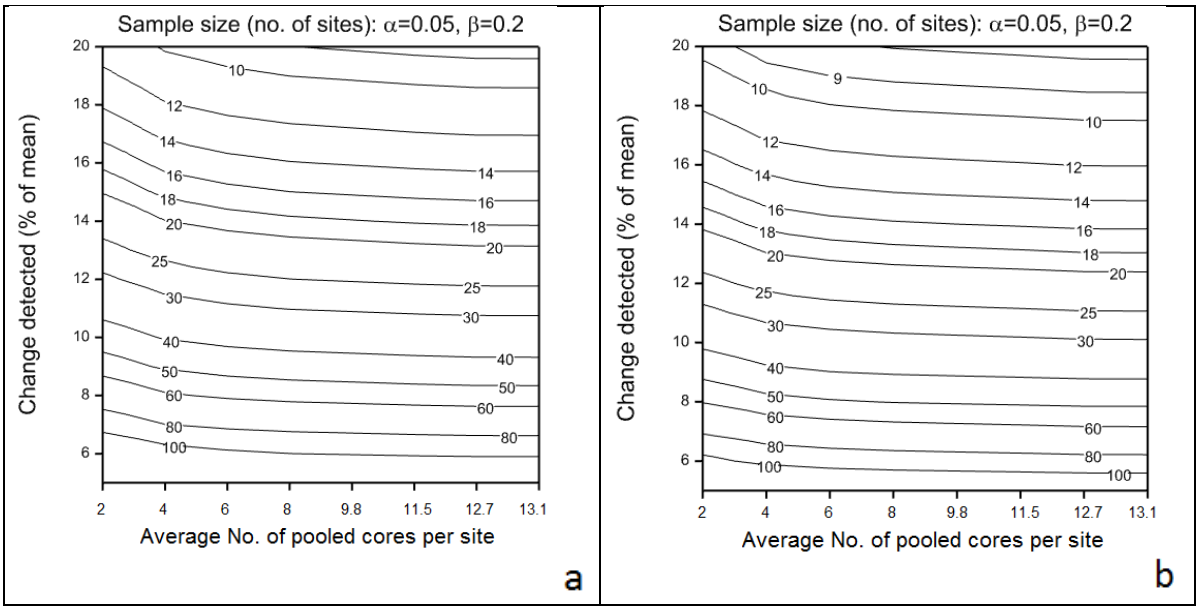


Figure 4. 7 Contour plots for the 0-50cm (a) and 0-100cm (b) soil layers, expressing the minimum number of sites required (number interrupting the curves) in the 6 year old orchard block as a function of the average number of pooled samples (cores) per site successfully sampled across the orchard block (X axis) and the change detected as a % of the mean carbon stock of the orchard (Y axis),. "α" is the statistical significance level and "β" = 1-statistical power.

For the 0-100 cm layer, 39 sites would be required at a sampling rate of two samples per site (78 core samples in total) to observe a change of 10% of the mean. This is the optimum sampling design in terms of total number of samples. On the other hand, at a rate of 8 samples per site, sampling 32 sites is necessary (256 core samples total). Therefore, increasing the number of cores per site has a very limited effect on the number of sites to be sampled. A similar relationship occurs for the 0-50 cm soil layer. In comparison to the "minimum sampling requirements" results of Section 4.3.3 of nine sites with four cores per site to observe a 10% change, then 34 sites would be required in the six year old orchard block. In total, this equals 136 soil samples. The same change could be observed by taking two samples per site and reducing by 43% the total number of samples collected. However, moving the equipment from site to site is certainly the most time consuming operation, and it may be preferable to take more cores per site. In addition, this would allow more certainty in the variance estimate in view of the second sampling campaign, some 15 to 20 years later.

Furthermore, it is interesting to note that, whatever the rate of core samples per site, sampling the 0-100 cm layer requires fewer sites than sampling the 0-50cm layer. This is due to the reduced variability in soil-carbon stocks in the 50-100 cm soil layer, which makes the variance relative to the mean smaller for the 0-100 cm layer compared to the 0-50 cm layer.

The realistically maximum sampling regime for research purposes as presented here of 10 sites, with an average of 13.1 samples per site successfully collected allowed detection of a change in carbon stocks of 18% of the mean for this orchard block. Therefore, the investigative sampling strategy carried out in this experiment in order to learn about the variability of soil carbon stocks in apple orchards was not well adapted to measuring small changes in these stocks. As discussed in Section 3.3.3, taking fewer samples at the ATA scale and sampling more ATAs is a more suited to detect small changes.

Overall, this experiment confirms that the level of variability determines the number of samples required to observe a given change in the soil-carbon stock. Therefore, it is not possible to define a standard sampling regime applicable to all orchard blocks. However, a change of 10% of the mean (140.9 ±19.7 t C/ha) could potentially be observed by collecting a total of 78 samples for carbon content, assuming that 39 bulk density profiles per orchard block are also collected. These findings are similar to the results of Don et al. (2007), who suggest a ratio of 60% carbon content samples to 40% bulk density samples based on the systematic sampling of two grassland sites. Nevertheless, according to Wendt and Hauser (2013), if more than two soil layers are sampled, it is possible to estimate soil-carbon stocks on an equivalent soil mass basis by simply weighing the soil samples, instead of sampling for bulk density.

In conclusion, the pooling of the minimum number of samples within each site and sampling a high number of sites seems to be the optimum strategy. However, this increases the uncertainty of the variance estimated for the second sampling campaign. Potentially, more sites would need to be sampled in the second sampling campaign. Alternatively, it would be possible to wait an extra apple orchard cycle (15 to 20 years) before sampling again. However, waiting 30 to 40 years before assessing practices would represent a high risk of realising that a decrease in soil-carbon stocks was occurring regardless of the carbon sequestering practices implemented on the orchard, and could result in high mitigation costs.

4.3.6. Cost of sampling

The most cost-effective approach for various sampling strategies of combinations of sites by samples per site was determined following the same methodology and assumptions presented in Section 3.3.4. Only the 0-100 cm layer was considered. The results are presented in Figure 4.6.

In the specific condition of the six year old orchard block assessed in this Chapter, observing a change of 10% (14.1 t C/ha) in soil carbon stocks would require sampling 39 sites at a rate

of two samples per site. Assuming that one bulk density profile is also collected in each site, the cost of one sampling campaign would be NZ$ 4,710. Monitoring soil carbon stocks every 20 years in this block would cost NZ$ 9,420 assuming an average change of 0.7t-C/ha/year. The equivalent figure when sampling 34 sites at a rate of four samples per site is NZ$ 12,280.

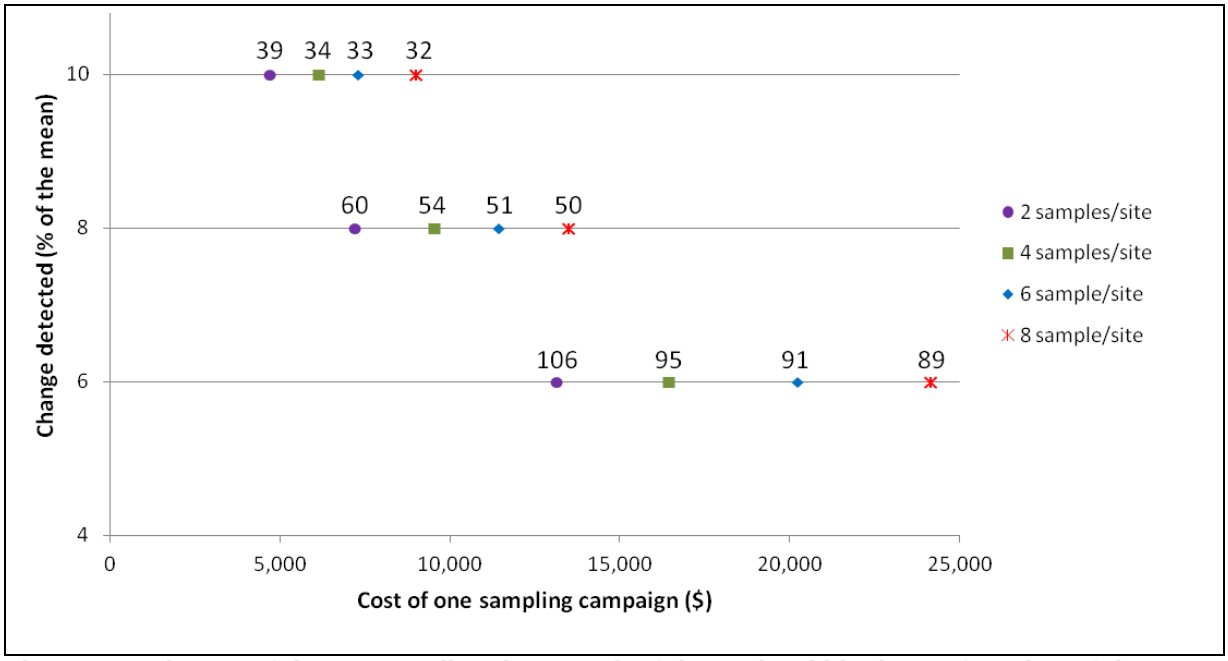


Figure 4. 8 Change of the mean soil carbon stock of the orchard block as a function of the cost of one sampling campaign, for the 0-100 cm layer, for different sampling regimes that have to be repeated in order to observe a change. The numbers situated above the data points are the number of sampling sites required within the orchard block for a particular number of core samples per site.

Following the assumption of a constant yield of 50 tons of export apples/ha, as well as the carbon change over time and the cost stated above for 39 sites and two samples per site, the price premium required to compensate for the cost of monitoring corresponds to NZ$0.2/carton of apples guaranteed over a period of 20 years. This represents an increase of approximately 1% in the price of a carton of apples (18kg) at the ship side (FAS) in a New Zealand port. The equivalent figure for 34 sites and four samples per site is NZ$ 0.26/carton of apples.

Measuring and monitoring soil carbon stocks in apple orchards at the block scale is therefore affordable.

4.4. Conclusions and perspectives

4.4.1. Spatial variability in soil-carbon stocks in similar apple orchard blocks of different ages

The variation in soil-carbon stocks can be very different for different orchard blocks. The variability levels found in the orchard block of interest in chapter 3 were not found in the other orchard blocks of the chrono-sequence. Each individual orchard block is affected by its specific level of variation and sampling at the level of the orchard block is necessary when monitoring soil-carbon stocks in apple orchards. In general, the variations in soil carbon stocks were non-spatial, which would enable the use of a “block sampling” strategy.

The six year old orchard block was the most variable compared to the other blocks and was therefore used to determine the sampling requirements for monitoring soil carbon stocks considering its relatively higher level of variability (CV=14% for the 0-100 cm layer). Analogous to the results of Chapter 3, a sampling strategy adapted to variability of soil-carbon stocks is necessary if a change is to be observed over time. An example protocol is described in Box 4.1. Pooling the minimum number of samples within each site and sampling a high number of sites seems to be the optimum strategy. However, the fewer samples per site in the first sampling campaign, the higher the uncertainty of the estimated variance for the second sampling campaign.

In addition, the carbon content of the 0-50 cm soil layer was correlated with the distance to the nearest tree in the four and six year-old orchard blocks and increased closer to the tree trunks; however, this increase was statistically significant in the four year-old block alone. This could be due to the transient growth characteristic of the roots of young apple trees, growing in a bowl shape from the root shank, and exploring more soil as the trees age (Hughes and Gandar 1993). Beyond four years after planting, the roots would have explored the entire ATA.

4.4.2. Suitability of a chrono-sequence to observe a statistically significant change of soil-carbon stocks over time in apple orchard blocks.

The analysis of the chrono-sequence with the sampling strategy used in this study did not allow observing a statistically significant change in soil carbon stocks. The four-year-old orchard block had a much higher soil-carbon stock than the three other blocks potentially because of the pre-history of this block and possibly because it was affected by a flooding in the 1980s. This demonstrates how small differences in “soil forming factors” (Stevens and Walker) can result in incomparable sampling sites, and the risk of using a chrono-sequence to assess changes in soil carbon stocks over time.

Excluding the four-year-old orchard block, and despite an important sampling effort, it was not possible to observe a statistically significant change in soil-carbon stocks over the 12 years of the chrono-sequence. Two interpretations are possible:

Firstly, following the assumption that a change in soil carbon stocks actually occurs over the 20 year lifespan of an orchard block, the current sampling strategy needs to modified to allow a sufficient level of statistical power (levels of statistical power of the sampling strategy are lower than 0.5) in order to observe a statistically significant change.

Secondly, based on the results, it is a possibility that current management practices are sustainable and are resulting in the maintenance of the soil carbon stocks over time in apple orchards, rather than a change. In this specific case, measuring and monitoring soil carbon stocks might not even be required to insure the sustainability of soil-carbon stocks in apple orchards. However, more research is required to confirm that this result is true and can be generalised, including testing these findings over a range of soils, climates and management practices.

4.4.3. Practical and economic feasibility of a standard protocol to measure and monitor soil-carbon stocks in apple orchards

It is not possible to define a standard sampling regime applicable to all orchard blocks because of site specific levels of variability. The number of samples to take would have to be adapted to the specific orchard block under study.

However, a change of 10% of the mean in the most variable six-year-old block could in theory be observed by collecting a total of 78 samples for carbon content, and 39 bulk density profiles. Therefore, monitoring soil carbon stocks in this block in order to observe a 10% change, by carrying out two sampling campaigns that are 20 years apart, would cost NZ$ 9,420 assuming an average change of 0.5% of the soil-carbon stock per year (0.7t-C/ha/year). This cost represents approximately an increase in 1% of the price of a carton of apples FAS in New Zealand.

While this cost seems small, and implementing such a sampling campaign at the scale of the industry seems affordable, careful consideration needs to be given to who pays for the cost of monitoring. Indeed, maintaining and increasing soil-carbon stocks has numerous benefits for the atmosphere, soil health and fertility, and the sustainability of food production systems. These factors need to be taken into account when attributing the costs of monitoring.

In future, if demonstration of a maintenance or reduction in the carbon footprint of apples is required for shelf access in global supermarkets, this research has shown that monitoring soil carbon stocks is a credible option for the New Zealand apple industry. Financial incentives, such as price premiums for eco-credentialed food products, could support the routine monitoring of soil-carbon stocks which would inform the carbon footprint of apples. Last but not least, routine monitoring of soil-carbon stocks would provide invaluable data to improve the scientific understanding of changes in soil-carbon stocks and to calibrate models increasingly suggested and used to inform policy decisions.

In a similar way as for the soil carbon stock, few data are available about the standing stocks of carbon in the woody biomass of apple orchards, and there are few methods to quantify this biomass rapidly and cost effectively. Furthermore, this biomass stores carbon temporarily and an agreement on a common methodology to account for temporary storage in LCA and CF has not yet been reached (Brandão et al. 2013). Yet, taking this temporary carbon storage into account could affect the results of LCA and carbon footprint studies (Levasseur et al. 2012). Chapter 5 considers the relevant literature, highlights the requirements to integrate woody biomass data of perennial cropping systems in LCA and CF and proposes a method to obtain reliable data to account for biomass carbon stocks in apple orchards.

Box 4.1. Indicative protocol to measure and monitor soil-carbon stocks in an apple orchard block

The aim of this protocol is to provide an example of how to measure and monitor soil-carbon stocks in an apple orchard block. A coefficient of variation of 14% is assumed for the carbon stocks in the orchard block assessed, as well as a cost of NZ$ 4,710 per sampling campaign to detect a change of 10% of the mean soil carbon stock at 20 years intervals. This protocol should be adapted to the specific characteristics of the area under study, in particular the variability of soil carbon stocks that determine the sampling intensity. In the future, this protocol could be used for purposes such as carbon accounting and footprinting. More details are available in the text of this chapter.

1. **Delimit the area of assessment**
    a. The area of assessment should be limited to one orchard block including a combination of one cultivar and one rootstock, all under the same management practices.
    b. Using soil maps of the orchard block, select an area with a consistent soil type. Furthermore, check this area for patterns that could indicate soil variations, such as tree vigour variations.
    c. Sample the soil to one meter depth in the four corners and the centre of the area of consistent soil type. Assess the soil texture of each one meter sample in 10 cm increments using the method of texture assessment by feel (Thien 1979). If one or more of the soil texture profiles are dissimilar, reduce the area until a homogeneous area is delimited.
2. **Determine the sampling strategy**
    a. Divide the area to be assessed into square blocks to allow good representation.

Box 4.1. (continued 1)

b. Sample as many sites as economically feasible, with at least two samples per site. Consider a strict minimum of 9 sites at a rate of four samples per site that will allow detecting a change of 10% assuming a coefficient of variation of 6.2%. Each sampling site is equivalent to the area allocated to one tree in the orchard block. Divide the total number of sampling sites equally between the square blocks, and distribute them randomly within each square block.

3. Sampling and processing for soil carbon content

a. In each sampling site, collect equal number of samples from two areas: between the wheel tracks and outside the wheel tracks. Collect a minimum of two soil samples within each sampling site. Collect samples to a soil depth of one meter using a hydraulic soil core sampler.

b. For each sampling site, pool the soil samples. Store the samples below 4°C until further processing.

c. Oven-dry the pooled soil samples overnight at 60°C. Sieve through a mesh of 2 mm in order to separate the fine earth fraction from stones, pumice rocks and roots.

d. Sub-sample using the riffle splitter method (see Gerlach et al. 2002).

e. Determine the total carbon content of the fine earth ($\% \, C_{fine\ earth}$) for each sampling site using a LECO TruSpec CN analyser (LECO Corporation, St. Joseph, Michigan, USA).

Box 4.1. (continued 2)

4. Sampling and processing for soil bulk density

a. In the centre of each sampling site, collect a one meter profile of undisturbed soil samples of known volume to determine the dry bulk density.

b. Oven-dry the soil samples at 105ºC until constant weight. Remove and weigh separately stones, roots and pumice rocks for volume correction.

c. The bulk density of the fine earth ($BD_{fine\ earth}$) is calculated as the amount of soil (in grams) per volume (in cm^3).

5. Calculate soil carbon stocks

a. The soil-carbon stock ($C\ stock$, in t C/ha) is calculated using the formula:

$$C\ stocks = BD_{fine\ earth}\ \times \%\ C_{fine\ earth} \times depth$$

Here $depth$ is the sampling-depth increment (cm).

6. Adjusting the number of samples

Determine if it is possible to observe a 10% change over an orchard cycle with the number of samples taken and considering the variability found in the area under study, a statistical significance level of 5% and a statistical power level of 0.8. If it is not possible, determine the number of sites required and carry out complementary sampling.

7. Monitoring soil carbon stocks

Repeat the whole procedure (Sections 2. to 5) every 20 years or following orchard re-development.

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Chapter 5:

Accounting for biogenic carbon of apple orchards in LCA: Measurements, end of life requirements and implications for the carbon footprint of New Zealand apples

Table of Contents

5.1. Introduction

Perennial cropland systems store carbon in their above ground vegetation (Albrecht and Kandji 2003). Through photosynthesis, atmospheric CO_2 is sequestered for several years, or decades, in the woody biomass of perennial systems, unlike annual components such as leaves, thinned fruits, flowers, and the pruned branches that are quickly degraded and integrated into the soil in the form of soil organic matter, or returned to the atmosphere through microbial respiration. According to the IPCC (2006; p 2.11)), "emissions from decay [of annually grown components] are balanced by removals due to re-growth making overall net C stocks in biomass rather stable in the long term". Therefore, instead, the woody biomass of apple orchards is the focus of this chapter because it can be considered as a carbon sink (Houghton et al. 1998).

As stated in Section 1.10 there are few methods to estimate the standing biomass of apple orchards. Furthermore, the carbon stored temporarily in woody biomass of orchards is generally excluded from LCA and carbon footprint guidelines despite several proposed methods (e.g. Brandão et al. 2013), as highlighted in Section 2.3.3.4.a - yet taking this temporary carbon storage into account could affect the results of LCA and carbon footprint studies (Levasseur et al. 2012).

In this chapter, a review of the literature quantifying the woody biomass in trees of apple orchards is presented and the requirements to integrate woody biomass data of perennial cropping systems in LCA and CF are discussed. A rapid and cost effective method to quantify the woody biomass carbon stock in an apple orchard block is proposed. Finally, the potential impact on the carbon footprint of New Zealand apples of various end-of-life scenarios for the apple trees is quantified.

5.1.1. The carbon footprint of New Zealand apples

The carbon footprint of New Zealand apples exported to the UK has been calculated by (McLaren et al. 2009). They found the total average footprint to be 0.9kg CO_2eq / kg apple. Fig 5.1 presents the fractions of the emissions between the various stages of the life cycle.

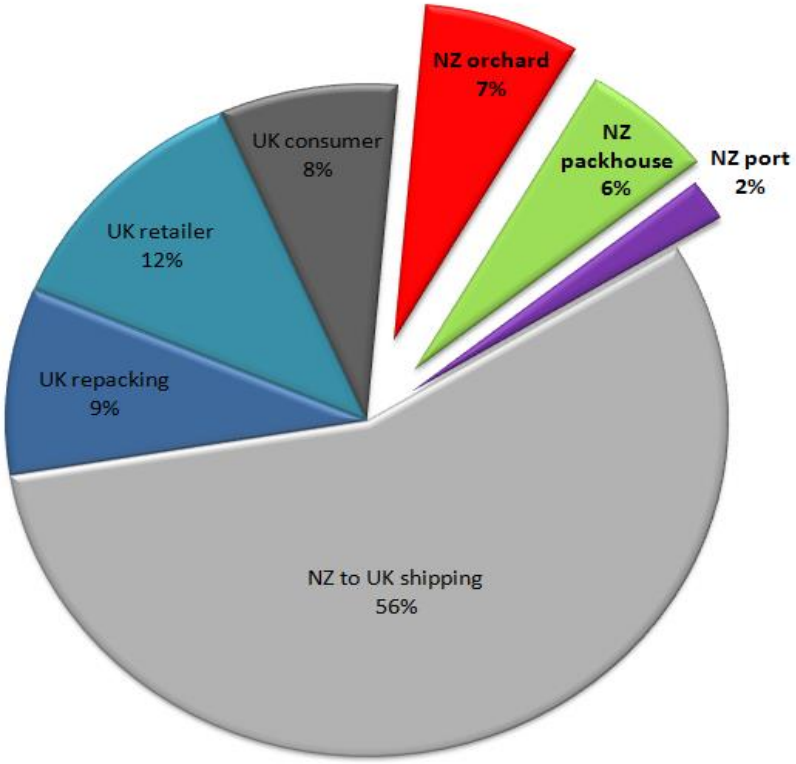

Figure 5. 1 Partitioning of the life cycle greenhouse gas emissions of a kilogram of New Zealand apples exported to the UK. Source: McLaren et al. (2009).

Within this life cycle, the New Zealand-based footprint, including the orchard, packhouse and port emissions, represents 15% of the greenhouse gas (GHG) emissions. However, the image of New Zealand apples is penalised by the distance between the respective locations of production and consumption, as explained in Section 1.6. Therefore, New Zealand apple growers are interested in finding ways to reduce their carbon footprint. They often mention that CO_2 is indeed being sequestered in the apple trees of their orchards, and they feel somewhat aggrieved that this is not accounted for. However, there are few data available about the changing stocks of woody biomass of apple orchards, and to date, rapid and cost-effective methods to quantify this biomass have not been developed and tested. These

methodological steps are a necessary first step towards obtaining reliable data to account for biogenic carbon of apple orchards in LCA and carbon footprinting.

5.1.2. Apple orchard block life cycle, replacement and end of life implications

5.1.2.1. Planting

The planting of an apple orchard block can happen in one of two ways that need to be distinguished: a previous apple orchard, or another previous land use. In the case of another land use, the trees are planted into rows with constant spacing between rows and between trees within each row. For example, for the semi-dwarf rootstock M.9, a commonly used spacing is 3.5 metres between rows and 1.5 meters between trees of the same row. However, if the previous land use is an apple orchard, the apple replant disorder, as reviewed by Traquair (1984), can prevent the immediate planting of new apple trees. This disorder causes “reduced growth and productivity” for the newly planted trees, as explained by Tustin et al. (2008), who investigated the effect of various soil treatments before replanting on the growth of young apple trees. However, a method sometimes used by growers and not described by Tustin et al. (2008) is to leave the land bare for one year before replanting after removal of the original trees (P. Greer and R. Wilson[1], 2011, pers. comm.).

