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

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the requirements for the degree of

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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 ( $175.1 \pm 10.8$  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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## Table of contents

<b>Abstract</b>	i	
<b>Acknowledgements</b>	iv	
<b>Table of contents</b>	v	
<b>List of figures</b>	xi	
<b>List of tables</b>	xv	
<b>List of abbreviations</b>	xvii	
<b>Chapter 1: Introduction and objectives</b>		
1.1.	Climate change and its drivers	3
1.2.	Climate change mitigation	4
1.3.	The composition and role of soil carbon	5
1.3.1.	The composition of soil carbon	5
1.3.2.	Soil-carbon sequestration to mitigate climate change	8
1.3.3.	Soil-carbon sequestration to sustain ecosystem services	13
1.4.	The soil paradox and GHG accounting guidelines	17
1.4.1.	Assessment of soil-carbon at the country scale	18
1.4.2.	Assessment of soil carbon at the product level	20
1.4.2.1.	Consideration of soil carbon in the PAS2050	21
1.4.2.2.	Consideration of soil carbon in the GHG Product Protocol	24
1.4.2.3.	Consideration of soil carbon in the ISO TS 14067	25
1.4.2.4.	Similarities and differences of the protocols	27
1.4.3.	Reasons for non-compulsory accounting	29
1.5.	Implications for New Zealand	30
1.5.1.	New Zealand GHG commitments under the Kyoto protocol	30
1.5.2.	Implication for New Zealand agricultural exports	31
1.6.	Implications for the New Zealand apple industry	32
1.6.1.	Accounting for above-ground biomass carbon	34
1.7.	Research objectives	36
1.8.	Structure of this dissertation	37

1.8.1.	Structure of Chapters 2 to 5	37
1.8.2.	Focus of each chapter	37
1.9.	References	39

## **Chapter 2: Soil carbon in LCA and carbon footprint - A review of case studies**

2.1.	Introduction	45
2.2.	Materials and methods	46
2.3.	Results and discussion	47
2.3.1.	Description of the literature body	47
2.3.2.	Qualitative and quantitative importance of soil carbon accounting in LCA	47
2.3.3.	Issues for soil carbon integration in LCA and CF	50
2.3.3.1.	Lack of data	50
2.3.3.2.	Uncertainty	53
2.3.3.3.	Site dependency and local specificity	56
2.3.3.4.	Timing of emissions	59
2.3.3.4.a.	Methods to account for emission timing and temporary carbon storage	59
2.3.3.4.b.	Timing of emissions in case studies	62
2.3.3.5.	Reference datum	64
2.3.3.6.	Modelling	65
2.3.3.7.	Indirect Land Use Change	67
2.3.3.8.	Permanent impact	68
2.4.	Conclusions	69
2.5.	References:	71

## **Chapter 3: Variability of bulk density, carbon content and carbon stock in an apple orchard block, and implication for measuring and monitoring**

3.1.	Introduction	79
3.2.	Materials and methods	82
3.2.1.	Definitions	83
3.2.2.	Experimental site description and recent history	83
3.2.3.	Sampling procedure	85

3.2.4.	Processing and analysis of samples	87
3.2.5.	Calculation of total carbon stocks	88
3.2.6.	Statistical analyses	89
3.2.6.1.	Importance of statistical power	90
3.2.6.2.	Number of samples calculations	91
3.2.7.	Geostatistical methods	91
3.3.	Results & discussion	92
3.3.1.	Variability at the tree scale	92
3.3.1.1.	Bulk density of the fine earth	92
3.3.1.2.	Carbon content	93
3.3.1.3.	Carbon stock	95
3.3.2.	Variability at the orchard scale (10 sites /orchard)	97
3.3.2.1.	Bulk density	97
3.3.2.2.	Carbon content	98
3.3.2.3.	Variation of carbon content within sampling sites according to their spatial position in the ATA	101
3.3.2.4.	Carbon stock	104
3.3.2.5.	Spatial characteristics of soil carbon stocks at the block scale	106
3.3.3.	Towards the minimum requirements to measure changes in soil carbon stocks at the scale of the orchard block	111
3.3.4.	Costs involved in sampling	117
3.4.	Critical Analysis	123
3.4.1.	Bulk Density	123
3.4.2.	Stocks: Depth or Mass Equivalence	123
3.5.	Conclusions & perspectives	125
3.6.	References	128

**Chapter 4: Monitoring soil-carbon stocks in apple orchards: practical and financial feasibility considering incentives through carbon footprinting**

4.1.	Introduction	133
4.2.	Methods	136

4.2.1.	Description of the orchard blocks	136
4.2.2.	Selection of suitable orchard blocks	139
4.2.3.	Sampling and sample processing	142
4.2.4.	Soil-carbon data modification and comparison	145
4.2.5.	Statistical analysis	146
4.2.6.	Geo-statistical analyses	146
4.3.	Results and discussion	146
4.3.1.	Characteristics of soil-carbon content and bulk density in four orchard blocks	146
4.3.1.1.	Soil layer 0-50cm	147
4.3.1.2.	Soil layer 50-100 cm	148
4.3.2.	Carbon changes as a function of the distance to the nearest tree	149
4.3.3.	Characteristics of the carbon stocks in the four orchard blocks	153
4.3.4.	Spatial characteristics of carbon stocks	158
4.3.5.	Measuring changes in soil-carbon stocks at the orchard block level	160
4.3.6.	Cost