As a result of active breeding programmes, many scion stocks (apple varieties) as well as rootstocks (root varieties) are available to apple growers. More than 15 years ago, the shift towards higher density orchards in New Zealand had started, as described by (Palmer 1999). Amongst other benefits, these intensive systems offer higher yields and are easier to manage because of their smaller size (Palmer 1999). However, more vigorous rootstocks tend to maintain high yields longer than dwarfing rootstocks, but they can also take longer to

[1] P Greer is an apple orchard owner and manager, and R Wilson is an orchard manager. These two apple growers located in the Hawke’s Bay of New Zealand and kindly accepted that blocks of their orchards be used for the soil-related work referred to in this thesis.

reach their full productivity stage. Generally, four types of rootstocks are available to apple growers: these are dwarfing (e.g. Mark), semi-dwarfing (e.g. M.9), semi-vigorous (e.g. MM106) and vigorous. Because they have an important effect on the size of the trees at least above-ground, these rootstocks partly determine the planting intensity in the orchard block. Roughly, semi-vigorous rootstocks allow tree planting at an intensity of around 1000 +/- 400 trees per hectare, while the equivalent figure for semi-dwarfing rootstocks is 2000 +/- 400 trees per hectare.

5.1.2.2. Trees' first years and establishment

After planting, apple trees on different rootstocks will need different amount of time to reach maturity and their maximum yields of high quality fruit. For example, Tustin and Palmer (2008) describe the adoption of high-intensity planting systems in New Zealand and they highlight that the general tendency for the New Zealand apple industry is to implement these intensive systems because of their capacity to produce high quality fruit within three to four years after planting. In general, during the first few years, the young trees do not require as much management time compared to fully producing trees.

Dwarfing rootstocks provide less anchoring to the ground due to their reduced size. In order to support the trees in case of high winds, as well as guiding them to grow straight, a physical support structure is usually put in place. Tall fence posts are planted every 10 to 20 meters along the tree rows in order to attach three to four metal wires at various heights. The wires run the whole length of the row and are attached to each tree which makes their removal difficult when the trees are removed or replaced (see Section 5.2.2.4)

5.1.2.3. Full production

The first apple harvest for trees growing on dwarf or semi-dwarf rootstocks occurs three to four years after planting. Within 6 years after planting, this type of tree is at full production, with yields that can be higher than 100 tonnes of apples per hectare. The average yield is around 65 tonne/ha (P. Greer, 2011, pers. comm.). After the harvest period, from the end of

summer to the end of autumn, depending on the variety, winter pruning takes place and will be finished at the beginning of spring at the latest. Additionally, a light pruning event often occurs in late spring. The winter pruning involves reducing the number of branches to allow the sunlight to reach better the fruit for skin colouring, and to control the vegetative growth of the trees. This affects the woody biomass of the trees as big branches are preferentially cut in order to maintain the tree structure of “many well-spaced weak horizontal or pendant side branches off an un-headed central leader” as explained by Tustin and Palmer (2008).

5.1.2.4. Orchard block removal or replacement

Apple orchard blocks can be removed and again replaced by growers for various reasons:

- To change the apple variety for economic reasons
- As a result of decline in productivity due to age
- To limit the spread of a disease to nearby orchard blocks
- To change the vigorous or semi-vigorous rootstock towards more dwarfing
- Due to the new orchard management strategy put in place by the new owner, or orchard manager.

Therefore, the time after which trees are pulled out or replaced can vary widely; it may be 10 years or less after planting in the case of disease, and 30 years or more after planting for healthy trees with a declining productivity. Indeed the decision to pull out or replace trees depends primarily on the economic profitability of the orchard block.

At the end of life of an orchard block, the general practice is to pull the trees out of the ground with a digger, including wires and sometimes wooden posts. Subsequently, the trees are pushed into one big pile, usually in the middle of the orchard block, and burned on site. Then, the ashes and other non combustible components (wires, staples, etc.) are collected, taken away and disposed of into landfill. Burning the trees is the usual method because it is the cheapest and the least time-consuming way to get rid of the trees. Additionally, at a later stage, the soil is aerated with a V-ripper in order to extract most structural roots within 60-

90cm of the soil profile. These roots are usually taken away and left to decompose as green waste.

As a result, most of the carbon stored in the tree frame and the structural roots over the life cycle of the orchard block is therefore released to the atmosphere. There is no incentive for the growers to process these trees differently since any other treatment would require higher investment in time and money. For example, removing the metal wires could be time consuming, as each tree is individually attached to the wire, and tree trunks can grow around and encase the wires during their lifetime. Furthermore, countries are not required to account for GHG emissions resulting from the burning of biomass when carrying out inventory and reporting of GHG emissions using the IPCC Tier 1 method. Indeed, emissions from burning biomass are explicitly excluded from the IPCC guidelines (IPCC 2006). As a result, there is no incentive to avoid this practice at the national level.

It is worth noting that some growers do chop up the trees at their end-of-life for firewood. But this practice is not widespread in the Hawke's Bay of New Zealand. Also, more recently attention has been given to the potential production of biochar from biomass, and returning it to soils as a means to sequester carbon and to improve soil properties such as enhancing soil fertility and reducing nutrient leaching, although more research is needed to define the potential future role of biochar in land based systems (Macías and Camps Arbestain 2010; Anaya de la Rosa 2014).

The production of biochar also yields two other co-products: bio-oil and bio-gas. From an LCA and carbon footprint perspective, the use of firewood, bio-oil and bio-gas could replace the use of other heating sources which may have higher carbon footprints and other environmental impacts. The use of biochar can also lead to carbon sequestration in the soil (Anaya de la Rosa 2014) as well as potential environmental benefits related to improved soil properties (Macías and Camps Arbestain 2010).

5.1.3. Data and variability

The quantity of standing woody biomass in apple orchards can vary substantially. These variations can be observed at all scales, including the local (orchard), regional (e.g. Hawke's Bay) and national scale.

The quantity of woody biomass is the result of a balance between many factors. Obviously the age of the trees is important. Also, at the orchard scale, orchard blocks of the same age but different rootstocks will have different standing woody biomass. Additionally, the scion variety and its interactions with the rootstock can modify tree growth rate and the final tree height and size. Moreover, soil parameters such as soil type and texture, as well as the water dynamics of the soil, can affect tree growth and vigour, and can vary within an orchard block. Finally, management practices such as training methods and pruning adapted to tree planting density, as well as irrigation, can influence greatly the woody biomass of apple trees. These factors can vary importantly within (and between) regions. For example, the soil map of the Heretaunga plains of the Hawke's Bay region is shown in Figure 5.2. More than 60% of New Zealand export apples are produced in this area. The map identifies the numerous soil textures, from the coarse sandy to almost pure fine clay. These different soil textures will have varying characteristics, which in turn affect the growth of tree roots and therefore tree development and above ground biomass.

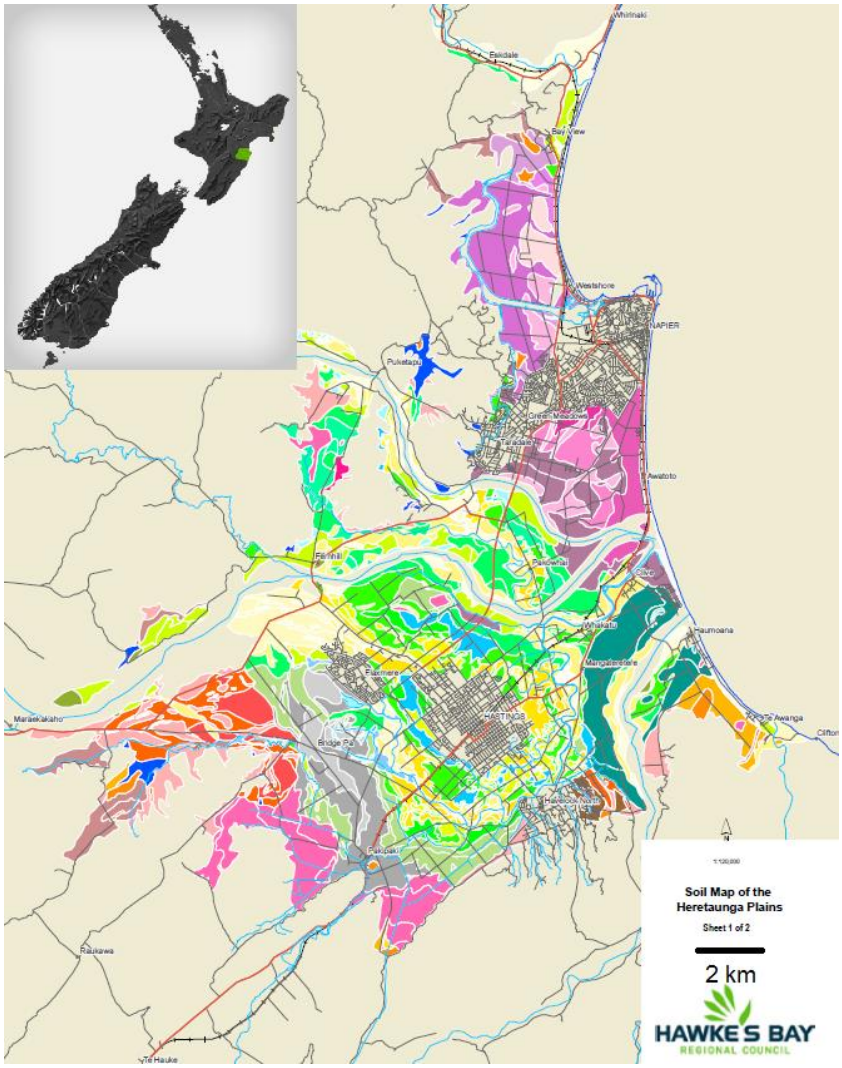

Figure 5. 2 Soil map of the Heretaunga plains in the Hawke's Bay. The colours represent the various soil textures of the area. For example: pink is sandy soil and dark green is clayey soil. The majority of New Zealand apples are grown on these very different soils. Source: adapted from http://www.winehawkesbay.co.nz/images/pdf/story-of-hawkesbay.pdf.

5.1.3.1. Dearth of data

The literature on the quantification of woody biomass in apple orchards is scarce. Furthermore, all reported measurements have been collected on experimental orchards rather than commercial ones, and so may not reflect the reality of a production orchard. Several studies have shown the impact of various cultivars, rootstocks and management practices on the partitioning of nutrients and dry matter in the various components of apple trees (e.g. Palmer 1988; Lakso et al. 1999; Palmer et al. 2002; Lo Bianco et al. 2003; Lo Bianco et al. 2012). Only two studies were identified that consider the carbon balance of apple trees for the purpose of carbon footprinting and carbon trading. Page et al. (2011)

used the “net balance approach” (CO_2 captured minus CO_2 emitted) in one particular year. Wu et al. (2012) calculated the “carbon sequestration capability” of apple orchards in China based on regional orchard area inventories and the carbon balance of three apple trees in each of three orchards that were 5, 18 and 22 years old. However, some aspects were not considered in these studies. In particular no account was made of the entire crop cycle, including non-productive years, and the end of life of the apple trees.

5.1.3.2. Types of data required for quantification on an area basis

Data for the quantification of the standing woody biomass on an area basis need to account for the total standing weight of the woody biomass per tree as well as the spacing of trees and rows. It is difficult to extrapolate from studies not presenting these data to more generalised quantification of the woody biomass stock on an area basis without major assumptions. As noted earlier, different rootstocks are likely to be planted at different densities, since the vigour of the trees is partly dependent upon the rootstock type and therefore more vigorous rootstocks will require more spacing between trees. In New Zealand, Palmer et al. (2002) examined the annual dry matter production at various tree and row spacings in an experimental orchard. The range of tree densities represented was between 1,190 to 2,198 tree/ha, and included three cultivars on an M.9 rootstock. However, as tree management methods improve, these characteristics can change quickly. For example, in the Hawke’s Bay of New Zealand, for more than 98% of the commercial apple orchard blocks planted on an M.9 rootstock between 2005 and 2010, tree spacings were between 1m and 2m and row spacings were between 3m and 4m (Pipfruit NZ, 2010, Pers. Com.). This led to a range of planting densities of between 1250 to 3333 trees/ha.

5.1.3.3. Woody biomass estimates at the orchard block scale

Several studies quantified the woody biomass of apple orchards at the orchard block scale. Their results are presented in Table 5.1

Table 5. 1 Literature woody biomass estimates and characteristics of the trials. All trees are on an M.9 rootstock.

Location	variety	Tree age (years)	spacing * (m); planting density (tree/ha)	Number of trees measured	Calculated woody biomass (t DM /ha)	source
New Zealand	Royal Gala	8	3.5 x 1.3; 2198	8	17	Palmer et al. (2002); (Palmer 2011)[2]
England	Crispin	5	1.5 x 0.75; 8889	nc[#]	15	
West Virginia, USA	Golden Delicious	5	3 x 3; 1111	15	8.6	Stutte et al. (1994)
Italy	Pink Lady	3	3.5 x 0.7; 4082	16	3.8	Lo Bianco et al. (2003)
Italy	Pink Lady	6	3.5 x 1; 2857	nc[#]	3.4	Lo Bianco et al. (2012)

* between rows x between trees, [#] not communicated

Firstly, the woody biomass results all correspond to research trials, rather than commercially grown trees. Secondly, when considering even just the semi-dwarf rootstock M.9, there is still substantial variability in the estimates of the standing woody biomass, even of the same age. This mainly due to different planting densities, although the location (that determines climatic conditions), as well as the variety can play a role. Therefore, this variability jeopardises the extrapolation of woody biomass estimates in commercial orchard blocks, let alone whole orchards estimates that can include very different orchard blocks.

5.1.3.4. Guidelines and uncertainty at large scales

The difficulty of estimating woody biomass accurately is also a problem at scales larger than the orchard, and this is confirmed by guidelines for carbon footprinting. For example, the latest version of the PAS2050 (BSI 2011) section 5.1.1, Note 4, excludes[3] changes in

[2] Palmer et al. (2002) (see also Section 5.2.3.2) observed a high variability in tree vigour in their experiment, supposedly due to soil variations. The results reported in Table 5.1 represent the most vigorous plots of their trial.

[3] The PAS 2050 (2011) states: "*5.1.1, Note 4: Carbon incorporated in plants or trees with a life of 20 years or more (e.g. fruit trees) that are not products themselves but are part of a product system should be treated in the same way as soil carbon, unless the plants and trees are resulting from a direct land use change occurring within the previous 20 years.*"

biomass carbon stock, called "biogenic carbon", from carbon footprint calculation requirements unless as a part of land-use change assessment. This exclusion was also present in the 2008 version of the PAS 2050. However, the more recently published ISO TS 14067 recognises, in section 6.4.9.2, the importance of this carbon stock for perennial crops, and requires the carbon stock in woody biomass to be accounted for in carbon footprint studies[4]. Nevertheless, if the biomass is not transformed into gases such as methane, its carbon stock accumulation is considered balanced by the subsequent emissions by the ISO TS 14067 (ISO 2013).

For the purpose of LCA, Muller-Wenk and Brandão (2010) suggested that calculations of the carbon stock in above-ground biomass should be based on the IPCC's Tier 1 default coefficients. However, these estimates carry an important nominal estimate of error of +/- 75% (IPCC 2006). Accordingly, Muller-Wenk and Brandão (2010) acknowledged that their assessment only permits the climatic impact calculations for the "main land uses, in the main biomes of the globe". Furthermore, land cover maps and databases are often used to estimate above ground biomass at regional or national scales (Smith et al. 2012). However, Smith et al. (2012) explained that these maps have many sources of variation due to their spatial resolution. Furthermore, large differences between various land use maps are observed in the land use classification criteria such as the threshold percentage soil cover by vegetation that is used to classify the land as a forest, even if these maps are based on the same remotely sensed raw data. Using different land cover maps, or databases, may therefore lead to very different biomass carbon stock results at the regional and larger scale. Finally, Koellner et al. (2012) recently published the "UNEP-SETAC guideline for Life Cycle Inventory (LCI) on a global scale" and concluded that, "[...] a meaningful simplification can only be achieved, when the detailed information of land use impacts across land use types,

[4] Section 6.4.9.2 of ISO 14067 states: "*Treatment of fossil and biogenic carbon GHG emissions and removals arising from fossil and biogenic carbon sources and sinks shall be included in the CFP and shall be documented separately in the CFP study report."* However, NOTE 1 to this section states: "*The amount of CO_2 uptake of biomass and the equivalent amount of CO_2 emissions from the biomass at the point of complete oxidation results in zero net CO_2 emissions when biomass carbon is not converted into methane, non methane volatile organic compounds (NMVOC) or other precursor gases."*

regions, and impact pathways will be available". This statement emphasizes that although up-scaling is difficult without detailed data, downscaling by using the average for the region when assessing a particular field is highly uncertain due to the variability embedded in global and regional estimated averages.

All in all, estimates of above ground woody biomass are uncertain at all scales. This may lead to estimation of unrepresentative biomass carbon stocks in apple orchards. It is therefore necessary to measure above ground biomass at the orchard block scale in order to provide reliable data for the purpose of LCA and CF.

5.1.4. Key parameters for LCA and CF

This section highlights the main findings of a recent review on the LCA of perennial cropland systems published by Bessou et al. (2013), who reviewed 103 full or partial LCA studies of perennial cropping systems. They discussed 85 peer reviewed publications. In their review, only 6 references discussed apple production systems, although all the findings of the review are entirely relevant to these systems.

Firstly, Bessou et al. (2013) reported that most studies did not account for the various productive and non-productive phases of the cropping cycle, and they noted that often the end of life of the perennial crop was not considered. The authors concluded that in order to represent more accurately the environmental impacts associated with perennial systems, the entire cropping cycle, from just after the removal of the previous crop to the removal of the crop under study must be considered. This includes the nursery stage, the crop establishment stage, the years of full production, and the decreasing production phase and the removal stages. For example, in some New Zealand apple orchards, it is (usually) necessary to include one extra year to the cropping cycle for land/soil preparation to mitigate the occurrence of replant disease (see Section 5.2.2.1). However, while this extra year may overlap with the nursery stage, inputs and emissions to air, soil and water in the bare field are still occurring and these need to be taken into account.

Secondly, Bessou et al. (2013) noted that most reviewed studies did not discuss the quality of the data used to calculate the potential environmental impacts of production. The authors explained that the collection of local primary data, including information about sampling size and the spatial and temporal representativeness of the data, is imperative to improve data quality and therefore the relevance and representativeness of the LCA results. Furthermore, Bessou et al. (2013) noticed that many studies used the results of mechanistic and process based models as a source of 'data', and they emphasized that these models require calibration with site specific data. Finally, the authors concluded that collecting representative data is "the only option" to improve the "quality and completeness" of life cycle inventories.

Thirdly, emissions linked to Land Use and Land Use Change (LULUC) were mostly ignored in the reviewed studies. Bessou et al. (2013) identified two reasons for this: a "lack of fundamental understanding" of the complex functioning of systems involving LULUC, and a "lack of data" exacerbated in perennial croplands compared to annual cropping systems. Accordingly, the authors suggested that research efforts should be directed towards "characterising biomass stands and the dynamics of soil cover and organic matter pools in relation with agricultural management" (Bessou et al. 2013). Regarding LUC in LCA, major uncertainties concern the assumptions by which the land based system is directly (dLUC) and indirectly (iLUC) affected by land use change (LUC) (Bessou et al. 2013). Additionally, the quantification of the resulting impacts is impaired because representative data are missing and, while several methods exist, there is no agreement on a single methodology to allow harmonisation of the LUC assessment framework in LCA (Bessou et al. 2013).

In conclusion, in order to integrate into LCA the data on standing woody biomass and the results of the estimation method developed in the previous sections of this chapter, it is necessary to:

- Consider the entire cropping cycle, including the time required to prepare the field for the successful establishment of the new crop.
- Provide a detailed inventory of data, including the relevant spatial and temporal information, as well as sampling size, and to
- Discuss the quality of these data as well as the implication of their extrapolation to larger scales and use in other LCA studies.

5.1.5. Timing of emissions & GWP accounting methods

The timing of emissions is also critical when considering the impact of carbon storage in biomass on climate change, especially because perennial crops such as apple orchards store carbon temporarily, over one to three decades. This is a “hotly debated topic” and some methods to take the timing of emissions into account in LCA are discussed in Section 2.3.3.4.

5.1.6. Objectives of this Chapter

Based on the issues discussed in Sections 5.1.1 to 5.1.4, the objectives of this chapter are:

- To investigate whether the woody biomass carbon stock can be quickly estimated at the orchard block scale at the end of life of the orchard block.
- To provide additional data of above ground biomass from a commercial apple orchard.
- To estimate the importance of the carbon sequestered in tree wood of apple orchards for the carbon footprint of New Zealand apples, according to various scenarios at end-of-life for the trees.

5.2. Materials and methods

5.2.1. Measurements

5.2.1.1. Measurements of apple trees woody biomass

On 26 and 27th of July 2011, a commercial orchard block of 0.54 ha with 12 year old apple trees of the variety 'Jazz' on an M.9 rootstock located in the Hawke's Bay of New Zealand (longitude: 176.807219, latitude: -39.649858), was undergoing orchard redevelopment for variety replacement. The soil is defined as a Weathered Fluvial Recent (WFR) Soil (NZ Soil Classification, Hewitt (1998)). On the day of the orchard block's removal, 10 trees were selected according to the widest possible range of trunk circumferences, as measured 20 cm above graft union using a flexible measuring-tape.

The Trunk Cross-sectional Area (TCA, in cm^2) was estimated from the trunk circumference (C, in cm) measurements, using well established geometric relationship in Equation 4.1:

$$TCA = C^2/4\pi \quad . \qquad \text{Eq. 5.1}$$

The trunk circumference is a more accurate measure than the trunk diameter to estimate TCA, because it allows for the irregular shape of the tree trunks.

Each tree was then divided into branches, trunk (above graft union), rootstock shank (below graft union, including above and below ground parts), and roots. The quantity of extracted roots (that stayed attached to each shank) was hugely variable between trees (see Table 5.1) and therefore roots were excluded from "whole tree dry mass" calculations. This high variability is due to the fact that pulling the trees out is not designed to extract the roots, which are removed at a later stage (see Section 5.1.2.4). Branches were cut into small sections using loppers. Trunks were chain-sawed into rings of approximately 4 cm thickness to accelerate the drying process and a large tarpaulin allowed the collection of the resulting sawdust for each tree trunk for further drying. A large enough oven was available and so the

whole trees (cut into the various components) were dried at 60°C until a constant weight was reached.

In order to obtain an estimate of the biomass of the orchard block without cutting and drying all the trees, the trunk circumferences of 49 additional trees in the orchard block were measured. As the contractor was pulling the trees out of the ground and putting them into a pile at the time of data collection, this was the maximum trees and tree circumferences that could be collected without major disturbance to his work.

In order to allow comparison with the studies reviewed in Section 5.1.3, the results of the tree measurement are reported in tonnes of dry matter per hectare. However, the carbon content of the dry matter is the relevant aspect when assessing the carbon footprint. Walton et al. (1999) reported that dry apple wood is 47% carbon. Therefore, when assessing the effects of various end-of-life scenarios on climate change, these were multiplied by 0.47 in order to reflect the carbon content of the dry biomass. Nevertheless, it is possible that this value varies with, for example, the age of the wood. More research to confirm these findings is therefore needed.

5.2.2. Scenarios for end of life

At the end of an orchard block's life cycle, the trees are usually pulled out and burned on site. However, as explained in Section 5.1.2.4, some growers cut the tree trunks up to make firewood, and the use of the wood to make biochar could also be of interest. With the aim of comparing these practices, the climate change impacts of three end-of-life scenarios for the woody biomass of this orchard were investigated:

- Scenario 1: Whole trees pulled out and burned on site
- Scenario 2: The trunk wood is taken away by the grower for firewood and displaces the use of other heating fuels. The branches are burned on site.

- Scenario 3: The whole woody biomass is turned onsite into biochar which is then reapplied to the soil, and the bio-oil and bio-gas displaces other fuels.

These three scenarios are presented in detail in Section 5.3.5. In order to avoid undue complexity, only the carbon stored in the tree wood is considered, and all other emissions are excluded, such as the energy used in machinery. In other words, for this case study, activities such as, for example, the GHG emissions resulting from the use of machinery to remove, process and transport the trees are excluded from the analysis. Anaya de la Rosa (2014) provide figures for some of these processes: For example, in the biochar scenario, the GHG emissions from mulching the prunings in the orchard, the biochar transport and incorporation into soils and the handling of the biomass were equivalent to 15%, 6.4% and 7.9% of the carbon sequestration due to biochar, respectively. While considering the emissions from these processes would affect the results of this study, all three scenarios involve handling the biomass, and the biochar Scenario is the only one to result in long term (more than 100 years) carbon sequestration.

5.2.3. Timing of emissions and temporary storage

Several methods for estimating the climate change impact of temporary storage in biomass have been developed, as introduced in Section 2.3.3.4a. For this chapter, the IPCC method and the dynamic LCA method are used to calculate the climate-change impact for each of the three end-of-life scenarios. For each method, two time periods are selected for assessment: 20 years and 100 years.

The IPCC method considers only the biomass accumulated that remains at the end of the timeframe allocated for changes. Therefore, under scenarios 1 and 2, the amount of carbon (equivalent to 47% of wood dry matter) sequestered is equal to zero since the wood is burned either in the field, or in a wood burner to provide heat. So the accumulated carbon is emitted back to the atmosphere in both cases. Under scenario 3, only the carbon that

remains sequestered at the end of the time horizon chosen, that is 20 or 100 years, is considered by the IPCC.

On the other hand, the dynamic LCA method (Levasseur et al. 2010) realistically assesses the time dependent radiative forcing impact of GHG emissions and removals. Several examples of application of the method are presented in Levasseur et al. (2010), Levasseur et al. (2012) and Levasseur et al. (2013). The dynamic LCA method permits to graphically display this time-dependent impact and therefore highlights the relevance of the choice of a time horizon, an issue yet to be resolved in LCA and carbon footprinting (Brandão et al. 2013).

5.2.4. Statistical considerations

Alongside the average values, both the standard deviation (SD) and the coefficient of variation (CV) are presented for the results for the different scenarios. The SD is a measure of variability that directly relates to the specific dataset, and is expressed in the same unit as the average. The CV is a measure of the variability weighed by the average and is expressed as a percentage of the average. Therefore, expressing the SD is important when analysing a specific dataset, while the CV is better for communication because it gives an order of magnitude of the variation within a sample and makes comparison between averages more intuitive.

5.3. Results & discussion

5.3.1. Woody biomass

Within one orchard block of the same apple variety and rootstock and which had been managed uniformly, the range of tree trunk circumferences is large. Table 5.2 presents a detailed inventory of the collected data. For the orchard block, the smallest trunk circumference measured 17 cm, while the largest was 31 cm. The CV for the 10 trees measured reached 18%. This can reflect differences in tree characteristics, such as the

quality and uniformity of the trees at planting, as well as soil characteristics, such as a change in soil texture or the probable impact of partial flooding of the orchard block. In addition, while this was not the case in this chapter, the proximity to shelterbelts can affect the growth of the trees due to shading.

The variability in dry weights of the various tree components is similar, with a CV between 33% and 34%. This result is expected, as the trees were chosen to cover the widest range of trunk circumferences in the orchard block. Furthermore, these variations are similar to the variation of TCA (CV= 33%), which suggests that TCA can be used to estimate tree dry weight.

Table 5. 2 Dry weight of woody components from 10 trees sampled in one orchard block, selected to represent as wide a range of trunk circumferences as possible. Within an orchard block, the variability of tree circumferences is high, and the variability of tree dry weights is even higher, which means that for the same trunk circumference, there is a variation in tree weights.

	Trunk wood above graft union (g)	Branches (g)	Rootstock shank (below graft union) (g)	Roots (g)	TCA (cm^2)
Min.	2834	2040	799	5	23
Max.	8211	6411	2431	645	76.5
Average (n=10)	5669 (49%)*	4345 (37%)*	1659 (14%)*	239	51.3
SD	1937 (2.5%)#	1471 (1.9%)#	551 (2.6%)#	215	17
CV (%)	34%	34%	33%	90%	33%

*In the row “average”, the average proportion of each component to the whole tree dry weight, excluding roots, is expressed in brackets.

#In the row “SD”, the standard deviation of these average proportions is expressed in brackets.

The average proportion for each of the components to the total tree dry weight (excluding roots) is different, with the trunk wood (above graft union) representing 49% of the total tree wood, the branches representing 37%, and the rootstock shank accounting for 14%. These proportions seem to be stable between trees, as shown by their standard deviations of less than 3%. This is confirmed by the fact that the standard deviations of the proportions are strongly driven by one tree for which the proportions are 43%, 36%, 21% for the trunk, branches and shank, respectively. This difference is primarily due to a higher shank weight as a function of TCA compared with the other trees (data not shown). Several explanations

are possible. First, the planting depth could have been different for this tree, as this factor is known to cause variation in the dwarfing effect of rootstocks (Ken Breen, 2014 *pers. comm*.). Another possibility is that the rootstock stem onto which the scion is grafted, could have been longer at the time of grafting. However, a longer rootstock stem usually induces a stronger dwarfing effect (Ken Breen, 2014 *pers. comm*.), but this tree showed a similar relationship of total dry weight to TCA compared to the other trees. In this case, the extra dwarfing effect was lost due to tree age.

The quantity of roots per tree is highly variable as shown by the CV of 90% (Table 5.1). This is because, as noted earlier, roots are not targeted when trees are pulled out, and so the weight of roots could have been very variable because there was little focus on them by the operator during tree extraction. Due to the fact that roots turn over and this eventually adds to soil carbon as well as atmospheric carbon through decomposition (see Section 5.1.2.4), as well as the time constraints and the difficulty of measuring accurately the root biomass in the field, this component was excluded.

Overall, despite vigour differences being partly evened out through pruning over the years, the measurements show that a wide range of tree TCA and woody dry weights can be present in a single orchard block, which confirms the fact that woody biomass needs to be measured at the orchard block scale.

5.3.2. Woody biomass dry weight and TCA

As previously suggested in the literature (Palmer et al. 2002; Lo Bianco et al. 2003), TCA is strongly correlated to total dry woody biomass, excluding roots (Fig. 5.3). This is indicated by the proximity to 1 of the coefficients of determination, R^2, a statistical measure of how close the measured data are to the linear regression in Fig. 5.3. This correlation was also found in experimental orchard blocks set out by Palmer et al. (2002) and Lo Bianco et al. (2003). Furthermore, Palmer et al. (2002) emphasised the “variable nature of tree growth” in their trial, resulting in standard deviation of TCA of 34%, 44% and 33% for the cultivars Royal

Gala, Braeburn and Fuji. These CVs are similar to this study's result of 33% CV for TCA for the 10 trees destructively harvested, even though the average TCA found in this study is more than double the values in Palmer et al. (2002). These CV values are also similar to the CV of 30% for the TCA measured on the additional 49 trees in this chapter (see Section 5.3.3). It seems therefore reasonable to assume that a CV around 30% for TCA can be found in commercial orchard blocks, and that this value is relatively conservative with tree growth.

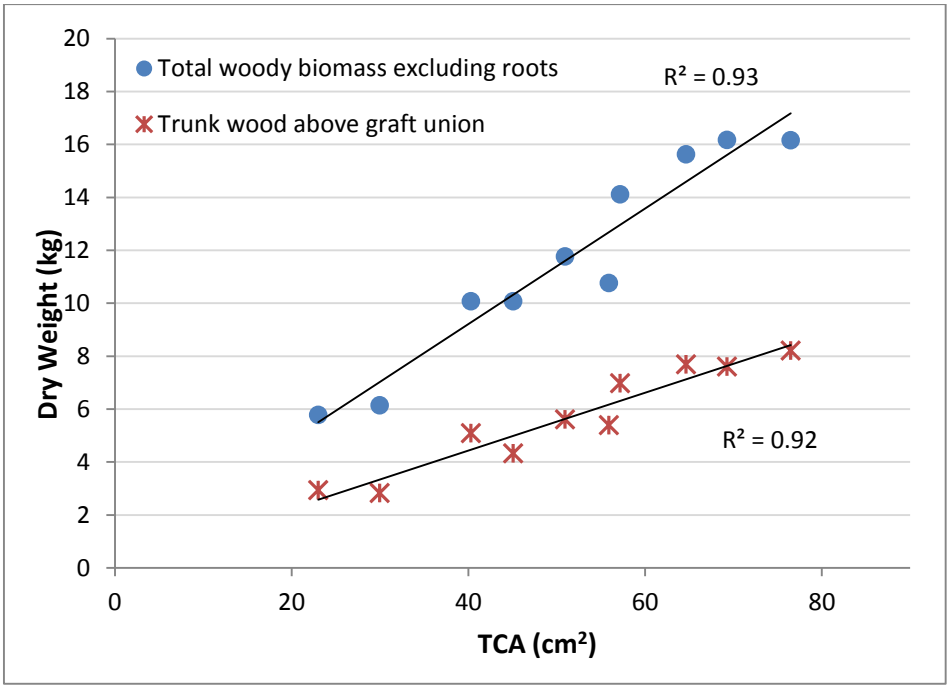

Figure 5. 3 Relationship between Trunk Cross-sectional Area (TCA, 20cm above graft union) and trunk (red stars) and whole tree dry wood biomass (trunk, branches and rootstock shank, excluding roots) (blue dots). Both coefficients of determination of the linear regressions (R2) show the relatively good capacity of TCA to estimate both tree trunk dry weight and whole tree dry woody biomass.

The various methods to estimate tree biomass in forests and related allometric equations were reviewed by Parresol (1999). Strong relationships are found between tree biomass and tree diameter at breast height, as well as with tree height. For example, Bartelink (1997) found, studying Beech tree (Fagus sylvatica L), that non-linear relationships based on diameter at breast height explained more than 90% of the variance in tree biomass. Similarly to the results presented in this chapter, Quinones et al. (2013) found, in citrus plantations

good fit between TCA and a range of Net Primary Productivity (NPP) parameters, but in particular for Total NPP.

Overall, these results and those of earlier studies indicate that using TCA to predict the dry weight of woody biomass is reliable even in commercial apple orchard blocks. In this experiment, based on the measurement and destructive harvest of 10 trees, a linear regression between TCA and woody dry weight with a high coefficient of determination could be defined. However, it is unknown if the minimum number of trees to determine a reliable relationship will vary for specific orchard blocks and more research is therefore required on this aspect.

5.3.3. Calculation of dry woody biomass for the orchard block

The steps required to estimate the woody biomass for the entire orchard block are now described following the estimation of the correlation for the specific orchard block under study. Here the orchard block described in Section 5.2.1.1 is taken as an example.

The first step (Eq.2) is the establishment of the linear regression that is specific to the orchard block from the destructive harvest of 10 trees, as developed in Section 5.3.2 of this chapter. In this study, the regression equation expressing the relationship between TCA and total dry woody biomass for a particular tree i ($\mathrm{DM}_{\mathrm{tree},\ i}$) is:

$$\mathrm{DM}_{\mathrm{tree},\ i} = 0.2184 \times TCA_i + 0.4749 \quad . \qquad \text{Eq. 2}$$

At the same time as the collection of the 10 trees used to determine the correlation, a large number (x) of trees were randomly selected within the orchard block for assessment. However, no definite value for x is suggested here as more tree measurements would be required in order to determine what would be a representative x. The value of x given below was the maximum number of trees that could be measured on the day in order to not disturb the removal of the trees that was happening simultaneously as explained in Section 5.2.1.1. However, in reality, one could imagine that growers take a little time to measure more trunk

circumferences, for example as a percentage of the total number of trees in the orchard, assuming that the correlation provided in this chapter has been verified over a range of tree varieties and spacings and can represent their orchard block with a high level of confidence.

In the third step, the trunk circumferences of the selected x trees are consistently measured 20 cm above graft union to calculate their related $TCA\,(x)$, which is used to predict the $\mathrm{DM}_{\mathrm{tree}}$ for each tree.

The third step (Eq. 5.3) involves collecting data about the orchard block area, A_{block} (ha), and the planting density, D (trees/ha) of the orchard block. These data are required to estimate the total number of trees in the orchard block under study. The equation to calculate the total standing dry woody biomass of the orchard block is then:

$$DM_{block} = \frac{\sum_{i=1}^{x} \mathrm{DM}_{\mathrm{tree}}}{x} \times A_{block} \times D_{block} \quad . \qquad \text{Eq. 5.3}$$

Table 5. 3 Data for measured and estimated parameters for both trunk DM and total woody DM in the case study orchard block (0.54 ha).

Variable		x	$\sum_{i=1}^{x} \mathrm{DM}_{\mathrm{tree}}$	A_{block}	D_{block}	DM_{block}
Description		Number of trunk circumfer-ences measured	Estimated dry woody biomass (49 trees) (Kg DM)	Orchard block area (ha)	Tree planting density (Trees/ ha)	Total biomass dry weight for orchard block (kg)
Value	Trunk	49	265.4	0.54	1759	5145.3
	Total wood		547.2			10608.2

Finally, the amount of carbon sequestered in the woody biomass of the orchard block can be calculated by multiplying DM_{block} by the amount of carbon in apple wood. This was taken as 47%, as determined by (Walton et al. 1999). Using the parameters described in Table 2, the

amount of carbon sequestered in the total woody biomass, excluding roots, of the 0.54 ha apple orchard at end-of-life is 4985.9 kg, which is equivalent to 9.23 t C/ha.

5.3.4. End of life of the orchard block

In order to obtain a first estimate of the importance of the carbon sequestered in the standing tree wood of apple orchards for the carbon footprint of New Zealand apples and its relevance to climate change, three scenarios of end-of-life for the trees have been established. For simplicity, several assumptions are relevant to all scenarios.

5.3.4.1. Assumptions common to all scenarios

For all scenarios, carbon accumulates through photosynthesis in the woody biomass of the orchard block during 12 years following planting, or at least until the orchardist decides to remove the trees. Since there are no data available on the growth rate of a block of apple trees on an M9 rootstock at various stages of their life cycle, and due to the fact that this rate possibly depends on the specific characteristics of the orchard block, it is assumed that there is a linear increase in dry standing biomass from planting to removal of the orchard block.

One life cycle of the orchard block is taken into account, from the removal of the previous orchard block to the removal of the current one. Therefore, the 12 year old orchard block under study in this chapter has a life cycle of 13 years in total, so as to include the “bare land” year necessary to avoid the apple replant disorder, as discussed in Section 5.1.4.

Only the climate change impact directly associated with the carbon in woody biomass is considered here, as well as the avoided GHG emissions that result from burning wood in place of other fuels (see Section 5.3.5.2). Roots were excluded from the assessment of the total biomass DM for the orchard block, as discussed in Section 5.3.1.

Finally, the structure composed of stainless steel wires and wooden “fence” posts that physically support apple trees with more dwarfing rootstocks is omitted from this analysis. However in the case of Scenarios 2 and 3, these would have to be carefully removed in

order to process the trees. In a future analysis, this would need to be taken into consideration.

5.3.4.2. Description of the scenarios

Scenario 1: Burning

Under Scenario 1, the entire woody biomass is burned on site and as a consequence, 100% of the accumulated carbon in dry biomass of the trees is re-emitted as CO_2 into the atmosphere.

Scenario 2: Firewood

Under Scenario 2, all branches are first cut off with a chainsaw. The tree trunks above the graft union are subsequently cut into small logs and taken away for drying during one year. The branches remaining on the orchard floor as well as the tree shanks are assumed to be burned on site.

The logs from trunks are split and burned in a firebox in a residential household, assuming a net calorific value of 19.6 MJ/kg (Sims 2002). The use of this wood for heating purposes is assumed to replace the use of the marginal source of home heating in New Zealand: fuel oil (according to Isaacs et al. (2006). The avoided GHG emissions[5] from burning a quantity of oil producing an amount of energy equivalent to the amount delivered through burning the apple logs were credited to the system. This amount of energy was found to be equivalent to 3.4 times the average yearly energy need per New Zealand household for home heating using data from Lloyd (2006)[6]. Therefore, the use of the wood and the avoided GHG emissions were spread over 3.4 years.

Scenario 3: Biochar

[5] Calculated with CO_2 eq emission factors from the "New Zealand Energy Data File 2012", produced by the Energy Information and Modelling Group of the NZ Ministry of Economic Development. http://www.med.govt.nz/sectors-industries/energy/energy-modelling/publications/energy-data-file.
[6] Lloyd (2006), average for the four main regions representing 47% of the New Zealand population: Auckland, Wellington, Christchurch and Dunedin.

Under Scenario 3 (biochar), the entire dry woody biomass of the orchard block is assumed to be transformed on site into biochar and its co-products, bio-oil and bio-gas, using a mobile pyrolysis plant such as has been developed in Australia[7].The following figures for the calculations in Scenario 3 were obtained from Anaya de la Rosa (2014)[8]:

- The biochar production process results in 31%, 23% and 12% of the total woody dry mass transformed into biochar, bio-oil and bio-gas, respectively. According to Anaya de la Rosa (2014), these figures do not add up to 100% because they represent "quantities of products effectively captured and exploited rather than actual product yields".
- The biochar produced is composed of 76.3% carbon[9] and 74% of this carbon is sequestered for more than 100 years after application in the orchard soil. The remaining carbon is decomposed and returned to the atmosphere in the form of CO_2 within the year of application. These estimates of carbon content are based on biochar from pine wood that tends to have less ash than biochar from apple wood. Moreover, pyrolysis conditions can change widely, especially the highest heating temperature, and this figure must be considered as an approximate estimate only.
- The bio-oil has a calorific value of 17 MJ/kg and an energy efficiency of 0.8 while equivalent values for bio-gas are 11MJ/kg and 0.9.

The avoided GHG emissions from burning a quantity of natural gas and fuel oil producing an amount of energy equivalent to the amount delivered in the bio-gas and bio-oil, respectively, were credited to the system. Furthermore, this amount of energy is equivalent to 1.54 times the average yearly energy need per New Zealand household for home heating, similarly to Scenario 2. Therefore, the avoided GHG emissions were spread over 1.54 years after the wood was converted to biochar and its co-products.

[7] http://www.biochar-international.org/projects/BiGchar
[8] Section 5.2.2, pp123-138
[9] Anaya de la Rosa (2014) used this value for slow pyrolysis of pine wood from Enders et al. (2012).

The results of the three scenarios are presented in Section 5.3.4.3. for both the IPCC and Dynamic LCA methods.

5.3.4.3. End-of-life scenarios results

As discussed in Section 5.2.3, the IPCC only accounts for the carbon that remains sequestered at the end of the accounting period, chosen as 20 and 100 years for this study. Therefore, since all the carbon stored in the trees is released before year 20 in Scenarios 1 and 2, the IPCC result for these scenarios is zero (Table 5.3). However, in Scenario 3, while the co-products of biochar, bio-gas and bio-oil are utilised within three years of being produced, 74% of the biochar applied to the soil is assumed to be sequestered there for at least 100 years. Therefore, under Scenario 3, 1.86 tons of carbon in the form of biochar are sequestered in the orchard soil as a result of the activities on the land over the 13 years, including one year of bare land and 12 years of apple tree growth. This is equivalent to 6.81 tonnes of CO_2 and this amount is directly taken into account by the IPCC without further calculations.

The Dynamic LCA method (Levasseur et al. 2010).allows the calculation of the instantaneous and the cumulative radiative forcing over time for each of the three scenarios and the results are presented in Figure 5.4a and 4.4b. The curves in Fig 5.4a show the instantaneous radiative forcing of the three scenarios over time calculated on a yearly basis. The curves for the three scenarios overlap for the first 11 years after planting, which corresponds to the atmospheric CO_2 uptake through photosynthesis and storage in the woody biomass. The annual components and the prunings are omitted. In Scenario 1, at the end of twelve years after planting, all the carbon embedded in the woody biomass is re-emitted to the atmosphere, and starts to be slowly reabsorbed by the Earth's biogeochemical cycles, as shown by the decaying aspect of the curve. In Scenario 2, after twelve years, only the trunks are conserved, while branches and shanks, representing about 52% of the woody biomass in the orchard block, are burned. In Scenario 2, the wood is burnt from year 13 onwards, until it runs out. In the meantime, there are avoided CO_2 emissions from burning

natural gas, which is why the peak in Fig 5.4a is lower for this scenario compared to the peak in Scenario 1. In Scenario 3, the woody biomass of the orchard block is processed to produce biochar, bio-oil and bio-gas. Most of the carbon embedded in the biochar is sequestered for a long time in the soil following its application, and added to the avoided CO_2 emissions from burning the biochar co-products that displace natural gas and fuel oil for home heating.

In Fig. 5.4b, it is clear that all three scenarios have a beneficial radiative forcing impact, and are therefore taking, and keeping, carbon out of the atmosphere for at least a short amount of time. As already demonstrated by Levasseur et al. (2012), this highlights the importance of accounting for temporary carbon storage in LCA. However, the effects of Scenarios 1 and 2 are only temporary, because carbon is kept out of the atmosphere for only a short period of time. On the other hand, soil carbon sequestration through incorporation of biochar from woody biomass into the orchard soil has a permanent beneficial impact on global warming, assuming that this carbon is permanently kept out of the atmosphere.

Subsequently, the climate change impact of keeping atmospheric CO_2 locked in the wood of apple trees over 12 years for Scenarios 1 and 2, and a fraction of this carbon sequestered in the soil in the form of biochar for 100 years in Scenario 3, can be calculated following the procedure described in (Levasseur et al. 2010).

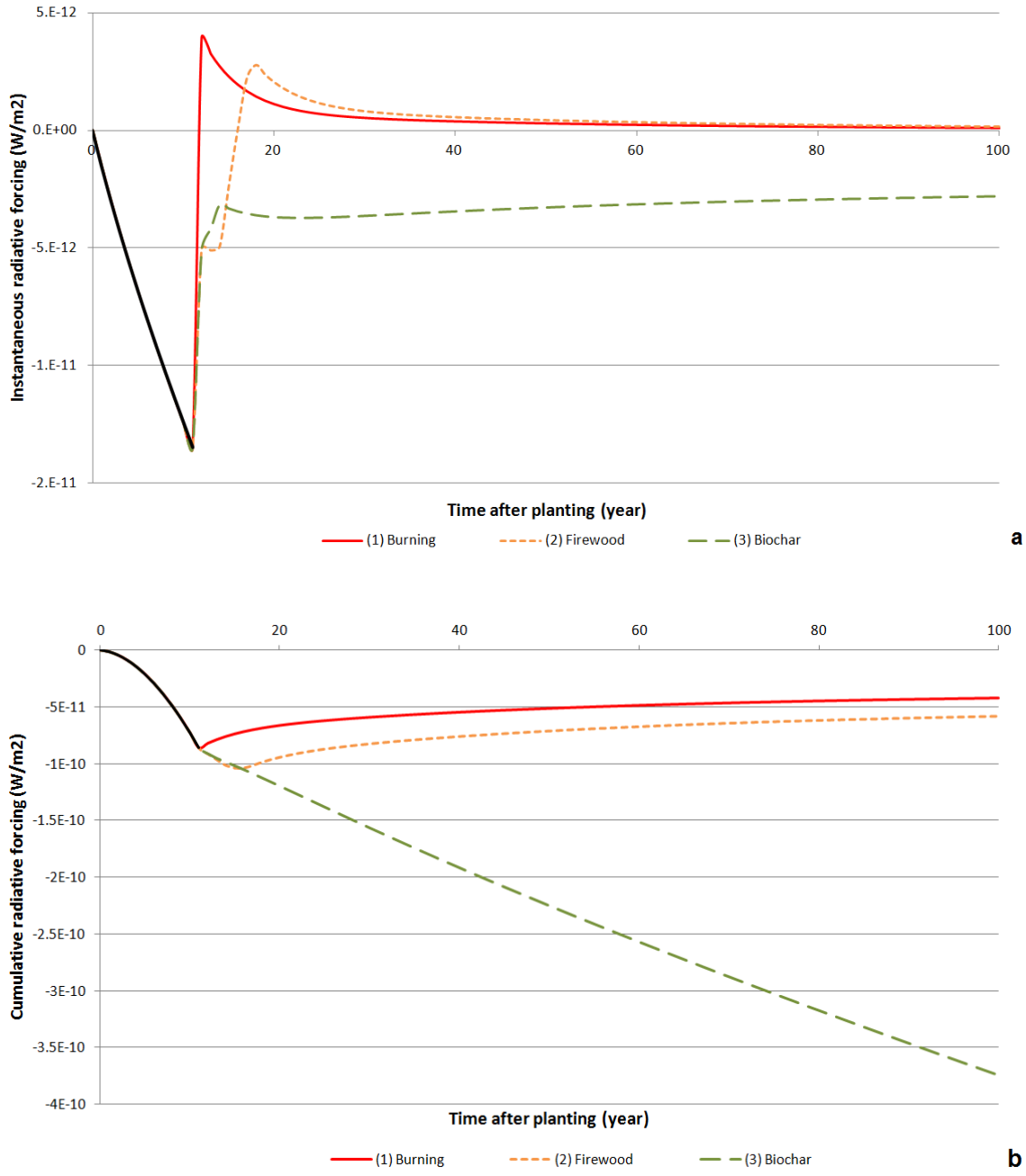

Figure 5. 4 (a) Instantaneous and (b) cumulative radiative forcing over time caused by one life cycle of an apple orchard block, including three end-of-life scenarios. In both (a) and (b), the curves for the three scenarios are overlaying each other for the first 11 years after planting (continuous black curve), corresponding to tree growth. These curves have been calculated following the method developed by Levasseur et al. (2010). Note the different scales for radiative forcing.

Finally, the climate change impact, in kg CO_2 equivalent, for both the IPCC method as well as the Dynamic LCA method, was used to determine the proportion of the NZ based (cradle to port) carbon footprint of a kg of NZ apples that is compensated for, using the CF value for apples described in Section 5.1.1. For these calculations, it is assumed that the apple

orchard produced 50 tons of export quality apples per hectare on average for the 12 years it remained standing. The results relative to the NZ based carbon footprint of a kg of NZ export apples are presented in Table 5.3.

Table 5. 4 Potential relative contribution of tree woody biomass as a percentage of the NZ based (cradle to port) carbon footprint of one kilogram of NZ apples exported to the UK (McLaren et al. 2009), as a function of the calculation method used and the timeframe chosen for assessment. The potential relative contribution of tree woody biomass as a percentage of the whole (cradle to grave) carbon footprint is show in brackets.

Method	IPCC (IPCC, 2006)		Dynamic LCA (Levasseur et al. 2010)	
Timeframe	20 years	100 years	20 years	100 years
Scenario 1: burning	0%	0%	0.82% (0.12%)	0.52% (0.08%)
Scenario 2: Firewood	0%	0%	1.16% (0.17%)	0.72% (0.11%)
Scenario 3: Biochar	7.8% (1.16%)	7.8% (1.16%)	1.47% (0.22%)	4.6% (0.69%)

First of all, it is important to note that the results presented in Figure 5.4 and Table 5.3 are only indicative. This is because the calculations do not account for the complete set of emissions and removals associated with the scenarios, following the assumptions described in Section 5.3.5.1 in this chapter. However, the assumptions are consistent across methods, timeframes and scenarios used and thus the results can nevertheless be discussed relative to each other. Furthermore, it should be borne in mind that the figures represent one life cycle of one orchard block of 0.54 ha.

Secondly, it is clear from Table 5.3 that different timeframes and calculation methods lead to different results, even for a single scenario. This is analogous to the conclusions of Levasseur et al. (2012). The results for all Scenarios using the dynamic LCA method show that selecting a shorter timeframe for assessment is equivalent to according more importance to what is happening at the beginning of the assessment period.

Thirdly, in Scenario 3, the IPCC results are identical for both timeframes. This is due to the IPCC accounting method which does not consider impacts on global warming, but rather the net carbon balance. For the same reason, the IPCC values are higher than the dynamic LCA results. Indeed, the dynamic LCA method takes into account the decay over time of each molecule of CO_2, corresponding to the re-absorption of these molecules by natural processes, such as dilution in the oceans.

Overall, growing trees keeps carbon out of the atmosphere, and even if this storage is temporary and the wood is burned at the end-of-life of the orchard block, it results in reduced global warming. Furthermore, using the wood for home heating or biochar accentuates this result. Using the dynamic LCA method, all scenarios directly result in a reduction of the carbon footprint of a kilogram of NZ apples. This reduction is 7.8% of the NZ based footprint (cradle to NZ port) for Scenario 3 using the IPCC method, 4.6% for scenario 3 using the Dynamic LCA method with 100 year timeframe, and below 1.5% for all other scenarios and timeframes using the Dynamic LCA method. When considering the cradle to grave carbon footprint, the order of magnitude of this reduction is around 1%.

However, if some technology allowed all the carbon embedded in the woody biomass of the 0.54 ha apple orchard block of this study to be stored for 100 years, and this orchard was replaced every 13 years by a new orchard block with similar characteristics, then 1.6 times the cradle-to-orchard gate carbon footprint of a kilogram of apples could be compensated for by simply keeping the land as an orchard block (see Box 5.1) This figure represents more than three quarters of the New Zealand-based footprint of a kg of apples, and about 11.5% of the cradle-to-grave carbon footprint.

Overall, these analyses give an order of magnitude of the potential carbon footprint reduction associated with the woody biomass of the orchard block.

Box 5.1 Scenario 4: orchard replaced every 13 years and 100% of the wood sequestered for 100 years.

For this Scenario 4, the following assumptions are considered:

- The 0.54 ha orchard block produces 4.99 t C/ha over 13 years, including 1 year of bare land (see Section 5.3.3).
- The orchard block is assumed to be replaced every 13 years for 100 years, and the carbon stock accumulated in woody biomass is assumed to be sequestered for 100 years.
- No carbon accumulation in woody biomass during the year of bare land is assumed.

For this particular setting, the Dynamic LCA method provides a value of 2795 kg CO_2eq accumulated over 100 years in the orchard block. Assuming a yield of 50 tonnes of apples per hectare and, according to McLaren et al. (2009) that the carbon footprint of apples is 0.9 kg CO_2eq per kg, the proportion P of the carbon footprint of a kg of apples compensated by the carbon accumulation in woody biomass would be 0.115 which is equivalent to 11.5% following this equation:

$$P = \frac{\frac{D_{LCA}}{A} \times \frac{1}{Y}}{CF \times 1000}$$

Here,

D_{LCA} is the Dynamic LCA result = 2795 kg CO_2eq

A is the area of the orchard block, = 0.54 hectare

Y is the yield of apples, = 50 tonnes per hectare

CF is the carbon footprint of apples, = 0.9 kg CO_2eq per kg of apples

And 1000 is a conversion factor to express the CF in kg CO_2eq per tonne of apples.

5.4. Conclusions

This chapter presents the first measurements of woody biomass in a commercial apple orchard block and explores the monitoring of woody biomass in apple orchards for the purpose of carbon footprinting.

Following a literature review of woody biomass and temporary storage , it was found that:

- There is a high variability in the woody biomass at various scales. Across a single orchard block, tree vigour and growth consistency depends on many factors, including local variation in soil texture. At the orchard scale different combinations of tree age, variety and rootstocks, tree spacing, and row spacing affect total standing woody biomass. At the regional scale, the management practices vary importantly. roviding a regional estimate from the measurement of a small proportion of orchard blocks is therefore uncertain.
- Considering the entire croping cycle as well as collecting site specific data and communicating sample size and uncertainty information will improve the reliability of the LCA for perennial cropping systems and of dynamic and process based models.
- Finally, harmonisation of methods and a consensus on protocols are urgently needed in the assessment of Land Use and Land Use Change in LCA.

Following the measurement and destructive harvest of 10 trees covering a wide range of trunk circumferences in an orchard block, as well as the measurement of trunk circumferences from 49 trees, it was found that measuring TCA could be used as a rapid and cost effective measure to estimate the total woody biomass stock at the orchard block scale and this can be used to calculate the standing carbon stock.

This method can be used to estimate regional biomass and carbon stocks in apple orchards for purposes such as carbon accounting in perennial croplands and for carbon footprinting.

The results of the Dynamic LCA method developed by Levasseur et al. (2010) showed that Temporary storage of atmospheric CO_2 in the woody biomass of apple orchards is beneficial for climate change, even if trees are burned at the end-of-life of the orchard block. Nonetheless, this benefit, of the order of 5%, is small compared to the NZ-based carbon footprint of a kilogram of apples exported to Europe.

Finally, the choice of a time horizon to assess the climate change impact of emissions and removals can make the carbon footprint results vary by several folds, and using the Dynamic LCA method is best to visualize these differences.

Based on this research, an indicative sampling protocol is described in Box 5.2 for assessing to estimate the standing carbon stock in an apple orchard block.

In summary, accounting for this temporarily sequestered carbon will provide incentives for orchardists to change their current practices and use the removed wood for other purposes rather than just burning for convenience. Some practical difficulties would need to be overcome, such as the removal of wires and posts, especially for trees on more dwarfing rootstocks.

In the future, it would be interesting to investigate the potential to use the above ground biomass of apple orchards for the production of other bioenergy sources, such as syngas and its subsequent transformation to liquid biodiesel. For this purpose, the implementation of medium to large size plants would be facilitated by the fact that apple orchards are highly centralised in two regions of New Zealand.

Box 5.2: Indicative protocol to estimate the standing carbon stock in an apple orchard block.

The aim of this protocol is to provide a method for estimating the above-ground standing carbon stock in an apple orchard block. It is the recommended approach, however, it involves cutting and drying a large number of trees, which can be costly and time consuming. A default approach is to directly use the relationship TCA vs tree weight provided in Section 5.3.3, although it has not been verified over for a range of soils, management practices and climatic conditions and therefore carries an important - and at this stage unknown - uncertainty.

1. **Delimit the area of assessment**

    a. The area of assessment should be limited to one orchard block including a combination of one cultivar and one rootstock. Tree size and vigour should be consistent within the orchard block, as well as management practices, especially pruning regime.

2. **Establish the relationship TCA vs tree weight**

    a. Select and tag 10 trees that cover the widest range of trunk circumferences available in the area of assessment.

    b. Measure the trunk circumference (C, in cm) 20 cm above the graft union, avoiding major asperities on the trunk.

    c. Determine the trunk cross sectional area (TCA, in cm^2) for each tree using the trunk circumference, using the formula:

$$TCA = C^2/4\pi$$

    d. Excavate the entire trees, including the root shank. This is best done with a small digger.

Box 5.2 (continued 1):

e. Cut and divide into the necessary parts such as root shank (below graft union), trunk (above graft union) and branches.

f. Oven-dry at 60°C until constant weight. Smaller cuts, perpendicular to the sap direction will allow faster drying.

g. Record the dry weight ($\mathrm{DM}_{\mathrm{tree}}$, in kg) of each tree separately.

h. Establish the linear approximation of the relationship TCA versus tree dry weight:

$$\mathrm{DM}_{\mathrm{tree}} = \mathrm{a} \times TCA_i + \mathrm{b}$$

Here, a and b are coefficients specific to the 10 trees destructively harvested.

3. Estimate the total standing carbon stock

a. Measure a large number (x) of trunk circumferences in the area of assessment and estimate their TCA using the formula in section 2.a.

b. Calculate the total woody biomass dry weight for orchard block (DM_{block}, in tonnes) using the formula:

$$DM_{block} = \frac{\sum_{i=1}^{x} \mathrm{DM}_{\mathrm{tree}}}{x \times 10^3} \times A_{block} \times D_{block}$$

Here, A_{block} is the area of assessment expressed in hectares (ha), D_{block} represents the tree planting density of this area, in trees/ ha, and 10^3 is a conversion factor of kg to tonnes.

Box 5.2 (continued 2):

c. Multiply the total biomass dry weight for the area assessed, by the carbon content of dry apple wood. As a default value, use 47% carbon content as determined by (Walton et al. 1999) to calculate the total standing carbon stock (in tonnes of carbon) of the area assessed.

Notes:

This protocol does not allow the determination of the uncertainty associated with the standing carbon stock estimate, and more research is needed to determine the number of trees needed in step 2.a and 3.a.

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Chapter 6:

Summary, discussion and conclusions

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6.1. Introduction

Soil carbon is essential for the sustainability of food production systems. It contributes to many of the ecosystem services provided by the soil, and its careful management can help mitigate climate change. However, the implementation and intensification of agriculture, in particular over the last century, has depleted the natural capital stocks of carbon in the soil in many places and this carbon has been released as CO_2 into the Earth's atmosphere. The natural and anthropogenic variability of soil-carbon stocks as well as their small changes over time relative to total soil-carbon stocks, make soil carbon a difficult and costly variable to measure, particularly at depth. Therefore, a general lack of data impairs our capacity to monitor soil carbon stocks. In consequence, accounting methods that quantify the greenhouse gas (GHG) emissions of products over their life cycles, namely Life Cycle Assessment (LCA) and carbon footprint (CF) methods, generally exclude the changes in soil carbon stocks from their analyses.

In New Zealand, horticultural products such as apples rely heavily on exports for commercialisation. However, the distance separating New Zealand from its export markets and the related GHG emissions associated with transporting products to market are a disadvantage for product marketing in countries where consumers are concerned about the environmental impacts associated with their products. On the other hand, horticultural production systems such as apple orchards have the potential to store large amounts of carbon, both above and below ground, due to atmospheric CO_2 uptake through photosynthesis. Therefore, if it can be demonstrated that the production of apples in New Zealand apple orchards increases, or at least maintains, the carbon stocks of the soil and above ground in orchards, this could lead to a reduced carbon footprint for New Zealand apples. This reduced carbon footprint may not only constitute a competitive advantage, but it could become a requirement for market access in the future. The NZ apple industry is therefore interested to find ways of improving its "green" image in overseas markets, as well as in mitigating climate change and realising benefits from enhanced ecosystem-services.

While the changes in soil carbon stocks are excluded in a majority of Life Cycle Assessment (LCA) and carbon footprint (CF) methods, a review of case studies (see Chapter 2) that account for the changes in soil-carbon helped identify the relative importance of these changes, the major issues, and the related research needs.

In LCA and CF studies assessing the climate-change and soil quality impacts of land-based systems, inclusion of soil-carbon stocks and change can have a large impact on the results (see Section 2.3.2), and Section 2.3.3 highlighted the related issues. The literature review confirmed that there is a crucial lack of soil carbon stocks and change data. Furthermore, while soil-carbon stocks and their changes over time are governed by site-specific factors, most studies have used data that are not site-specific. Various dynamic or biophysical models to predict changes in soil-carbon stocks have been used, but the lack of data doesn't allow for testing and validation of these models at the site-specific level. Therefore the vast majority of soil-carbon related results in LCA are characterised by a large, yet often not quantified, uncertainty.

Additionally, the time-related aspects of land-based production systems such as the influence of crop rotations, and the timing of emissions and removals of soil carbon and their impact on radiative forcing, are in most cases omitted. Furthermore, the choice of a reference against which any soil carbon change is calculated is arbitrary and contentious, and calculation of impacts associated with indirect Land Use Change depends upon complex economic and environmental factors. Finally, any permanent impact of a change in soil-carbon stocks depends on what happens to the land in the future, beyond the assessment timeframe, and is therefore highly uncertain.

The conclusion of the review (Section 2.3.4) therefore identified several research gaps:

- Research focusing on collecting data on soil-carbon stocks and change is required. Deep, site specific, geo-localised and time dependent soil carbon estimates are needed.

- The inherent variability and statistical uncertainty of soil carbon stock averages needs to be quantified and stated in LCA and CF studies assessing land-based systems. This will improve the transparency of these studies.
- Soil carbon stocks and change data need to be accompanied by information describing the environmental and management conditions associated with these data. Such information will facilitate the testing and calibration of soil carbon models and therefore contribute to reducing the uncertainty of future soil-carbon stocks and change predictions.

If these gaps are addressed, LCA and CF results will become more accurate and reliable, and thus provide better support to decision-making.

6.1.1. Objectives

In order to address these research gaps, the main aim of this research was to develop a practical methodology to measure a statistically significant and powerful change in the soil carbon stock of an apple orchard block in New Zealand, and a methodology to estimate the ongoing biomass carbon stock in apple orchards, in order to provide reliable data for the carbon footprint of New Zealand apples.

Since there are no data available on changes in soil-carbon stocks in apple orchards, this research sought to quantify these changes by means of a chrono-sequence.

The specific objectives of the research were therefore:

1. To quantify the spatial variability, both horizontally and with depth, of the soil's carbon content, bulk density and carbon stock in an apple orchard block, in order to define the minimum sampling requirements to measure and monitor these soil parameters at the orchard block scale, and to infer the cost of such monitoring.

2. To determine the possibility of observing a statistically significant and powerful change in soil carbon stocks using a chrono-sequence of four orchard blocks aged 1 to 12 years after planting.

3. To develop a method to quantify the woody biomass carbon stock in an apple orchard block on a routine basis, and to estimate the importance of this carbon stock for the carbon footprint of NZ apples.

4. To define standard protocols to measure and monitor soil carbon stocks and woody biomass carbon stocks in apple orchards.

6.2. Objective 1: Spatial variability and sampling requirements

In order to start filling the data gaps, intensive soil sampling at both the tree and the orchard-block scales of an apple orchard block was carried out. The results are presented in Chapter 3. The quantified variability of the soil's carbon content, bulk density and carbon stock helped determine the minimum sampling requirements and the associated costs for measuring and monitoring soil carbon stocks in an apple orchard block.

It was found that the planting pattern at the tree and the orchard block scales affected the soil's bulk density, carbon content and carbon stock:

- In the top 50 cm of soil, carbon content decreased at a rate of 0.29% C/m with increasing distance away from a tree, potentially influenced by tree and grass roots. For the 0-100 cm soil layer, bulk density (BD) was significantly different between tree row and grass alley while carbon content (%C) and carbon stocks were not (see Section 3.3.1)
- At the orchard block scale, the variation of %C between sampling sites was relatively low (CV= 4.7%) in the 0-50 cm soil layer, while it was relatively high (CV=24.3%) in the 50-100 cm layer. Semi-variograms showed that the variance between 0-50 cm-depth soil samples was mostly non spatial, but increased up to a distance of 13.6 m.

In contrast, the variance between 50-100 cm-depth samples was almost only distance-dependent. As a result, the variance in the top meter of soil was partly non-spatially correlated, and partly increasing with the distance between samples. Some 80% of the carbon stock in the top metre of soil was measured by sampling to at least 50 cm depth although a number of studies suggest sampling deeper depths (see Section 3.3.2).

In view of these results, the minimum requirements for this orchard block should involve sampling to a depth of one metre, evenly between and outside the wheel tracks within sampling sites. Also, repeating sampling at the tree scale to represent all the areas at the tree scale, as well as stratifying the sampling across a systematic grid with a minimum grid cell size of 13.6 m is required.

In addition, pooling core samples in each sampling site reduces the costs of monitoring because fewer samples are processed and analysed. Therefore the number of sampling sites required to detect a change in soil carbon stocks as a function of the number of pooled cores per site was investigated in Section 3.3.3. As a result, sampling more sites with fewer samples per site enables detection of smaller changes. However, a minimum of four to six samples per site is required in order to reduce the variance of the orchard block mean.

Considering the site-specific conditions of the orchard block and reasonable cost assumptions for sampling, processing and analyses of the samples, detecting a change of 10% of the mean in the top metre involved a cost of NZ$1590 per sampling campaign, and required sampling nine sites at a rate of four samples per site. This cost of measuring and monitoring soil carbon stocks is equivalent to a price premium of 0.5% of the value of apples produced from a New Zealand apple orchard.

Therefore, despite its inherent variability, measuring and monitoring soil-carbon stocks to one meter depth in apple orchards seems practically and economically feasible. However, one young apple orchard block was assessed and these results needed to be repeated and

confirmed to develop a standard protocol for measuring and monitoring soil-carbon stocks in apple orchards (see Section 6.6). Therefore, three other orchard blocks were selected constituting a chrono-sequence of four similar apple orchard blocks planted one to 12 years before sampling (see Chapter 4), including the block used in the research reported in Chapter 3. The exact same investigative sampling strategy as was implemented in the research reported in Chapter 3, was also conducted in the three additional blocks. It was found that:

- The variability of soil carbon stocks horizontally and with depth was different for each of the orchard blocks of the chrono-sequence (see Sections 4.3.3 and 4.3.4). Therefore it is not possible to generalise a defined number of samples for a standard protocol applicable to all orchard blocks.
- The carbon content of the 0-50 cm soil layer was correlated with the distance to the nearest tree in the four and six year-old orchard blocks, but a statistically significant decreasing trend was only observed in the four year old block. There was no observable correlation in the one and twelve year old blocks. The growth pattern of the roots of young apple trees, growing in a bowl shape could explain these observations. In addition, the different levels of variation of soil-carbon stocks in the four orchard blocks and the variations in soil carbon stocks at the orchard block scale were in general non-spatial (see Section 4.3.2). Therefore sampling at the scale of the orchard block is necessary when monitoring soil-carbon stocks in apple orchards. Also, a systematic sampling or a “block sampling” strategy is best adapted to measure and monitor soil carbon stocks.
- The soil-carbon stocks of the six-year-old block were used to determine the sampling requirements for monitoring soil carbon stocks considering its relatively higher level of variability (CV=14% for the 0-100 cm layer) compared to the other blocks. As a result, in the six-year-old block, a change of 10% of the mean could in theory be

observed by collecting a total of 78 samples, bulked two by two, for carbon content, and 39 bulk density profiles, all to one meter depth (see Section 4.3.5).

- For the six-year-old block, an illustrative cost analysis indicated that monitoring soil-carbon stocks every 20 years in this block would cost NZ$ 9,420 assuming an average change of 0.5% of the mean soil-carbon stock per year (0.7t-C/ha/year). Compensating for the cost of this monitoring represents an increase of approximately 1.0% of the price of a carton of apples at the ship side in New Zealand (see Section 4.3.6). Therefore even in this relatively more variable orchard block, measuring and monitoring soil-carbon stocks seems affordable given the right market signals.

6.3. Objective 2: Change in soil carbon stocks

An experiment to observe a change over time in the stocks of carbon in apple orchard soils through a 12 year chrono-sequence is described in Chapter 4.

The comparison of soil carbon stocks between orchard blocks indicated that the four-year-old block had significantly higher soil-carbon stocks compared with the three other blocks. Most likely, this results from the effect of a flooding incident in the 1980s (see Section 4.3.3). Considering the three other blocks, it was not possible to observe a statistically significant change in soil-carbon stocks over the 12 years of the chrono-sequence, despite an important sampling effort. There are two alternative explanations for this result:

- The current sampling regime needs to be expanded to collect more samples, or it needs to be extended over a longer time period, in order to observe a statistically significant change.
- Alternatively, it may be that current management practices are actually maintaining soil-carbon stocks over time. This finding needs testing over a range of soils, climates and management practices in order to be generalised in any way. If this is the correct explanation, then current management practices in these three orchard

blocks are sustainable with regards to soil-carbon stocks, and measuring and monitoring soil-carbon stocks might not be required if management practices remain constant.

Nevertheless, measuring and monitoring soil-carbon stocks is merited in order to assess the potential of management practices to increase soil-carbon stocks. The results suggest that it would best be done over the 15 to 20 years between orchard redevelopments, in order to increase the chance of detecting a statistically significant change over time.

6.4. Objective 3: estimating biogenic carbon stocks and implications for the carbon footprint of NZ apples.

In a similar way as for the soil carbon stock, there is a lack of data and methods for quantifying the standing stocks of carbon in the woody biomass of apple orchards, and LCA and CF methods for assessing this temporary carbon storage are still debated. Therefore, Chapter 5 considers the relevant literature, proposes a practical and cost effective method to quantify the woody biomass carbon stock in an apple orchard block, and compares three end-of-life scenarios for the apple trees and their potential impact on the carbon footprint of New Zealand apples: burning (the current practice), chopping trunks for firewood, and producing biochar to add to the soil.

The literature review in Chapter 5 revealed a reported high variability in the woody biomass in apple orchards at the orchard scale due to many factors, including environmental characteristics as well as management decisions. At the regional scale, a range of management practices (such as pruning and tree replacement policy) increase the variability (see Section 5.1.3). Therefore, obtaining a regional estimate from the measurement of a small proportion of orchard blocks is uncertain. Due to the variability, better estimates of the above ground biomass at all scales involve measurements of the woody biomass at the

orchard block scale. Practically, these measurements can only be carried out during orchard re-development due to their destructive nature.

In addition, the literature review suggested that site specific data, accompanied with sample size and uncertainty information are needed. Also, in LCA studies of perennial systems, consideration of the entire crop cycle, as well as harmonised and agreed-upon methods for Land Use and Land Use Change assessment are required. These would improve the quality and reliability of the results of LCA studies for perennial cropping systems, including apple production systems and the accuracy of predictions of dynamic and process-based models:

To quantify the woody biomass carbon stock in a commercial apple orchard block, a practical and cost effective method is needed. For its development, 10 trees covering a wide range of trunk circumferences in an orchard block were measured and destructively harvested in order to build a relationship between the trunk cross-sectional area (TCA) and the woody dry mass (DM) of the trees. Also, the TCA from of 49 trees was estimated from their trunk circumferences (see Section 5.2.1).

It was found that, estimating TCA from trunk circumferences is rapid and cost effective and could allow estimating the total woody biomass stock at the orchard block scale. However, the relationship between TCA and DM might be orchard-block specific. Subsequently, this estimate can be used to convert woody biomass stock to standing carbon stock. The method could be used to estimate more accurately regional biomass and carbon stocks in apple orchards for purposes such as carbon accounting in perennial croplands and for carbon footprinting.

This woody biomass of the trees at end-of-life could be utilized for several purposes, and the impact on the carbon footprint of New Zealand apples of three end-of-life scenarios for the trees were investigated (see Section 5.3.4). These included the common and current practice of simply burning the trees at the end of the orchard cycle, the recovery of the trunks for firewood, and the transformation of the entire standing woody biomass into biochar

for its subsequent application to the orchard soil. The Dynamic LCA method was used to account for the time-dependent impact on radiative forcing of the sequestration of atmospheric CO_2 in the woody biomass of apple orchards through photosynthesis. Overall it was found that:

- All scenarios maintained carbon out of the atmosphere, and this temporary storage is beneficial for climate change, even if trees are burned at the end-of-life of the orchard block.
- This benefit is of the order of 1% compared with the carbon footprint of a kilogram of apples exported to Europe. Even compared to the NZ-based portion of this footprint, this order of magnitude remains inferior to 5%.
- The biochar production for woody biomass provides the most reduction compared to the other scenarios. Additionally, biochar application to soils may provide other benefits such as enhancing soil fertility and reducing nutrient leaching, although this depends on many factors.
- The use of the Dynamic LCA method highlighted that the choice of a time horizon to assess the climate change impact of emissions and removals was critical: for the biochar scenario, the carbon footprint reduction calculated over 100 years was about three times the carbon footprint reduction calculated over 20 years.

In summary, it can be concluded that accounting for this temporarily sequestered carbon is important because at least it will provide an incentive for orchardists to avoid burning the standing biomass in the orchard purely for convenience.

6.5. Objective 4: standard protocols

Overall, this research has highlighted the necessity and the feasibility - both practically and economically - of measuring and monitoring the change in soil and biomass carbon stocks in apple orchards for multiple purposes. These include insuring the sustainability of the natural

capital stocks of soil carbon, and providing reliable data for the carbon footprinting of New Zealand apples as well as to improve soil-carbon models and their future predictions to inform policy decisions.

Chapter 3 and 4 present the development and validation of a detailed sampling strategy that is affordable and potentially adaptable to all apple orchard blocks, for measuring and monitoring soil-carbon stocks to one meter depth. An indicative protocol to measure and monitor soil-carbon stocks in an apple orchard block is presented in Box 4.1.

Chapter 5 presents the first rapid and cost effective method for the measurements of woody biomass and its embedded standing carbon stocks in a commercial apple orchard block. An indicative protocol to estimate the standing carbon stock in an apple orchard block is given in Box 5.2.

6.6. Discussion and conclusions

In this research, a practical methodology to measure a statistically significant and powerful change in the soil carbon stock of an apple orchard block, and a methodology to estimate the ongoing biomass carbon stock in apple orchards, were developed.

In the future, if demonstration of a maintenance or reduction in the carbon footprint of apples is required for shelf access in global supermarkets, monitoring soil and biomass carbon stocks using these methodologies is therefore possible. The costs of measuring and monitoring soil carbon stocks presented in this study seem small, and implementing such a sampling campaign is a credible option for the New Zealand apple industry. Financial incentives, such as price premiums for food products with environmental credentials, could support the routine monitoring of soil-carbon stocks.

In addition, this research developed the protocols to allow for the compulsory accounting of soil and biogenic carbon stocks in carbon footprint and LCA studies of apple orchards. This accounting could constitute a “push” towards facilitation of measuring and monitoring of soil-

carbon stocks, which would provide invaluable data towards calibrating models increasingly suggested and used to inform policy decisions. In this sense, this thesis presents an important amount of data on soil and biogenic carbon stocks in apple orchards, and therefore contributes to improving the scientific understanding of changes in soil-carbon stocks.

While this research evaluates briefly the potential impact on climate change of re-using the above ground biomass of apple orchards for the production of other bioenergy sources, advanced technologies such as syngas and its subsequent transformation to liquid biodiesel could be investigated. For this purpose, the implementation of medium to large size plants would be facilitated by the fact that apple orchards are highly centralised in two regions of New Zealand: the Hawke's Bay and Nelson.

Furthermore, it is critical to consider at all times the necessity of calculating, using statistical significance as well as statistical power, the minimum sampling requirements before any sampling campaign starts. This avoids the wasting of scarce resources in samplings that would be destined to fail. As well, such considerations give the best chance of observing the statistically significant differences sought. If these critical analyses are not performed at the design stage, a post-hoc power analysis should be carried out, to determine the likeliness of observing a statistically significant difference between treatments. A power level of 0.8 is the generally accepted minimum requirement. Useful references include Webster (2001), Barker Bausell and Li (2002), Syswerda et al. (2011) and Kravchenko and Robertson (2011).

It is important to point out that the variability levels of soil-carbon stocks presented in this thesis are probably, at most, in the middle of the natural variability range, because the orchard blocks were carefully selected for their homogeneity of soil texture to one metre depth, their depth of the water table, the management practices, as well as general tree health and canopy size. However implementing the sampling strategy developed in this

thesis with higher variability level may require dividing the area to be assessed in smaller blocks of higher homogeneity.

Practically, in the application of methods and protocols to measure and monitor soil-carbon stocks in agricultural fields, there is a need to assess the time and effort required to performing such measurements routinely, as well as the potential consequences of soil sampling on future crop health and orchard economics. Examples of questions to answer are: What are the time and practical constraints of access to the sampling area? What is the physical difficulty of collecting and processing the samples? How could the physical disturbance of the soil impact the dynamics in the sampling area? Are there any potential impacts of sampling on the financial returns to the owner of the agricultural field? Additionally, an estimate of the total time required for a sampling campaign will need to be conservative because new problems invariably arise during measurement of natural variables and processes, and solving them may require creativity and assessment of their impact on the results.

Regarding future research, investment would be welcomed into new, high resolution, cheaper and faster technologies that exists to measure soil carbon stocks. Large efforts are made to make soil carbon measurements cheaper and faster, and such technologies allow widespread and routine non-destructive measurements and real-time monitoring of soil carbon stocks. One rapidly developing technology is Visible Near Infra-Red (VNIR or Vis-NIR) spectroscopy (e.g. Kim et al. 2014), which can be used in combination with Electromagnetic Mapping (EM) covariates (Roudier et al. 2012) in order to minimise the soil carbon sampling effort, and produce detailed maps of several soil characteristics, including soil carbon stocks, while reducing the soil sampling efforts to less than half.

However, until these new technologies are adopted for routine measurements and sampling requirements are reduced, it is important to continue with the soil sampling effort in order to:

- Provide meaningful data to calibrate models that assess the carbon sequestering efficiency of management practices and that can therefore inform improved soil-carbon management.

- Provide realistic and credible estimates for the various tools assessing the potential environmental impacts of products and services, such as Life Cycle Assessment and carbon footprinting. This will allow decision makers and consumers at international, national, regional and local levels to base their decisions on peer reviewed scientific evidence, rather than un-calibrated models, expert opinions, or value choices.

Gaining a better understanding of the carbon dynamics in the soil, which control so many of the ecosystem services delivered to all humans, is a modest but sure step towards a sustainable future.

6.7. References

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Appendix A1.1 General principles of LCA

In LCA, environmental aspects (rather than social or economic) of products or services are assessed. A life cycle perspective is adopted in LCA, beginning with the extraction of raw materials, through the production phase, the product's use and waste treatment, through to the final disposal (Baumann and Tillman 2004). LCA can be used in a range of contexts, such as the identification of environmental improvement opportunities, informing decision makers, or marketing purposes (ISO 2006a). The transparency principle ensures proper interpretation of results and the comprehensiveness principle, the identification of tradeoffs between the related aspects of the natural environment, human health and resources associated with a product life cycle. Finally, priority is given to the scientific approach (natural science or other sciences based) to define the various methodological decisions within LCA, although value choices are permitted if this is not possible. Here, a short overview of LCA is provided since the method has been extensively described in numerous books (e.g. Baumann and Tillman 2004), and has its own ISO standards:

- ISO 14040: 2006 "Environmental management — Life cycle assessment — Principles and framework" (ISO 2006a), and
- ISO 14044: 2006 "Environmental management — Life cycle assessment — Requirements and guidelines" (ISO 2006b)

There are four phases of LCA: the goal and scope definition, the life cycle inventory stage (LCI), life cycle impact assessment (LCIA) and then interpretation.

Goal and scope

First, the goal and scope of the study are defined. This could be the environmental impact of producing one kg of a product or comparing two products on with regard to the same unit of product or service delivered. An LCA can be conducted in different ways, and the ISO standards allow flexibility.

This step includes:

- The definition of a “functional unit” to measure inputs and outputs associated with the system on a common basis.
- The definition of system boundaries which delimits whether processes are included or excluded in the analysis.
- The justification of the assumptions and limitations of the study, for example, exclusion of processes if the specific data are not available.
- The design of a flow diagram of the product system which details the various stages and processes of the product system. This flow diagram is often called the LCA model, although it is very different from a biophysical, deterministic, mathematical or ecosystem model. The aim of an LCA model is not to simulate natural processes, but its main objective is to visualise and describe the flows of goods and services between industrial processes.
- The description of allocation procedures, which allow for the distribution of inputs and emissions in the case that several products result from the same process.

Inventory Analysis

At Inventory Analysis, data representing the flows of inputs, such as raw materials and energy, and outputs, such as emissions and waste to the environment, for each process within the system boundary are collected. The LCA practitioner generally gathers these data by sending questionnaires to respondents, or by generating it from databases available in the various LCA tools.

Impact Assessment

In LCA, the evaluation of the environmental impacts of production is performed with the aim to safeguard “areas for protection”. Different classifications exist in the literature, although the natural environment, human health and resources are the three main areas for protection. “Environmental mechanisms” describe the chain of relationships between the human interventions, inputs to, and outputs from the production system, and the areas for protection. Life Cycle Impact Assessment (LCIA) addresses only the environmental issues that are specified in the goal and scope. LCIA consists of classifying inputs and outputs from the LCI in accordance with environmental mechanisms and relating these to impact categories. Impact categories are chosen, such as resource depletion, eutrophication, climate change, toxicity and others, and these choices depend on the goal and scope of the study. Practically, for each impact category, the LCI results are multiplied by a “characterisation factor” to be expressed in the specific impact category unit. Although there is no scientific basis for it, it is possible through the process of “weighing”, to reduce various category indicators (that have different units) to one overall score or number (ISO 14040). ISO 14040 refers, as well as category indicators, to category “endpoints” which are defined as “*attribute or aspect of* [the areas for protection] *identifying an environmental issue giving cause for concern”* and can be used to characterise impact categories. However, because they are situated closer to the end of environmental mechanisms, category endpoints results are very uncertain.

Interpretation

The purpose of the interpretation phase is to consider the results from the LCI and LCIA phase together, according to the goal and scope of the study. The interpretation is needed to verify the study as complete and consistent, and a sensitivity analysis is performed. The LCA practitioner evaluates the effect of changing or modifying the quantity of several inputs, or outputs, on the final results. Lastly the justified conclusions, explained limitations and recommendations are provided to complete the interpretation phase. An LCA study requires peer review only if it is to be released to the public.

Appendix A1.2 Soil-carbon stocks: Inventory and reporting under IPCC guidelines

An introduction to the IPCC methodology to inventory and report changes in soil carbon stocks is briefly presented in this appendix, together with an example calculation.

Volume 4 of the Guidelines for National GHG Inventories (IPCC 2006) is on "Agriculture, Forestry and Other Land Uses" (AFOLU), and is an evolution of three previous IPCC documents:

- Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 1997).
- The Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories (IPCC 2000).
- the Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC 2003).

The AFOLU chapter provides a guide on inventory formulation and the reporting of GHG emissions and removals at a country level. It covers all managed land use types: Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land. For each land category, guidance is given separately for land remaining in the same category (also called land use), and land converted into another category (also called land use change or land conversion).For each land category, the methodology to consider changes in carbon stocks of biomass, dead organic matter and soil carbon are included. The calculation of GHG emissions and removals is organised in three tiers that "*that range from default emission factors and simple equations to the use of country-specific data and models to accommodate national circumstances*" (IPCC 2006). Therefore, reporting under a higher tier indicates a higher level of accuracy, and lower uncertainty in the reported values. Considering the importance for climate change mitigation of the changes in soil carbon

stocks resulting from land use, as opposed to land use change, an overview of the section considering soil-carbon stock change for cropland that remains cropland is provided below.

Three sinks and sources for GHGs are defined by the IPCC, and calculated separately. These are “mineral soils”, “organic soils” and “liming”. The calculation method for mineral soils is described here, as an example.

Tier 1 is the simplest way to calculate the inventory and report changes in the soil-carbon stock. This only requires the use of default stocks and coefficients provided by the guidelines. For mineral soils, under Tier 1, the difference in soil-carbon stocks between the beginning and the end of the inventory time-period is calculated. Both stock values are calculated from default soil-carbon stock reference averages, which depend on the climate region and soil types. For each given reference stock characterised by its particular soil-climate combination, a default error estimate of +/- 90% of the stock value is assumed, being the equivalent to two standard deviations. Furthermore, three multiplication coefficients are applied to the reference stocks, depending on land use type (long term cultivated, paddy rice, perennial tree crop, and set aside), tillage regime (full, reduced and no till) and input quantity (low, medium or high, with or without the addition of manure). The ranges for each of these multiplication coefficients are: 0.48 to 1.10 depending on land use type, 1.00 to 1.22 for tillage regime and 0.92 to 1.44 for input quantity. An error band of +/- 4% to +/- 61% applies for the specific multiplication coefficients, making it clear that estimates of changes in soil-carbon stocks under Tier 1 are, at best, highly uncertain. A fixed assessment timeframe of 20 years is used to calculate these changes, and by default only the carbon stocks in the top 30 cm of soil are considered. An example calculation for perennial cropland is described in Table A1.2.1. In this example, in a warm temperate, moist climate region, perennial cropland (e.g. fruit trees) has been established for more than 40 years (although the average yearly change in soil-carbon stock is calculated for the last 20 years) on a drained wetland soil, and has been managed the same way: no till, with a medium input rate. The annual change in soil carbon stocks is calculated according to IPCC default values (IPCC, 2006).

The nominal error of each value and each coefficient is propagated to the annual change in soil carbon stocks according to approach 1 for error propagation of the IPCC guidelines (Section 3.2.3., Chapter 3, Volume 1, IPCC (2006)), and corrected with the procedure to for dealing with large uncertainties in approach 1 (Section 3.2.7., Chapter 3, Volume 1, IPCC (2006))

Reporting under Tier 2 involves using the same equations, default stocks and coefficients as developed for Tier 1, but requires the use of country specific data to improve some components used for the calculation. Tier 1 management systems, climate region and soil types can be disaggregated, and a different reference C stock can be chosen if it improves the robustness of the assessment. The stock-change factors that are specific to any country can also be estimated from measurements and modelling.

It is worth noting that reporting under Tier 1 and 2 is based on two major assumptions:

- the linearity of changes in soil-carbon stocks over time,
- the fact that an equilibrium soil-carbon stock is eventually reached over time.

On the other hand, Tier 3 reporting requires capturing annual variations of soil-carbon stocks in specific locations through either dynamic modelling or measurements, or both. Reporting under Tier 3 can be carried by using mechanistic models, which have been updated and verified thanks to benchmark monitoring sites that are regularly sampled. Alternatively, it is possible to use a measurement-based inventory through regular monitoring. This can either be based on soil sampling, or through the use of eddy correlation flux towers[1]. However, while soil sampling is likely to be time and cost intensive, and flux-tower measurements require a high number of units of expensive equipment to cover the whole country.

[1] Eddy correlation flux towers are instruments allowing the simultaneous recording of vertical air flows (also called “eddies”) and GHGs concentrations, both at a very high frequency. This equipment allows the measurement of average GHG exchanges between land and atmosphere over very large areas such as an agricultural field. One disadvantage of this method is that it is difficult to attribute the average flow to the numerous individual components of the land responsible for this overall flow, such as soil, vegetation, animals, and waterways.

In conclusion, the three tiers methodology developed by the IPCC to carry out the inventory and report GHG emissions and removals at a country level allows for a clear understanding of the level of spatial differentiation and accuracy of the estimates used, thanks to the calculation of uncertainty. For changes in soil-carbon stocks, this expression of uncertainty is extremely important, because it helps realising the large spatial variability of the stocks, and therefore encourages higher tiers to be used for these estimations.

Sector	Agriculture, Forestry and Other Land Use								
Category	Cropland Remaining Cropland: Annual change in carbon stocks in mineral soils								
Equation	**EQUATION 2.25** **ANNUAL CHANGE IN ORGANIC CARBON STOCKS IN MINERAL SOILS** $$\Delta C_{Mineral} = \frac{(SOC_0 - SOC_{(0-T)})}{D}$$ $$SOC = \sum_{c,s,i} \left(SOC_{REF_{c,s,i}} \bullet F_{LU_{c,s,i}} \bullet F_{MG_{c,s,i}} \bullet F_{I_{c,s,i}} \bullet A_{c,s,i} \right)$$								
Land-use category	Area in the last year of an inventory period	Area at the beginning of an inventory period	Reference carbon stock in the last year of an inventory period	Reference carbon stock at the beginning of an inventory period	Time dependence of stock change factors (D)	Stock change factor for land-use system or sub-system	Stock change factor for manage-ment regime	Stock change factor for input of organic matter	Annual change in carbon stocks in mineral soils
Unit	ha	ha	tonnes C ha^{-1} (0-30cm)	tonnes C ha^{-1} (0-30cm)	Years (default is 20 years)	-	-	-	tonnes C yr^{-1}
Equation parameters	**$A_{(0)}$**	**$A_{(0-T)}$**	**$SOC_{ref(0)}$**	**$SOC_{ref(T-0)}$**	**D**	**F_{LU}**	**F_{MG}**	**F_I**	**$\Delta C_{Mineral}$**
Parameters' values	1	1	**116.4**	**101.2**	20	1	1.15	1	**0.8**
Nominative error	-	-	**+/-134%**	**+/- 110 %**	-	+/- 50%	+/- 4%	-	**+/- 93%**

Table A1.2.1 Table detailing the equation for the calculation of changes in soil-carbon stocks in mineral soils for cropland remaining cropland. Example of perennial cropland under a tier 1 methodology. Adapted from worksheet "3B2a cropland remaining cropland", available at http://www.ipcc-nggip.iges.or.jp/public/2006gl/worksheets/3B2a_CL%20Remaining%20CL.xls. Equation 2.25 is from IPCC (2006)

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Appendix A1.3: Documents that aim at being a globally recognised product carbon footprint standard

A general introduction to the PAS2050:2011, the GHG protocols and the ISO TS 14067, is succinctly presented in this Appendix.

The PAS2050:2011, the GHG protocols and the ISO TS 14067 provides requirements and guidelines to assess GHG emissions from the life cycle of products. These documents therefore focus on the single issue: the global warming impact of GHG emissions. Subsequently, they do not account for other environmental consequences of product systems, such as toxicity or biodiversity effects.

PAS2050

The PAS 2050 was developed by the British Standard Institute (BSI), to answer a "*broad community and industry desire for a consistent method for assessing the life cycle GHG emissions of goods and services*", and was first published in 2008. It builds on ISO 14040 and ISO 14044 (see Box 1). Following two years of use experience, the PAS2050:2008 was revised and replaced by the PAS2050:2011. The PAS 2050:2011 states its objectives as:

"*PAS 2050 offers organizations a method to deliver improved understanding of the GHG emissions arising from their supply chains, but the primary objective of this PAS is to provide a common basis for GHG emission quantification that will inform and enable meaningful GHG emission reduction programmes.*"

In the PAS2050:2011, "*requirements are specified for identifying the system boundary, the sources of GHG emissions associated with products that fall inside the system boundary, the data requirements for carrying out the analysis, and the calculation of the results.*" However, the document "*does not specify requirements for the disclosure or communication of the results of a quantification of the life cycle GHG emissions of goods and services.*"

GHG protocol initiative

The Greenhouse Gas Protocol Initiative (GHG PI) was launched in 1998, and "[…] *is a multi-stakeholder partnership of businesses, non-governmental organizations (NGOs), governments, and others, convened by the World Resources Institute (WRI) […], and the World Business Council for Sustainable Development (WBCSD)[…]."* The GHG PI states its missions as: "*to develop internationally accepted greenhouse gas accounting and reporting standards and tools, and to promote their adoption in order to achieve a low emissions economy worldwide*."

The GHG PI published a number of standards, protocols and guidelines since 1998, including three main standards for GHG accounting and reporting.

- ***GHG Protocol Corporate Accounting and Reporting Standard*** *(2004): A standardized methodology for companies to quantify and report their corporate GHG emissions.*
- ***GHG Protocol Product Life Cycle Accounting and Reporting Standard*** *(2011): A standardized methodology to quantify and report GHG emissions associated with individual products throughout their life cycle. Also referred to as the Product Standard.*
- ***GHG Protocol Corporate Value Chain (Scope 3) Accounting and Reporting Standard*** *(2011): A standardized methodology for companies to quantify and report their corporate value chain (scope 3) GHG emissions, to be used in conjunction with the Corporate Standard. Also referred to as the Scope 3 Standard.*

The relationship between the Product Standard, the Corporate Standard, and the Scope 3 Standard are described in Figure A1:

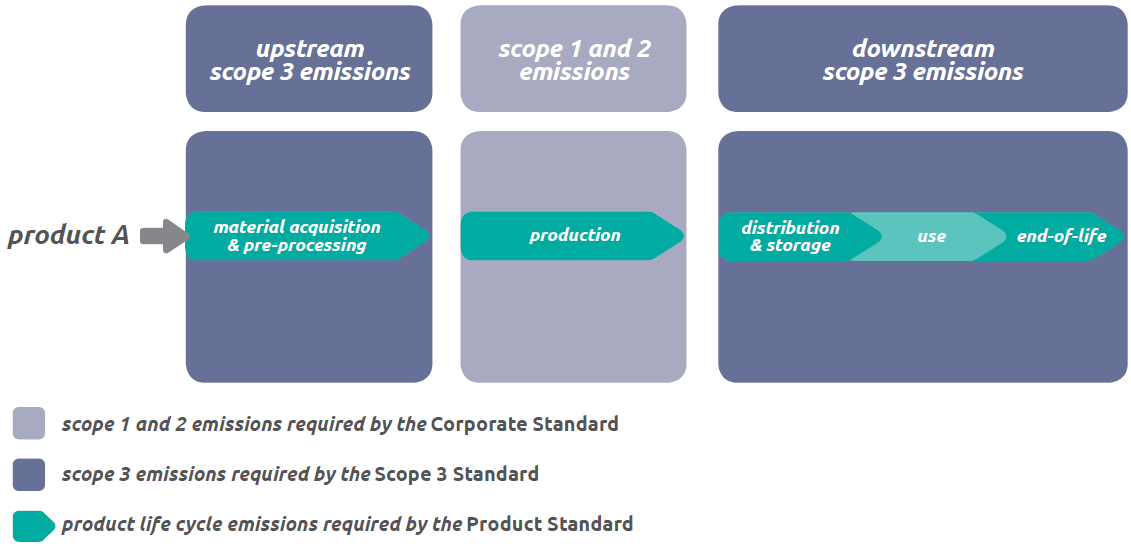

Figure A1.3.1: Relationship between the Product Standard, the Corporate Standard, and the Scope 3 Standard of the GHG Protocol Initiative for a company producing a product A. The three standards are complementary. (Figure 1.1 of the GHG PP, WRI and WBCSD, 2011)

The GHG Product standard, such as the PAS 2050:2011 focuses on the assessment of product related GHG emissions. Efforts have been made to harmonize the protocols, in order to come closer to an international agreement. The GHGPP and the PAS2050:2011 are very similar; however the “GHG protocol PAS 2050 Factsheet” (2011) points out some differences between the PAS2050 and the GHG product protocol regarding particular points, such as the use of specific “product sector rules” and the treatment of changes in soil-carbon stocks.

ISO TS 14067

The International Standard Organisation (ISO) is the world’s largest developer of voluntary International Standards. National bodies for standardisation from 163 countries form the members of ISO. The ISO standards are based on consensus, which implies that each International Standard is submitted to a vote by the ISO members. The ISO publishes three types of normative documents depending of the level of agreement between the member bodies:

- An International Standard, (IS) published with the highest level of agreement,
- A Technical Specification, (TS) published with the second highest level of agreement, with following revision, the potential for future publication as an IS.
- Public Available Specification (PAS), published with the relative lowest level of agreement (but still a majority), with, following revision, the potential for future publication as a TS or as an IS.

The ISO TS 14067 "Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication" "*specifies principles, requirements and guidelines for the quantification and communication of the carbon footprint of a product (CFP)*". The ISO TS 14067 was published in 2013, following years of discussions between the member bodies and failure to reach a consensus to be adopted as an IS.

While harmonisation efforts have been made between the three documents for a globally recognised product GHG accounting and reporting methodology, including the sharing of experts, differences exist between these documents. The "PAS 2050: YOUR QUESTIONS ANSWERED" document[1] explains this:

The key difference between the PAS 2050 approach and the ISO 14067 and GHG Protocol Product Standard is that:

- *PAS 2050 focuses on providing a consistent quantification method only*
- *The purpose for the GHG Protocol Product Standard methodology is to underpin a public inventory report*
- *ISO 14067 is aimed at providing a standard for both the quantification and communication of carbon footprints.*

Overall, several documents can be used in order to assess the carbon footprint of products, and the consensus towards a single globally recognised method is still to be reached. This

[1] Available at www.bsigroup.com/PAS2050 . Accessed on 9 September 2013**.**

can introduce inconsistencies between CFP of products fulfilling the same function(s) if different CFP reglementation have been used for the calculation process, and imply a limited comparability of the results.

Appendix 3.1 Engine driven drill soil corer description and validation

Drill soil corer composition

The drill soil corer is powered by an “Earth auger” motor (STHIL, model BT 121), actioning a gear box to slow the rotation speed for it to be manoeuvrable and minimize disturbance of the soil sampled. The drill is composed of an outside tube with an helicoidal outside edge (similar to an endless screw) and an inside core tube that can be dismantled from the outside tube. The inside core tube contains a split tube that receives the soil core. Two teeth at the tip of the outside tube, in the prolongation of the helix, allow the active penetration of the drill in the soil. The circular mouth (diameter =0.512 cm) of the inside core tube is situated between the teeth, and lets the soil core sample penetrating the tube. The inside split tube sits on the inside edge of the mouth of the core tube, in a way that the soil is not damaged during the process. Two metal handles allow the guidance of the soil corer in the soil. A (black) joystick with an (orange) trigger situated on the right hand side handle on Fig. A3.1.1. was used to control the speed of drilling.

Figure A 3.1.1: Photo of the drill soil corer put 1 metre depth in the soil. The block of wood between the soil surface and the black rectangular gear box was used as a measure to stop the drilling.

Figure A 3.1.2: Nathan Arnold (left) and the author testing the drill soil corer in the apple orchard.

Drill soil corer operation

First, the precise position of the soil sample is determined and marked with spray paint on the grass free soil (the grass is cut short with a sharp knife or scissors, rather than pulled out, to avoid top soil disturbance). The corer is positioned vertically on the sample location. A magnetic level positioned on the gear box is used to maintain the corer vertical (the drill tube axis perpendicular to the soil surface) during the drilling process.

Because of the active soil penetration process (thanks to the teeth), it is necessary to hold the corer by the handles in order to slow the drilling process and allow the soil to clear out of the helicoidal edge. Indeed, a control of the drill penetration is necessary to allow a removal of the corer from the soil once the drilling step is finished. This removal step is operated by hand in a similar but much slower and smoother way weightlifters carry out the “clean and jerk”, although the jerk part of the movement is replaced by a slow and smooth lift just

sufficient to pull the bottom of the drill and maintain the teeth above the soil surface. In our relatively soft soil without stones, two physically fit operators are required to hold the corer during the drilling process and to pull the corer out of the soil.

The corer is then rested on its side (handles axis parallel to the soil surface), allowing the inside core tube to be separated (pulled out) of the outside drill tube. Subsequently, the split tube is pulled out of the inside core tube and split to let the soil core sample appear. The soil sample length is then measured and, for the “site” experiment presented in this chapter, cut in two halves of equal length with a sharp knife. The two resulting samples, representing the 0-50 cm and 50-100cm layers, are bagged and labelled.

Light compaction can occur and it is difficult (and would require a specific study of the process) to assert the compaction to any particular part of the sample before cutting. Therefore, samples were discarded when more than 5% compaction occurred (soil core sample inferior to 95cm total length).

Drill soil corer testing and validation

In order to test the soil corer, and its ability to represent the soil carbon content and the bulk density of the whole soil profile, 5 core samples were taken beside the 5 grass alley locations of the “pit” experiment (see sections 3.2.3 and 3.3.1 of this chapter for a description and results of the “pit” sampling). For this experiment, the samples were not cut in halves, but processed whole to determine the bulk density and the carbon content of the soil.

Bulk density

For processing of the bulk density samples, the exact same procedure than applied for the bulk density samples of the pit experiment was followed. However, the soil was dried at 60 °C in order to avoid affecting the carbon content analysis by drying them at a higher temperature of 105 °C, as usually practised to remove the entire water fraction of the samples. It was not necessary to apply any correction to these bulk density results for

comparison with the samples of the “pit” experiment, since these were dried at 60 °C prior to be dried at 105 °C (see section 3.2.3 and 3.2.4).

Carbon content

For measuring the carbon content of the samples, following weighing for bulk density determination, the samples were mixed thoroughly by hand for at least one minute of constant and vigorous shaking of the large plastic bag containing each of them. Indeed, the riffle splitter for the sub-sampling operation was unavailable at the time. Subsequently, 10 subsamples per sample were collected by hand at different locations within the sample bags.

Statistical analyses

The average bulk density and the average soil carbon content of the top metre of soil (0-1m depth increment) for each treatment were compared using a Welch’s *t* test, used for independent variables, equal or unequal sample sizes and unequal variances. Differences were interpreted to be statistically significant at the 5% level and a “tendency for a difference” was highlighted when significant differences at the 10% level were detected. A statistical power analysis (Barker Bausell and Li 2002) was conducted when no significant difference was found between treatments.

The results are presented in table A3.1.

Table A 1: Comparison of carbon content and bulk density in the grass alley between the pit experiment and the soil core samples (1metre length).

	Average *grass alley pit* *(n=5)*	**Average soil core samples (n=5)**	**p value (Welch’ *t* test)**	**Power**
Bulk density (	1.32 (SE=0.003)	1.14 (SE= 0.04)	0.008	/
Carbon content (%C)	1.30 (SE=0.03)	1.29 (SE=0.08)	0.9	0.06

Results

Bulk density

For the bulk density of the top metre of soil, a statistically significant difference was observed between the grass alley pit samples and the soil core samples ($p<0.01$). Furthermore, the standard error of the average bulk density of the soil core samples is one order of magnitude higher than for SE of the average for the grass alley pit samples. In conclusion, the drill soil corer underestimated bulk density of the soil, but also provided far less consistent results than provided by the pit soil profiles, which emphasises that a correction factor applied to all soil core samples would not allow a reliable estimation of the bulk density. It is therefore necessary to determine the soil bulk density by other means.

Carbon content

For the carbon content of the top metre of soil, there was no statistically significant difference between the two treatments. However, the statistical power was very low, meaning that even if the difference between treatments was statistically significant, there was practically no chance of observing it.

Nevertheless, the statistical power of this experiment needs to be balanced with two observations. Firstly, the actual difference between the two averages is very small, making it almost impossible to detect this difference, even with small standard errors. Secondly, the standard errors of the carbon contents, as opposed to the standard errors of the bulk density, are of the same order of magnitude, meaning that the confidence with which each average is describing its respective true mean is relatively similar. For these reasons, It was decided that the carbon contents given by the soil corer were representing the “real” carbon contents in a proper manner, and that no further calibration was required.

Conclusion

Overall, the drill soil corer was incorrectly and inconsistently representing the real bulk density, but was correctly and consistently representing the carbon content of the soil. It was therefore necessary to sample bulk density separately for each sampling sit of the site experiment.

Appendix 4.1 Detailed geo-localised dataset for carbon content, bulk density and soil carbon stock in the four orchard blocks of the chrono-sequence. Sample ID: The first digit is the last number of the year the orchard was planted (0=2010; 8= 2008; 6= 2006; 9= 1999; the next two digits represent the sampling site number (01 to 10); the first letter T or B stands for Top (0-50 cm soil depth) and Bottom (50-100cm soil depth); the last two digits represent the sample number within each sampling site (01 to 16). Gaps represent failed soil samples.

Sample ID	% carbon	Bulk Density (g/cm3)	Carbon stock ESM (tC/ha)	Sample ID	% carbon	Bulk Density (g/cm3)	Carbon stock ESM (tC/ha)	GPS coodinates of sampling site
0-50 cm	0-50 cm	0-50 cm	0-50 cm	50-100 cm	50-100 cm	50-100 cm	50-100 cm	
001TC01	1.91	1.22	110.9	001BC01	0.43	1.18	31.0	39º35'21.15"S; 176º47'56.35"E
001TC02	2	1.22	116.1	001BC02	0.48	1.18	33.7	39º35'21.15"S; 176º47'56.35"E
001TC03	1.69	1.22	98.1	001BC03	0.41	1.18	28.9	39º35'21.15"S; 176º47'56.35"E
001TC04	1.81	1.22	105.1	001BC04	0.40	1.18	28.5	39º35'21.15"S; 176º47'56.35"E
001TC05	1.86	1.22	108.0	001BC05	0.45	1.18	31.7	39º35'21.15"S; 176º47'56.35"E
001TC06	1.83	1.22	106.2	001BC06	0.44	1.18	31.2	39º35'21.15"S; 176º47'56.35"E
001TC07	1.62	1.22	94.1	001BC07	0.36	1.18	26.0	39º35'21.15"S; 176º47'56.35"E
001TC08	1.97	1.22	114.4	001BC08	0.44	1.18	31.7	39º35'21.15"S; 176º47'56.35"E
001TC09	1.93	1.22	112.1	001BC09	0.36	1.18	26.5	39º35'21.15"S; 176º47'56.35"E
001TC10	1.9	1.22	110.3	001BC10	0.40	1.18	28.7	39º35'21.15"S; 176º47'56.35"E
001TC11	1.87	1.22	108.6	001BC11	0.43	1.18	30.7	39º35'21.15"S; 176º47'56.35"E
001TC12	1.96	1.22	113.8	001BC12	0.36	1.18	26.9	39º35'21.15"S; 176º47'56.35"E
001TC13	1.68	1.22	97.5	001BC13	0.47	1.18	32.2	39º35'21.15"S; 176º47'56.35"E
001TC14	1.85	1.22	107.4	001BC14	0.39	1.18	28.5	39º35'21.15"S; 176º47'56.35"E
001TC15	2.07	1.22	120.2	001BC15	0.43	1.18	31.4	39º35'21.15"S; 176º47'56.35"E
001TC16	2.2	1.22	127.7	001BC16	0.48	1.18	34.5	39º35'21.15"S; 176º47'56.35"E
002TC01	1.55	1.24	90.0	002BC01	0.38	1.21	27.5	39º35'21.10"S; 176º47'56.68"E
002TC02				002BC02				39º35'21.10"S; 176º47'56.68"E
002TC03	1.5	1.24	87.1	002BC03	0.43	1.21	30.2	39º35'21.10"S; 176º47'56.68"E
002TC04	1.66	1.24	96.4	002BC04	0.44	1.21	31.2	39º35'21.10"S; 176º47'56.68"E
002TC05	1.52	1.24	88.3	002BC05	0.27	1.21	21.1	39º35'21.10"S; 176º47'56.68"E
002TC06	1.68	1.24	97.5	002BC06	0.21	1.21	18.1	39º35'21.10"S; 176º47'56.68"E

002TC07	1.64	1.24	95.2	002BC07	0.19	1.21	16.7	39°35'21.10"S; 176°47'56.68"E
002TC08	1.59	1.24	92.3	002BC08	0.28	1.21	21.7	39°35'21.10"S; 176°47'56.68"E
002TC09	1.87	1.24	108.6	002BC09	0.27	1.21	22.4	39°35'21.10"S; 176°47'56.68"E
002TC10	1.53	1.24	88.8	002BC10	0.20	1.21	16.9	39°35'21.10"S; 176°47'56.68"E
002TC11	1.64	1.24	95.2	002BC11	0.18	1.21	16.3	39°35'21.10"S; 176°47'56.68"E
002TC12	1.52	1.24	88.3	002BC12	0.19	1.21	16.7	39°35'21.10"S; 176°47'56.68"E
002TC13	2.05	1.24	119.0	002BC13	0.27	1.21	22.9	39°35'21.10"S; 176°47'56.68"E
002TC14	1.74	1.24	101.0	002BC14	0.25	1.21	20.8	39°35'21.10"S; 176°47'56.68"E
002TC15	1.99	1.24	115.5	002BC15	0.26	1.21	22.4	39°35'21.10"S; 176°47'56.68"E
002TC16	1.76	1.24	102.2	002BC16	0.22	1.21	19.0	39°35'21.10"S; 176°47'56.68"E
003TC01	1.51	1.24	87.7	003BC01	0.43	1.20	30.3	39°35'22.66"S; 176°47'54.28"E
003TC02	1.49	1.24	86.5	003BC02	0.37	1.20	27.0	39°35'22.66"S; 176°47'54.28"E
003TC03	1.62	1.24	94.1	003BC03	0.35	1.20	26.0	39°35'22.66"S; 176°47'54.28"E
003TC04	1.49	1.24	86.5	003BC04	0.44	1.20	30.6	39°35'22.66"S; 176°47'54.28"E
003TC05	1.41	1.24	81.9	003BC05	0.32	1.20	23.6	39°35'22.66"S; 176°47'54.28"E
003TC06	1.45	1.24	84.2	003BC06	0.33	1.20	24.5	39°35'22.66"S; 176°47'54.28"E
003TC07	1.58	1.24	91.7	003BC07	0.36	1.20	26.8	39°35'22.66"S; 176°47'54.28"E
003TC08	1.8	1.24	104.5	003BC08	0.38	1.20	28.4	39°35'22.66"S; 176°47'54.28"E
003TC09	1.92	1.24	111.5	003BC09	0.31	1.20	25.1	39°35'22.66"S; 176°47'54.28"E
003TC10	1.58	1.24	91.7	003BC10	0.32	1.20	24.5	39°35'22.66"S; 176°47'54.28"E
003TC11	1.69	1.24	98.1	003BC11	0.43	1.20	31.0	39°35'22.66"S; 176°47'54.28"E
003TC12	1.76	1.24	102.2	003BC12	0.37	1.20	27.8	39°35'22.66"S; 176°47'54.28"E
003TC13	2.26	1.24	131.2	003BC13	0.35	1.20	28.6	39°35'22.66"S; 176°47'54.28"E
003TC14	2.2	1.24	127.7	003BC14	0.33	1.20	27.7	39°35'22.66"S; 176°47'54.28"E
003TC15	2.28	1.24	132.4	003BC15	0.36	1.20	29.6	39°35'22.66"S; 176°47'54.28"E
003TC16	2.29	1.24	133.0	003BC16	0.37	1.20	29.9	39°35'22.66"S; 176°47'54.28"E
004TC01	1.71	1.30	99.3	004BC01	0.37	1.14	32.1	39°35'22.62"S; 176°47'54.86"E
004TC02	1.88	1.30	109.2	004BC02	0.42	1.14	35.5	39°35'22.62"S; 176°47'54.86"E

004TC03	1.93	1.30	112.1	004BC03	0.36	1.14	32.6	39º35'22.62"S; 176º47'54.86"E
004TC04	1.87	1.30	108.6	004BC04	0.34	1.14	31.4	39º35'22.62"S; 176º47'54.86"E
004TC05	1.86	1.30	108.0	004BC05	0.43	1.14	36.1	39º35'22.62"S; 176º47'54.86"E
004TC06	1.62	1.30	94.1	004BC06	0.37	1.14	31.1	39º35'22.62"S; 176º47'54.86"E
004TC07	1.71	1.30	99.3	004BC07	0.33	1.14	29.5	39º35'22.62"S; 176º47'54.86"E
004TC08	1.77	1.30	102.8	004BC08	0.40	1.14	33.8	39º35'22.62"S; 176º47'54.86"E
004TC09	1.86	1.30	108.0	004BC09	0.39	1.14	34.0	39º35'22.62"S; 176º47'54.86"E
004TC10	1.81	1.30	105.1	004BC10	0.40	1.14	34.3	39º35'22.62"S; 176º47'54.86"E
004TC11	2.12	1.30	123.1	004BC11	0.34	1.14	33.3	39º35'22.62"S; 176º47'54.86"E
004TC12	1.88	1.30	109.2	004BC12	0.34	1.14	31.2	39º35'22.62"S; 176º47'54.86"E
004TC13	1.88	1.30	109.2	004BC13	0.34	1.14	31.5	39º35'22.62"S; 176º47'54.86"E
004TC14	1.69	1.30	98.1	004BC14	0.37	1.14	31.7	39º35'22.62"S; 176º47'54.86"E
004TC15	1.87	1.30	108.6	004BC15	0.38	1.14	33.6	39º35'22.62"S; 176º47'54.86"E
004TC16	1.95	1.30	113.2	004BC16	0.55	1.14	43.4	39º35'22.62"S; 176º47'54.86"E
005TC01	1.55	1.27	90.0	005BC01	0.46	1.17	34.2	39º35'21.75"S; 176º47'56.16"E
005TC02	1.55	1.27	90.0	005BC02	0.40	1.17	30.9	39º35'21.75"S; 176º47'56.16"E
005TC03				005BC03				39º35'21.75"S; 176º47'56.16"E
005TC04	1.62	1.27	94.1	005BC04	0.45	1.17	34.0	39º35'21.75"S; 176º47'56.16"E
005TC05	1.6	1.27	92.9	005BC05	0.42	1.17	32.0	39º35'21.75"S; 176º47'56.16"E
005TC06				005BC06				39º35'21.75"S; 176º47'56.16"E
005TC07				005BC07				39º35'21.75"S; 176º47'56.16"E
005TC08	1.78	1.27	103.3	005BC08	0.43	1.17	33.5	39º35'21.75"S; 176º47'56.16"E
005TC09	1.68	1.27	97.5	005BC09	0.42	1.17	32.6	39º35'21.75"S; 176º47'56.16"E
005TC10	1.55	1.27	90.0	005BC10	0.38	1.17	29.4	39º35'21.75"S; 176º47'56.16"E
005TC11	1.73	1.27	100.4	005BC11	0.41	1.17	32.3	39º35'21.75"S; 176º47'56.16"E
005TC12	1.78	1.27	103.3	005BC12	0.42	1.17	33.1	39º35'21.75"S; 176º47'56.16"E
005TC13	1.73	1.27	100.4	005BC13	0.27	1.17	24.6	39º35'21.75"S; 176º47'56.16"E
005TC14	1.53	1.27	88.8	005BC14	0.57	1.17	39.8	39º35'21.75"S; 176º47'56.16"E

005TC15	1.89	1.27	109.7	005BC15	0.49	1.17	37.5	39º35'21.75"S; 176º47'56.16"E
005TC16	1.74	1.27	101.0	005BC16	0.40	1.17	31.9	39º35'21.75"S; 176º47'56.16"E
006TC01	1.76	1.26	102.2	006BC01	0.32	1.30	26.8	39º35'21.90"S; 176º47'56.22"E
006TC02	1.84	1.26	106.8	006BC02	0.32	1.30	26.9	39º35'21.90"S; 176º47'56.22"E
006TC03	2.07	1.26	120.2	006BC03	0.29	1.30	26.5	39º35'21.90"S; 176º47'56.22"E
006TC04	2	1.26	116.1	006BC04	0.26	1.30	24.3	39º35'21.90"S; 176º47'56.22"E
006TC05	1.67	1.26	97.0	006BC05	0.28	1.30	24.0	39º35'21.90"S; 176º47'56.22"E
006TC06	1.59	1.26	92.3	006BC06	0.27	1.30	22.9	39º35'21.90"S; 176º47'56.22"E
006TC07	1.73	1.26	100.4	006BC07	0.32	1.30	26.2	39º35'21.90"S; 176º47'56.22"E
006TC08	2.07	1.26	120.2	006BC08	0.28	1.30	25.8	39º35'21.90"S; 176º47'56.22"E
006TC09	1.79	1.26	103.9	006BC09	0.25	1.30	22.6	39º35'21.90"S; 176º47'56.22"E
006TC10	1.75	1.26	101.6	006BC10	0.31	1.30	25.9	39º35'21.90"S; 176º47'56.22"E
006TC11	1.91	1.26	110.9	006BC11	0.36	1.30	29.6	39º35'21.90"S; 176º47'56.22"E
006TC12	1.61	1.26	93.5	006BC12	0.29	1.30	24.2	39º35'21.90"S; 176º47'56.22"E
006TC13	1.62	1.26	94.1	006BC13	0.29	1.30	23.9	39º35'21.90"S; 176º47'56.22"E
006TC14	1.72	1.26	99.9	006BC14	0.28	1.30	24.2	39º35'21.90"S; 176º47'56.22"E
006TC15	1.79	1.26	103.9	006BC15	0.27	1.30	23.7	39º35'21.90"S; 176º47'56.22"E
006TC16	1.83	1.26	106.2	006BC16	0.31	1.30	26.4	39º35'21.90"S; 176º47'56.22"E
007TC01	1.36	1.25	79.0	007BC01	0.29	1.26	22.6	39º35'21.30"S; 176º47'57.17"E
007TC02	1.36	1.25	79.0	007BC02	0.24	1.26	19.5	39º35'21.30"S; 176º47'57.17"E
007TC03	1.7	1.25	98.7	007BC03	0.26	1.26	22.0	39º35'21.30"S; 176º47'57.17"E
007TC04	1.62	1.25	94.1	007BC04	0.28	1.26	23.1	39º35'21.30"S; 176º47'57.17"E
007TC05	1.47	1.25	85.3	007BC05	0.29	1.26	22.6	39º35'21.30"S; 176º47'57.17"E
007TC06				007BC06				39º35'21.30"S; 176º47'57.17"E
007TC07	1.49	1.25	86.5	007BC07	0.27	1.26	21.8	39º35'21.30"S; 176º47'57.17"E
007TC08				007BC08				39º35'21.30"S; 176º47'57.17"E
007TC09	1.56	1.25	90.6	007BC09	0.33	1.26	25.5	39º35'21.30"S; 176º47'57.17"E
007TC10	1.5	1.25	87.1	007BC10	0.32	1.26	24.7	39º35'21.30"S; 176º47'57.17"E

007TC11	1.6	1.25	92.9	007BC11	0.31	1.26	24.8	39°35'21.30"S; 176°47'57.17"E
007TC12	1.7	1.25	98.7	007BC12	0.30	1.26	24.6	39°35'21.30"S; 176°47'57.17"E
007TC13				007BC13				39°35'21.30"S; 176°47'57.17"E
007TC14	1.34	1.25	77.8	007BC14	0.39	1.26	27.9	39°35'21.30"S; 176°47'57.17"E
007TC15	1.42	1.25	82.4	007BC15	0.30	1.26	23.4	39°35'21.30"S; 176°47'57.17"E
007TC16	1.49	1.25	86.5	007BC16	0.28	1.26	22.6	39°35'21.30"S; 176°47'57.17"E
008TC01	1.43	1.24	83.0	008BC01	0.36	1.14	25.9	39°35'21.04"S; 176°47'57.04"E
008TC02	1.47	1.24	85.3	008BC02	0.31	1.14	23.1	39°35'21.04"S; 176°47'57.04"E
008TC03				008BC03				39°35'21.04"S; 176°47'57.04"E
008TC04				008BC04				39°35'21.04"S; 176°47'57.04"E
008TC05	1.62	1.24	94.1	008BC05	0.41	1.14	29.1	39°35'21.04"S; 176°47'57.04"E
008TC06				008BC06				39°35'21.04"S; 176°47'57.04"E
008TC07	1.53	1.24	88.8	008BC07	0.39	1.14	27.9	39°35'21.04"S; 176°47'57.04"E
008TC08	1.45	1.24	84.2	008BC08	0.35	1.14	25.5	39°35'21.04"S; 176°47'57.04"E
008TC09	1.38	1.24	80.1	008BC09	0.37	1.14	26.4	39°35'21.04"S; 176°47'57.04"E
008TC10	1.7	1.24	98.7	008BC10	0.40	1.14	29.0	39°35'21.04"S; 176°47'57.04"E
008TC11				008BC11				39°35'21.04"S; 176°47'57.04"E
008TC12				008BC12				39°35'21.04"S; 176°47'57.04"E
008TC13	1.63	1.24	94.6	008BC13	0.42	1.14	30.2	39°35'21.04"S; 176°47'57.04"E
008TC14	1.61	1.24	93.5	008BC14	0.48	1.14	33.6	39°35'21.04"S; 176°47'57.04"E
008TC15	1.53	1.24	88.8	008BC15	0.38	1.14	27.5	39°35'21.04"S; 176°47'57.04"E
008TC16				008BC16				39°35'21.04"S; 176°47'57.04"E
009TC01	1.5	1.27	87.1	009BC01	0.29	1.21	24.4	39°35'22.41"S; 176°47'55.70"E
009TC02	1.57	1.27	91.2	009BC02	0.34	1.21	27.7	39°35'22.41"S; 176°47'55.70"E
009TC03	1.86	1.27	108.0	009BC03	0.35	1.21	29.9	39°35'22.41"S; 176°47'55.70"E
009TC04	1.38	1.27	80.1	009BC04	0.33	1.21	25.8	39°35'22.41"S; 176°47'55.70"E
009TC05	1.75	1.27	101.6	009BC05	0.34	1.21	28.7	39°35'22.41"S; 176°47'55.70"E
009TC06	1.59	1.27	92.3	009BC06	0.34	1.21	28.0	39°35'22.41"S; 176°47'55.70"E

009TC07	1.8	1.27	104.5	009BC07	0.36	1.21	30.1	39°35'22.41"S; 176°47'55.70"E
009TC08	1.85	1.27	107.4	009BC08	0.39	1.21	31.7	39°35'22.41"S; 176°47'55.70"E
009TC09	1.69	1.27	98.1	009BC09	0.32	1.21	27.4	39°35'22.41"S; 176°47'55.70"E
009TC10	1.69	1.27	98.1	009BC10	0.33	1.21	27.7	39°35'22.41"S; 176°47'55.70"E
009TC11	1.93	1.27	112.1	009BC11	0.37	1.21	31.4	39°35'22.41"S; 176°47'55.70"E
009TC12	1.93	1.27	112.1	009BC12	0.36	1.21	30.9	39°35'22.41"S; 176°47'55.70"E
009TC13	1.96	1.27	113.8	009BC13	0.40	1.21	33.0	39°35'22.41"S; 176°47'55.70"E
009TC14	2.01	1.27	116.7	009BC14	0.37	1.21	31.6	39°35'22.41"S; 176°47'55.70"E
009TC15	1.91	1.27	110.9	009BC15	0.38	1.21	31.6	39°35'22.41"S; 176°47'55.70"E
009TC16	1.91	1.27	110.9	009BC16	0.45	1.21	35.6	39°35'22.41"S; 176°47'55.70"E
010TC01	1.7	1.21	98.7	010BC01	0.37	1.20	25.5	39°35'22.17"S; 176°47'56.05"E
010TC02	1.85	1.21	107.4	010BC02	0.43	1.20	29.7	39°35'22.17"S; 176°47'56.05"E
010TC03				010BC03				39°35'22.17"S; 176°47'56.05"E
010TC04	1.6	1.21	92.9	010BC04	0.37	1.20	25.5	39°35'22.17"S; 176°47'56.05"E
010TC05	2.1	1.21	121.9	010BC05	0.38	1.20	27.0	39°35'22.17"S; 176°47'56.05"E
010TC06	2	1.21	116.1	010BC06	0.43	1.20	29.9	39°35'22.17"S; 176°47'56.05"E
010TC07	2.12	1.21	123.1	010BC07	0.39	1.20	27.6	39°35'22.17"S; 176°47'56.05"E
010TC08	1.94	1.21	112.6	010BC08	0.35	1.20	25.0	39°35'22.17"S; 176°47'56.05"E
010TC09	2.02	1.21	117.3	010BC09	0.33	1.20	23.9	39°35'22.17"S; 176°47'56.05"E
010TC10	2.17	1.21	126.0	010BC10	0.41	1.20	29.3	39°35'22.17"S; 176°47'56.05"E
010TC11	1.96	1.21	113.8	010BC11	0.34	1.20	24.3	39°35'22.17"S; 176°47'56.05"E
010TC12	1.92	1.21	111.5	010BC12	0.38	1.20	26.6	39°35'22.17"S; 176°47'56.05"E
010TC13	2.18	1.21	126.6	010BC13	0.27	1.20	20.8	39°35'22.17"S; 176°47'56.05"E
010TC14	1.98	1.21	115.0	010BC14	0.27	1.20	20.5	39°35'22.17"S; 176°47'56.05"E
010TC15	1.67	1.21	97.0	010BC15	0.30	1.20	21.2	39°35'22.17"S; 176°47'56.05"E
010TC16	1.86	1.21	108.0	010BC16	0.31	1.20	22.4	39°35'22.17"S; 176°47'56.05"E
8S04TC01	2.02	1.26	117.3	8S04BC01	0.32	1.35	27.9	39°35'11.27"S; 176°48'02.41"E
8S04TC02	2.51	1.26	145.7	8S04BC02	0.32	1.35	30.3	39°35'11.27"S; 176°48'02.41"E

8S04TC03	2.5	1.26	145.2	8S04BC03	0.29	1.35	28.7	39°35'11.27"S; 176°48'02.41"E
8S04TC04	2.23	1.26	129.5	8S04BC04	0.29	1.35	27.3	39°35'11.27"S; 176°48'02.41"E
8S04TC05	2.56	1.26	148.6	8S04BC05	0.42	1.35	35.8	39°35'11.27"S; 176°48'02.41"E
8S04TC06	2.36	1.26	137.0	8S04BC06	0.48	1.35	38.5	39°35'11.27"S; 176°48'02.41"E
8S04TC07	2.41	1.26	139.9	8S04BC07	0.42	1.35	35.4	39°35'11.27"S; 176°48'02.41"E
8S04TC08	2.33	1.26	135.3	8S04BC08	0.50	1.35	39.4	39°35'11.27"S; 176°48'02.41"E
8S04TC09	2.12	1.26	123.1	8S04BC09	0.27	1.35	25.7	39°35'11.27"S; 176°48'02.41"E
8S04TC10	2.38	1.26	138.2	8S04BC10	0.33	1.35	30.0	39°35'11.27"S; 176°48'02.41"E
8S04TC11	2.44	1.26	141.7	8S04BC11	0.42	1.35	35.2	39°35'11.27"S; 176°48'02.41"E
8S04TC12	2.68	1.26	155.6	8S04BC12	0.43	1.35	36.9	39°35'11.27"S; 176°48'02.41"E
8S04TC13	2.58	1.26	149.8	8S04BC13	0.34	1.35	31.9	39°35'11.27"S; 176°48'02.41"E
8S04TC14	2.5	1.26	145.2	8S04BC14	0.39	1.35	33.9	39°35'11.27"S; 176°48'02.41"E
8S04TC15	2.16	1.26	125.4	8S04BC15	0.34	1.35	29.4	39°35'11.27"S; 176°48'02.41"E
8S04TC16	2.43	1.26	141.1	8S04BC16	0.43	1.35	35.7	39°35'11.27"S; 176°48'02.41"E
8S05TC01	2.34	1.22	135.9	8S05BC01	0.49	1.26	35.5	39°35'10.28"S; 176°48'00.92"E
8S05TC02	2.46	1.22	142.8	8S05BC02	0.51	1.26	36.8	39°35'10.28"S; 176°48'00.92"E
8S05TC03				8S05BC03				39°35'10.28"S; 176°48'00.92"E
8S05TC04	2.56	1.22	148.6	8S05BC04	0.46	1.26	34.2	39°35'10.28"S; 176°48'00.92"E
8S05TC05	2.35	1.22	136.4	8S05BC05	0.47	1.26	34.0	39°35'10.28"S; 176°48'00.92"E
8S05TC06	2.26	1.22	131.2	8S05BC06	0.51	1.26	36.2	39°35'10.28"S; 176°48'00.92"E
8S05TC07	2.4	1.22	139.3	8S05BC07	0.56	1.26	39.3	39°35'10.28"S; 176°48'00.92"E
8S05TC08	2.28	1.22	132.4	8S05BC08	0.44	1.26	32.4	39°35'10.28"S; 176°48'00.92"E
8S05TC09	2.54	1.22	147.5	8S05BC09	0.57	1.26	40.6	39°35'10.28"S; 176°48'00.92"E
8S05TC10	2.14	1.22	124.2	8S05BC10	0.55	1.26	38.1	39°35'10.28"S; 176°48'00.92"E
8S05TC11				8S05BC11				39°35'10.28"S; 176°48'00.92"E
8S05TC12	2.16	1.22	125.4	8S05BC12	0.50	1.26	35.5	39°35'10.28"S; 176°48'00.92"E
8S05TC13	2.36	1.22	137.0	8S05BC13	0.49	1.26	35.2	39°35'10.28"S; 176°48'00.92"E
8S05TC14	2.56	1.22	148.6	8S05BC14	0.78	1.26	52.7	39°35'10.28"S; 176°48'00.92"E
8S05TC15	2.59	1.22	150.4	8S05BC15	0.50	1.26	36.7	39°35'10.28"S; 176°48'00.92"E

8S05TC16	2.46	1.22	142.8	8S05BC16	0.56	1.26	39.5	39^{0}35'10.28"S; 176^{0}48'00.92"E
8S06TC01	2.47	1.17	143.4	8S06BC01	0.39	1.24	25.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC02	2.63	1.17	152.7	8S06BC02	0.42	1.24	26.9	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC03	2.57	1.17	149.2	8S06BC03	0.36	1.24	23.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC04	2.56	1.17	148.6	8S06BC04	0.39	1.24	24.7	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC05	2.66	1.17	154.4	8S06BC05	0.50	1.24	31.4	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC06	2.45	1.17	142.2	8S06BC06	0.48	1.24	30.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC07	2.28	1.17	132.4	8S06BC07	0.40	1.24	25.4	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC08	2.23	1.17	129.5	8S06BC08	0.44	1.24	27.8	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC09	2.23	1.17	129.5	8S06BC09	0.33	1.24	21.2	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC10	2.35	1.17	136.4	8S06BC10	0.40	1.24	25.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC11	2.13	1.17	123.7	8S06BC11	0.42	1.24	26.3	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC12	2.31	1.17	134.1	8S06BC12	0.34	1.24	22.0	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC13	2.28	1.17	132.4	8S06BC13	0.32	1.24	20.3	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC14	2.29	1.17	133.0	8S06BC14	0.36	1.24	23.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC15	2.56	1.17	148.6	8S06BC15	0.43	1.24	27.4	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S06TC16	2.57	1.17	149.2	8S06BC16	0.43	1.24	27.1	39^{0}35'11.15"S; 176^{0}48'01.86"E
8S07TC01	3.01	1.20	174.8	8S07BC01	0.50	1.24	35.8	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC02	2.76	1.20	160.2	8S07BC02	0.51	1.24	36.1	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC03				8S07BC03				39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC04	2.26	1.20	131.2	8S07BC04	0.52	1.24	35.5	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC05	2.57	1.20	149.2	8S07BC05	0.60	1.24	40.9	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC06	2.36	1.20	137.0	8S07BC06	0.52	1.24	35.3	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC07	2.25	1.20	130.6	8S07BC07	0.54	1.24	36.2	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC08	2.53	1.20	146.9	8S07BC08	0.43	1.24	30.5	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC09				8S07BC09				39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC10	2.56	1.20	148.6	8S07BC10	0.58	1.24	39.4	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC11	2.49	1.20	144.6	8S07BC11	0.65	1.24	43.4	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC12	2.34	1.20	135.9	8S07BC12	0.60	1.24	40.0	39^{0}35'10.19"S; 176^{0}48'00.82"E

8S07TC13	2.24	1.20	130.1	8S07BC13	0.48	1.24	33.0	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC14	2.61	1.20	151.5	8S07BC14	0.53	1.24	36.9	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC15	2.68	1.20	155.6	8S07BC15	0.50	1.24	35.3	39^{0}35'10.19"S; 176^{0}48'00.82"E
8S07TC16				8S07BC16				39^{0}35'10.19"S; 176^{0}48'00.82"E
8S08TC01	2.67	1.26	155.0	8S08BC01	0.35	1.32	33.5	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC02	2.34	1.26	135.9	8S08BC02	0.38	1.32	32.9	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC03	2.61	1.26	151.5	8S08BC03	0.38	1.32	34.3	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC04	2.65	1.26	153.9	8S08BC04	0.36	1.32	33.9	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC05	2.31	1.26	134.1	8S08BC05	0.38	1.32	33.2	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC06	2.13	1.26	123.7	8S08BC06	0.31	1.32	28.4	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC07	2.13	1.26	123.7	8S08BC07	0.34	1.32	30.1	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC08	2.04	1.26	118.4	8S08BC08	0.29	1.32	26.7	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC09	2.29	1.26	133.0	8S08BC09	0.31	1.32	29.2	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC10	2.29	1.26	133.0	8S08BC10	0.34	1.32	30.5	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC11	2.32	1.26	134.7	8S08BC11	0.44	1.32	36.5	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC12	2.17	1.26	126.0	8S08BC12	0.27	1.32	26.3	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC13	2.56	1.26	148.6	8S08BC13	0.31	1.32	30.4	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC14	2.33	1.26	135.3	8S08BC14	0.29	1.32	28.0	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC15	2.34	1.26	135.9	8S08BC15	0.36	1.32	31.9	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S08TC16	2.17	1.26	126.0	8S08BC16	0.30	1.32	28.0	39^{0}35'11.33"S; 176^{0}48'02.08"E
8S09TC01	2.36	1.27	137.0	8S09BC01	0.36	1.31	32.9	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC02	2.3	1.27	133.5	8S09BC02	0.43	1.31	36.1	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC03	2.13	1.27	123.7	8S09BC03	0.33	1.31	29.9	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC04	2.2	1.27	127.7	8S09BC04	0.39	1.31	33.6	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC05				8S09BC05				39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC06				8S09BC06				39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC07	2.29	1.27	133.0	8S09BC07	0.37	1.31	32.6	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC08	2.35	1.27	136.4	8S09BC08	0.43	1.31	36.7	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC09				8S09BC09				39^{0}35'11.35"S; 176^{0}48'02.51"E

8S09TC10				8S09BC10				39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC11	2.28	1.27	132.4	8S09BC11	0.32	1.31	29.8	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC12	2.13	1.27	123.7	8S09BC12	0.33	1.31	29.9	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC13	2.33	1.27	135.3	8S09BC13	0.44	1.31	36.8	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC14	2.47	1.27	143.4	8S09BC14	0.47	1.31	39.4	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC15	2.56	1.27	148.6	8S09BC15	0.47	1.31	40.1	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S09TC16	3.03	1.27	175.9	8S09BC16	0.42	1.31	39.7	39^{0}35'11.35"S; 176^{0}48'02.51"E
8S10TC01	3.47	1.24	201.5	8S10BC01	0.42	1.29	37.6	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC02	2.54	1.24	147.5	8S10BC02	0.39	1.29	32.7	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC03	2.46	1.24	142.8	8S10BC03	0.29	1.29	26.3	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC04	2.57	1.24	149.2	8S10BC04	0.38	1.29	31.9	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC05	2.8	1.24	162.6	8S10BC05	0.40	1.29	34.2	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC06	2.79	1.24	162.0	8S10BC06	0.43	1.29	35.4	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC07	2.32	1.24	134.7	8S10BC07	0.36	1.29	29.5	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC08	2.15	1.24	124.8	8S10BC08	0.28	1.29	24.6	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC09	2.36	1.24	137.0	8S10BC09	0.35	1.29	29.5	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC10	2.61	1.24	151.5	8S10BC10	0.48	1.29	37.8	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC11	2.19	1.24	127.2	8S10BC11	0.36	1.29	29.2	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC12	2.81	1.24	163.1	8S10BC12	0.52	1.29	40.6	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC13	2.39	1.24	138.8	8S10BC13	0.32	1.29	27.7	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC14	2.43	1.24	141.1	8S10BC14	0.35	1.29	29.5	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC15	2.17	1.24	126.0	8S10BC15	0.29	1.29	25.0	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S10TC16	2.41	1.24	139.9	8S10BC16	0.26	1.29	24.2	39^{0}35'10.70"S; 176^{0}48'01.59"E
8S11TC01	2.39	1.22	138.8	8S11BC01	0.80	1.19	53.6	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC02	3.21	1.22	186.4	8S11BC02	0.74	1.19	52.8	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC03	2.48	1.22	144.0	8S11BC03	0.70	1.19	47.9	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC04	2.72	1.22	157.9	8S11BC04	0.63	1.19	45.2	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC05	2.16	1.22	125.4	8S11BC05	0.73	1.19	48.8	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC06	2.37	1.22	137.6	8S11BC06	0.62	1.19	43.4	39^{0}35'09.94"S; 176^{0}48'00.97"E

8S11TC07	2.52	1.22	146.3	8S11BC07	0.62	1.19	43.4	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC08				8S11BC08				39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC09	2.64	1.22	153.3	8S11BC09	0.66	1.19	46.5	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC10	2.15	1.22	124.8	8S11BC10	0.56	1.19	38.8	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC11	2.76	1.22	160.2	8S11BC11	0.51	1.19	37.9	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC12	2.47	1.22	143.4	8S11BC12	0.64	1.19	44.9	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC13	2.23	1.22	129.5	8S11BC13	0.55	1.19	39.0	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC14				8S11BC14				39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC15	3.05	1.22	177.1	8S11BC15	0.71	1.19	50.4	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S11TC16	2.63	1.22	152.7	8S11BC16	0.48	1.19	36.1	39^{0}35'09.94"S; 176^{0}48'00.97"E
8S12TC01				8S12BC01				39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC02	2.44	1.23	141.7	8S12BC02	0.47	1.29	35.5	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC03	2.45	1.23	142.2	8S12BC03	0.38	1.29	30.4	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC04	2.38	1.23	138.2	8S12BC04	0.35	1.29	28.7	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC05	2.27	1.23	131.8	8S12BC05	0.23	1.29	21.5	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC06	2.16	1.23	125.4	8S12BC06	0.33	1.29	26.6	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC07	2.1	1.23	121.9	8S12BC07	0.28	1.29	23.5	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC08	2.4	1.23	139.3	8S12BC08	0.36	1.29	29.0	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC09	2.18	1.23	126.6	8S12BC09	0.30	1.29	24.8	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC10	2.2	1.23	127.7	8S12BC10	0.29	1.29	24.6	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC11	2.25	1.23	130.6	8S12BC11	0.34	1.29	27.4	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC12	2.27	1.23	131.8	8S12BC12	0.35	1.29	28.0	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC13	2.45	1.23	142.2	8S12BC13	0.40	1.29	31.7	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC14	2.43	1.23	141.1	8S12BC14	0.40	1.29	31.6	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC15	2.49	1.23	144.6	8S12BC15	0.43	1.29	33.3	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S12TC16	2.96	1.23	171.9	8S12BC16	0.45	1.29	36.1	39^{0}35'11.08"S; 176^{0}48'02.21"E
8S13TC01	2.36	1.23	137.0	8S13BC01	0.33	1.33	27.6	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC02	2.26	1.23	131.2	8S13BC02	0.40	1.33	30.9	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC03	2.29	1.23	133.0	8S13BC03	0.36	1.33	28.7	39^{0}35'11.75"S; 176^{0}48'02.51"E

8S13TC04	2.47	1.23	143.4	8S13BC04	0.36	1.33	29.6	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC05	2.01	1.23	116.7	8S13BC05	0.31	1.33	25.2	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC06	2	1.23	116.1	8S13BC06	0.31	1.33	25.2	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC07	2.14	1.23	124.2	8S13BC07	0.36	1.33	28.5	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC08	2.06	1.23	119.6	8S13BC08	0.37	1.33	28.5	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC09	2.07	1.23	120.2	8S13BC09	0.30	1.33	24.4	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC10	2.18	1.23	126.6	8S13BC10	0.29	1.33	24.2	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC11	2.26	1.23	131.2	8S13BC11	0.33	1.33	26.9	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC12	2.13	1.23	123.7	8S13BC12	0.37	1.33	28.9	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC13	2.18	1.23	126.6	8S13BC13	0.34	1.33	27.3	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC14	2.11	1.23	122.5	8S13BC14	0.29	1.33	24.1	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC15	1.94	1.23	112.6	8S13BC15	0.30	1.33	23.9	39^{0}35'11.75"S; 176^{0}48'02.51"E
8S13TC16				8S13BC16				39^{0}35'11.75"S; 176^{0}48'02.51"E
601TC01	2.04	1.29	118.4	601BC01	0.51	1.19	40.5	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC02	2.16	1.29	125.4	601BC02	0.60	1.19	45.9	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC03	2.19	1.29	127.2	601BC03	0.53	1.19	42.7	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC04	2.06	1.29	119.6	601BC04	0.46	1.19	37.9	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC05	2.26	1.29	131.2	601BC05	0.57	1.19	44.9	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC06	1.77	1.29	102.8	601BC06	0.49	1.19	37.6	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC07	2.13	1.29	123.7	601BC07	0.49	1.19	39.7	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC08	1.78	1.29	103.3	601BC08	0.55	1.19	40.8	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC09				601BC09				39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC10	2.12	1.29	123.1	601BC10	0.62	1.19	47.0	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC11	2.21	1.29	128.3	601BC11	0.49	1.19	40.3	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC12	2.03	1.29	117.9	601BC12	0.49	1.19	39.4	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC13				601BC13				39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC14	2.06	1.29	119.6	601BC14	0.51	1.19	40.3	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC15	1.91	1.29	110.9	601BC15	0.51	1.19	39.7	39^{0}35'19.51"S; 176^{0}47'54.75"E
601TC16	1.83	1.29	106.2	601BC16	0.56	1.19	42.0	39^{0}35'19.51"S; 176^{0}47'54.75"E

602TC01	1.76	1.21	102.2	602BC01	0.45	1.19	30.4	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC02	1.67	1.21	97.0	602BC02	0.54	1.19	35.5	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC03	1.94	1.21	112.6	602BC03	0.49	1.19	33.3	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC04	2.02	1.21	117.3	602BC04	0.45	1.19	31.2	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC05	2.04	1.21	118.4	602BC05	0.55	1.19	37.0	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC06	1.99	1.21	115.5	602BC06	0.57	1.19	38.1	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC07	2.21	1.21	128.3	602BC07	0.52	1.19	35.5	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC08	1.8	1.21	104.5	602BC08	0.56	1.19	37.0	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC09	1.82	1.21	105.7	602BC09	0.54	1.19	35.7	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC10	1.93	1.21	112.1	602BC10	0.53	1.19	35.6	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC11	1.99	1.21	115.5	602BC11	0.51	1.19	34.6	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC12	1.82	1.21	105.7	602BC12	0.52	1.19	34.8	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC13	1.83	1.21	106.2	602BC13	0.55	1.19	36.6	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC14	2	1.21	116.1	602BC14	0.45	1.19	31.2	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC15	1.86	1.21	108.0	602BC15	0.49	1.19	33.0	39^{0}35'19.04"S; 176^{0}48'55.48"E
602TC16	1.99	1.21	115.5	602BC16	0.43	1.19	29.6	39^{0}35'19.04"S; 176^{0}48'55.48"E
603TC01	2.38	1.19	138.2	603BC01	0.39	1.23	26.6	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC02	2.41	1.19	139.9	603BC02	0.49	1.23	33.0	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC03				603BC03				39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC04	2.3	1.19	133.5	603BC04	0.46	1.23	30.6	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC05				603BC05				39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC06				603BC06				39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC07	2.21	1.19	128.3	603BC07	0.50	1.23	33.0	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC08	2.37	1.19	137.6	603BC08	0.49	1.23	32.7	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC09	2.12	1.19	123.1	603BC09	0.52	1.23	34.3	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC10				603BC10				39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC11	2.19	1.19	127.2	603BC11	0.47	1.23	31.1	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC12	1.99	1.19	115.5	603BC12	0.45	1.23	29.8	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC13	1.85	1.19	107.4	603BC13	0.60	1.23	38.2	39^{0}35'18.60"S; 176^{0}48'56.37"E

603TC14	1.8	1.19	104.5	603BC14	0.52	1.23	33.8	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC15	1.86	1.19	108.0	603BC15	0.52	1.23	33.7	39^{0}35'18.60"S; 176^{0}48'56.37"E
603TC16	1.85	1.19	107.4	603BC16	0.55	1.23	35.3	39^{0}35'18.60"S; 176^{0}48'56.37"E
604TC01	1.79	1.24	103.9	604BC01	0.60	1.26	41.2	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC02	1.55	1.24	90.0	604BC02	0.51	1.26	35.0	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC03	1.62	1.24	94.1	604BC03	0.51	1.26	35.8	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC04	1.52	1.24	88.3	604BC04	0.50	1.26	34.4	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC05	1.52	1.24	88.3	604BC05	0.54	1.26	36.7	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC06				604BC06				39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC07	1.69	1.24	98.1	604BC07	0.43	1.26	31.3	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC08				604BC08				39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC09	1.46	1.24	84.8	604BC09	0.49	1.26	33.7	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC10	1.68	1.24	97.5	604BC10	0.56	1.26	38.7	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC11	1.56	1.24	90.6	604BC11	0.49	1.26	34.2	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC12				604BC12				39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC13	1.59	1.24	92.3	604BC13	0.43	1.26	30.6	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC14	1.42	1.24	82.4	604BC14	0.49	1.26	33.3	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC15	1.59	1.24	92.3	604BC15	0.52	1.26	35.9	39^{0}35'19.00"S; 176^{0}48'56.15"E
604TC16	1.84	1.24	106.8	604BC16	0.50	1.26	35.8	39^{0}35'19.00"S; 176^{0}48'56.15"E
605TC01	1.45	1.19	84.2	605BC01	0.27	1.37	17.9	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC02	1.12	1.19	65.0	605BC02	0.27	1.37	17.5	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC03	1.46	1.19	84.8	605BC03	0.27	1.37	17.6	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC04				605BC04				39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC05	1.53	1.19	88.8	605BC05	0.30	1.37	19.5	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC06	1.59	1.19	92.3	605BC06	0.41	1.37	26.2	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC07	1.7	1.19	98.7	605BC07	0.24	1.37	16.6	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC08	1.38	1.19	80.1	605BC08	0.23	1.37	15.3	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC09	1.55	1.19	90.0	605BC09	0.23	1.37	15.6	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC10	1.61	1.19	93.5	605BC10	0.27	1.37	17.9	39^{0}35'20.50"S; 176^{0}48'54.27"E

605TC11				605BC11				39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC12	1.65	1.19	95.8	605BC12	0.21	1.37	14.5	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC13	1.66	1.19	96.4	605BC13	0.29	1.37	19.0	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC14	1.63	1.19	94.6	605BC14	0.27	1.37	18.3	39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC15				605BC15				39^{0}35'20.50"S; 176^{0}48'54.27"E
605TC16	1.57	1.19	91.2	605BC16	0.29	1.37	19.0	39^{0}35'20.50"S; 176^{0}48'54.27"E
606TC01	1.75	1.21	101.6	606BC01	0.47	1.17	31.9	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC02	1.67	1.21	97.0	606BC02	0.44	1.17	29.7	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC03	1.66	1.21	96.4	606BC03	0.42	1.17	28.6	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC04	1.85	1.21	107.4	606BC04	0.50	1.17	33.6	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC05	1.74	1.21	101.0	606BC05	0.49	1.17	32.9	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC06				606BC06				39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC07	1.66	1.21	96.4	606BC07	0.49	1.17	32.7	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC08	1.58	1.21	91.7	606BC08	0.49	1.17	32.3	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC09				606BC09				39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC10	1.75	1.21	101.6	606BC10	0.48	1.17	32.6	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC11				606BC11				39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC12				606BC12				39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC13	2.25	1.21	130.6	606BC13	0.55	1.17	37.7	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC14	2.03	1.21	117.9	606BC14	0.53	1.17	36.1	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC15	2.21	1.21	128.3	606BC15	0.48	1.17	33.7	39^{0}35'18.98"S; 176^{0}48'56.39"E
606TC16	2.09	1.21	121.3	606BC16	0.49	1.17	34.1	39^{0}35'18.98"S; 176^{0}48'56.39"E
607TC01	1.67	1.24	97.0	607BC01	0.57	1.18	39.4	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC02	1.59	1.24	92.3	607BC02	0.55	1.18	37.9	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC03	1.76	1.24	102.2	607BC03	0.55	1.18	38.2	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC04	1.7	1.24	98.7	607BC04	0.55	1.18	38.1	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC05	1.84	1.24	106.8	607BC05	0.48	1.18	34.9	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC06	1.88	1.24	109.2	607BC06	0.62	1.18	42.8	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC07				607BC07				39^{0}35'18.88"S; 176^{0}48'56.75"E

607TC08	2.04	1.24	118.4	607BC08	0.57	1.18	40.6	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC09				607BC09				39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC10				607BC10				39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC11	2.08	1.24	120.8	607BC11	0.45	1.18	34.2	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC12				607BC12				39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC13	1.93	1.24	112.1	607BC13	0.40	1.18	30.5	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC14				607BC14				39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC15	2.04	1.24	118.4	607BC15	0.43	1.18	33.0	39^{0}35'18.88"S; 176^{0}48'56.75"E
607TC16	2.11	1.24	122.5	607BC16	0.43	1.18	33.2	39^{0}35'18.88"S; 176^{0}48'56.75"E
608TC01				608BC01				39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC02	2.15	1.16	124.8	608BC02	0.57	1.22	34.8	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC03	2.47	1.16	143.4	608BC03	0.51	1.22	30.9	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC04	2.64	1.16	153.3	608BC04	0.44	1.22	26.7	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC05				608BC05				39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC06	2.85	1.16	165.5	608BC06	0.84	1.22	51.0	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC07	3.03	1.16	175.9	608BC07	0.72	1.22	43.5	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC08				608BC08				39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC09	2.46	1.16	142.8	608BC09	0.59	1.22	35.7	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC10	2.58	1.16	149.8	608BC10	0.74	1.22	44.7	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC11	1.94	1.16	112.6	608BC11	0.56	1.22	34.0	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC12	2.02	1.16	117.3	608BC12	0.49	1.22	29.6	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC13				608BC13				39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC14	2	1.16	116.1	608BC14	0.45	1.22	27.6	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC15	1.89	1.16	109.7	608BC15	0.49	1.22	29.9	39^{0}35'19.01"S; 176^{0}48'55.74"E
608TC16	2.12	1.16	123.1	608BC16	0.51	1.22	30.8	39^{0}35'19.01"S; 176^{0}48'55.74"E
609TC01	1.37	1.35	79.5	609BC01	0.37	1.13	32.0	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC02	1.36	1.35	79.0	609BC02	0.38	1.13	32.3	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC03	1.37	1.35	79.5	609BC03	0.40	1.13	33.2	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC04	1.52	1.35	88.3	609BC04	0.41	1.13	35.5	39^{0}35'18.68"S; 176^{0}48'56.02"E

609TC05	1.47	1.35	85.3	609BC05	0.33	1.13	30.7	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC06	1.36	1.35	79.0	609BC06	0.38	1.13	32.2	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC07	1.44	1.35	83.6	609BC07	0.35	1.13	31.4	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC08	1.32	1.35	76.6	609BC08	0.28	1.13	26.6	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC09				609BC09				39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC10	1.42	1.35	82.4	609BC10	0.35	1.13	31.2	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC11	1.35	1.35	78.4	609BC11	0.29	1.13	27.6	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC12				609BC12				39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC13	1.68	1.35	97.5	609BC13	0.29	1.13	30.7	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC14	1.57	1.35	91.2	609BC14	0.32	1.13	31.0	39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC15				609BC15				39^{0}35'18.68"S; 176^{0}48'56.02"E
609TC16	1.56	1.35	90.6	609BC16	0.27	1.13	28.7	39^{0}35'18.68"S; 176^{0}48'56.02"E
610TC01	1.81	1.25	105.1	610BC01	0.39	1.20	29.7	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC02	1.62	1.25	94.1	610BC02	0.44	1.20	31.4	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC03	1.73	1.25	100.4	610BC03	0.46	1.20	33.5	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC04	2.15	1.25	124.8	610BC04	0.45	1.20	34.5	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC05	1.66	1.25	96.4	610BC05	0.44	1.20	32.0	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC06	1.85	1.25	107.4	610BC06	0.46	1.20	33.6	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC07	1.84	1.25	106.8	610BC07	0.50	1.20	36.2	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC08	2.01	1.25	116.7	610BC08	0.57	1.20	40.9	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC09	1.58	1.25	91.7	610BC09	0.52	1.20	35.8	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC10	1.64	1.25	95.2	610BC10	0.53	1.20	37.0	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC11	1.84	1.25	106.8	610BC11	0.62	1.20	42.6	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC12	1.95	1.25	113.2	610BC12	0.52	1.20	37.4	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC13	1.9	1.25	110.3	610BC13	0.54	1.20	38.6	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC14	1.93	1.25	112.1	610BC14	0.56	1.20	39.9	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC15	1.9	1.25	110.3	610BC15	0.51	1.20	37.1	39^{0}35'20.31"S; 176^{0}48'53.73"E
610TC16	1.64	1.25	95.2	610BC16	0.49	1.20	34.6	39^{0}35'20.31"S; 176^{0}48'53.73"E
901TC01	1.34	1.33	77.8	901BC01	0.19	1.25	21.4	39^{0}35'20.96"S; 176^{0}47'51.37"E

901TC02	1.47	1.33	85.3	901BC02	0.21	1.25	23.4	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC03	1.43	1.33	83.0	901BC03	0.22	1.25	23.7	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC04	1.73	1.33	100.4	901BC04	0.26	1.25	28.4	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC05	1.58	1.33	91.7	901BC05	0.26	1.25	26.7	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC06	1.8	1.33	104.5	901BC06	0.28	1.25	29.8	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC07	1.7	1.33	98.7	901BC07	0.33	1.25	31.7	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC08	1.67	1.33	97.0	901BC08	0.27	1.25	28.3	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC09	1.71	1.33	99.3	901BC09	0.27	1.25	28.4	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC10	1.75	1.33	101.6	901BC10	0.24	1.25	27.3	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC11	1.73	1.33	100.4	901BC11	0.27	1.25	28.8	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC12	1.71	1.33	99.3	901BC12	0.29	1.25	29.4	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC13	1.61	1.33	93.5	901BC13	0.28	1.25	28.2	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC14	1.62	1.33	94.1	901BC14	0.27	1.25	27.8	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC15	1.41	1.33	81.9	901BC15	0.25	1.25	24.7	39^{0}35'20.96"S; 176^{0}47'51.37"E
901TC16	1.46	1.33	84.8	901BC16	0.26	1.25	25.9	39^{0}35'20.96"S; 176^{0}47'51.37"E
902TC01	1.48	1.25	85.9	902BC01	0.25	1.24	20.5	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC02	1.47	1.25	85.3	902BC02	0.25	1.24	20.3	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC03	1.64	1.25	95.2	902BC03	0.26	1.24	21.7	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC04	1.75	1.25	101.6	902BC04	0.29	1.24	24.1	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC05	1.84	1.25	106.8	902BC05	0.36	1.24	28.5	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC06	1.78	1.25	103.3	902BC06	0.23	1.24	20.9	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC07	1.84	1.25	106.8	902BC07	0.27	1.24	23.5	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC08	1.86	1.25	108.0	902BC08	0.28	1.24	23.8	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC09	1.91	1.25	110.9	902BC09	0.28	1.24	24.2	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC10	1.96	1.25	113.8	902BC10	0.28	1.24	24.1	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC11	1.8	1.25	104.5	902BC11	0.32	1.24	25.8	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC12	1.71	1.25	99.3	902BC12	0.28	1.24	23.2	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC13	2.01	1.25	116.7	902BC13	0.26	1.24	23.5	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC14	1.73	1.25	100.4	902BC14	0.26	1.24	22.2	39^{0}35'20.64"S; 176^{0}47'51.21"E

902TC15	1.74	1.25	101.0	902BC15	0.35	1.24	27.4	39^{0}35'20.64"S; 176^{0}47'51.21"E
902TC16	1.7	1.25	98.7	902BC16	0.27	1.24	22.9	39^{0}35'20.64"S; 176^{0}47'51.21"E
903TC01	1.66	1.31	96.4	903BC01	0.29	1.21	27.8	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC02	1.5	1.31	87.1	903BC02	0.31	1.21	27.6	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC03	1.59	1.31	92.3	903BC03	0.28	1.21	26.8	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC04	1.79	1.31	103.9	903BC04	0.28	1.21	28.2	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC05	1.53	1.31	88.8	903BC05	0.29	1.21	26.7	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC06	1.89	1.31	109.7	903BC06	0.31	1.21	30.3	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC07	1.64	1.31	95.2	903BC07	0.27	1.21	26.8	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC08	1.52	1.31	88.3	903BC08	0.29	1.21	26.5	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC09	1.68	1.31	97.5	903BC09	0.29	1.21	27.9	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC10	1.69	1.31	98.1	903BC10	0.33	1.21	29.9	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC11	1.53	1.31	88.8	903BC11	0.25	1.21	24.4	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC12				903BC12				39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC13	1.7	1.31	98.7	903BC13	0.25	1.21	25.9	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC14	1.59	1.31	92.3	903BC14	0.29	1.21	27.4	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC15	1.69	1.31	98.1	903BC15	0.26	1.21	26.4	39^{0}35'21.44"S; 176^{0}47'49.98"E
903TC16	1.69	1.31	98.1	903BC16	0.23	1.21	24.6	39^{0}35'21.44"S; 176^{0}47'49.98"E
904TC01	1.65	1.34	95.8	904BC01	0.23	1.24	26.9	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC02	1.35	1.34	78.4	904BC02	0.23	1.24	24.3	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC03	1.41	1.34	81.9	904BC03	0.27	1.24	26.7	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC04	1.55	1.34	90.0	904BC04	0.22	1.24	25.6	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC05	1.38	1.34	80.1	904BC05	0.29	1.24	27.4	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC06	1.46	1.34	84.8	904BC06	0.24	1.24	25.5	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC07	1.4	1.34	81.3	904BC07	0.18	1.24	22.1	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC08	1.31	1.34	76.1	904BC08	0.19	1.24	21.7	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC09	1.4	1.34	81.3	904BC09	0.25	1.24	25.5	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC10	1.28	1.34	74.3	904BC10	0.21	1.24	22.6	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC11	1.55	1.34	90.0	904BC11	0.20	1.24	24.2	39^{0}35'20.70"S; 176^{0}47'51.55"E

904TC12	1.49	1.34	86.5	904BC12	0.19	1.24	23.3	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC13	1.53	1.34	88.8	904BC13	0.26	1.24	27.2	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC14	1.5	1.34	87.1	904BC14	0.23	1.24	25.5	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC15	1.52	1.34	88.3	904BC15	0.20	1.24	23.9	39^{0}35'20.70"S; 176^{0}47'51.55"E
904TC16	1.54	1.34	89.4	904BC16	0.26	1.24	27.4	39^{0}35'20.70"S; 176^{0}47'51.55"E
905TC01	1.95	1.28	113.2	905BC01	0.36	1.15	30.8	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC02	1.7	1.28	98.7	905BC02	0.32	1.15	27.1	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC03	1.56	1.28	90.6	905BC03	0.33	1.15	27.1	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC04	1.68	1.28	97.5	905BC04	0.24	1.15	23.0	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC05	1.55	1.28	90.0	905BC05	0.31	1.15	25.7	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC06	1.68	1.28	97.5	905BC06	0.33	1.15	27.6	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC07	1.57	1.28	91.2	905BC07	0.28	1.15	24.5	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC08	1.7	1.28	98.7	905BC08	0.29	1.15	25.5	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC09	1.59	1.28	92.3	905BC09	0.24	1.15	22.5	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC10	1.57	1.28	91.2	905BC10	0.23	1.15	21.8	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC11	1.49	1.28	86.5	905BC11	0.30	1.15	24.9	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC12	1.61	1.28	93.5	905BC12	0.24	1.15	22.5	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC13	1.68	1.28	97.5	905BC13	0.27	1.15	24.4	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC14	1.61	1.28	93.5	905BC14	0.25	1.15	22.8	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC15	1.82	1.28	105.7	905BC15	0.29	1.15	26.4	39^{0}35'22.90"S; 176^{0}47'48.15"E
905TC16	1.84	1.28	106.8	905BC16	0.27	1.15	25.3	39^{0}35'22.90"S; 176^{0}47'48.15"E
906TC01	1.77	1.32	102.8	906BC01	0.30	1.30	30.3	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC02	1.81	1.32	105.1	906BC02	0.36	1.30	33.4	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC03	1.72	1.32	99.9	906BC03	0.33	1.30	31.2	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC04	1.7	1.32	98.7	906BC04	0.30	1.30	29.6	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC05	1.74	1.32	101.0	906BC05	0.27	1.30	28.5	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC06	1.85	1.32	107.4	906BC06	0.34	1.30	33.1	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC07	1.82	1.32	105.7	906BC07	0.34	1.30	32.4	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC08	2.09	1.32	121.3	906BC08	0.32	1.30	33.8	39^{0}35'22.49"S; 176^{0}47'49.24"E

906TC09	1.94	1.32	112.6	906BC09	0.28	1.30	30.6	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC10	1.85	1.32	107.4	906BC10	0.37	1.30	34.7	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC11	2.01	1.32	116.7	906BC11	0.38	1.30	36.4	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC12	1.84	1.32	106.8	906BC12	0.29	1.30	30.1	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC13	1.54	1.32	89.4	906BC13	0.35	1.30	31.1	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC14	2.26	1.32	131.2	906BC14	0.27	1.30	32.5	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC15	2.2	1.32	127.7	906BC15	0.26	1.30	31.4	39^{0}35'22.49"S; 176^{0}47'49.24"E
906TC16	2.35	1.32	136.4	906BC16	0.30	1.30	34.9	39^{0}35'22.49"S; 176^{0}47'49.24"E
907TC01	1.7	1.36	98.7	907BC01	0.27	1.27	30.1	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC02	1.81	1.36	105.1	907BC02	0.26	1.27	30.8	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC03	1.7	1.36	98.7	907BC03	0.32	1.27	32.7	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC04	1.56	1.36	90.6	907BC04	0.34	1.27	32.6	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC05	1.79	1.36	103.9	907BC05	0.41	1.27	38.3	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC06	1.66	1.36	96.4	907BC06	0.32	1.27	32.6	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC07	1.9	1.36	110.3	907BC07	0.29	1.27	33.4	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC08	1.64	1.36	95.2	907BC08	0.34	1.27	33.2	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC09	1.72	1.36	99.9	907BC09	0.28	1.27	31.0	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC10	1.87	1.36	108.6	907BC10	0.39	1.27	38.0	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC11	1.66	1.36	96.4	907BC11	0.31	1.27	32.2	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC12	1.76	1.36	102.2	907BC12	0.23	1.27	29.0	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC13				907BC13				39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC14	1.78	1.36	103.3	907BC14	0.35	1.27	35.0	39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC15				907BC15				39^{0}35'22.84"S; 176^{0}47'48.49"E
907TC16	1.63	1.36	94.6	907BC16	0.30	1.27	31.3	39^{0}35'22.84"S; 176^{0}47'48.49"E
908TC01	2.84	1.27	164.9	908BC01	0.29	1.23	31.2	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC02	2.43	1.27	141.1	908BC02	0.28	1.23	28.4	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC03	2.37	1.27	137.6	908BC03	0.28	1.23	28.1	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC04	2.13	1.27	123.7	908BC04	0.30	1.23	28.1	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC05	2.2	1.27	127.7	908BC05	0.28	1.23	27.3	39^{0}35'22.28"S; 176^{0}47'49.11"E

908TC06	1.97	1.27	114.4	908BC06	0.28	1.23	26.0	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC07	1.9	1.27	110.3	908BC07	0.32	1.23	27.5	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC08	1.93	1.27	112.1	908BC08	0.28	1.23	25.9	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC09	2.01	1.27	116.7	908BC09	0.34	1.23	29.4	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC10	2.11	1.27	122.5	908BC10	0.34	1.23	30.2	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC11	1.98	1.27	115.0	908BC11	0.40	1.23	32.5	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC12	1.93	1.27	112.1	908BC12	0.32	1.23	27.7	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC13	2.08	1.27	120.8	908BC13	0.27	1.23	26.0	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC14	1.83	1.27	106.2	908BC14	0.30	1.23	26.5	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC15	2.26	1.27	131.2	908BC15	0.31	1.23	29.0	39^{0}35'22.28"S; 176^{0}47'49.11"E
908TC16	2.39	1.27	138.8	908BC16	0.29	1.23	28.4	39^{0}35'22.28"S; 176^{0}47'49.11"E
909TC01	1.45	1.29	84.2	909BC01	0.33	1.15	27.1	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC02	1.58	1.29	91.7	909BC02	0.36	1.15	29.7	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC03	1.46	1.29	84.8	909BC03	0.27	1.15	23.9	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC04	1.55	1.29	90.0	909BC04	0.23	1.15	22.4	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC05	1.5	1.29	87.1	909BC05	0.29	1.15	25.5	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC06	1.27	1.29	73.7	909BC06	0.24	1.15	21.2	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC07	1.24	1.29	72.0	909BC07	0.22	1.15	19.7	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC08	1.3	1.29	75.5	909BC08	0.23	1.15	20.9	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC09	1.56	1.29	90.6	909BC09	0.29	1.15	25.5	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC10	1.4	1.29	81.3	909BC10	0.21	1.15	20.1	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC11	1.4	1.29	81.3	909BC11	0.19	1.15	19.3	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC12	1.4	1.29	81.3	909BC12	0.24	1.15	21.7	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC13	1.44	1.29	83.6	909BC13	0.25	1.15	22.7	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC14	1.44	1.29	83.6	909BC14	0.25	1.15	22.8	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC15	1.76	1.29	102.2	909BC15	0.28	1.15	26.4	39^{0}35'22.46"S; 176^{0}47'48.18"E
909TC16	1.38	1.29	80.1	909BC16	0.28	1.15	24.1	39^{0}35'22.46"S; 176^{0}47'48.18"E
910TC01	1.53	1.34	88.8	910BC01	0.22	1.21	24.7	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC02	1.79	1.34	103.9	910BC02	0.28	1.21	30.2	39^{0}35'21.64"S; 176^{0}47'49.46"E

910TC03	1.46	1.34	84.8	910BC03	0.21	1.21	23.8	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC04	1.57	1.34	91.2	910BC04	0.28	1.21	28.1	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC05	1.46	1.34	84.8	910BC05	0.20	1.21	23.4	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC06	1.44	1.34	83.6	910BC06	0.20	1.21	22.7	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC07	1.32	1.34	76.6	910BC07	0.20	1.21	22.0	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC08	1.64	1.34	95.2	910BC08	0.21	1.21	25.3	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC09	1.63	1.34	94.6	910BC09	0.21	1.21	25.1	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC10	1.51	1.34	87.7	910BC10	0.17	1.21	22.2	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC11	1.67	1.34	97.0	910BC11	0.19	1.21	24.3	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC12	1.65	1.34	95.8	910BC12	0.20	1.21	24.9	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC13	1.86	1.34	108.0	910BC13	0.23	1.21	28.2	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC14	1.73	1.34	100.4	910BC14	0.24	1.21	27.6	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC15	1.83	1.34	106.2	910BC15	0.26	1.21	29.5	39^{0}35'21.64"S; 176^{0}47'49.46"E
910TC16	1.63	1.34	94.6	910BC16	0.21	1.21	25.4	39^{0}35'21.64"S; 176^{0}47'49.46"E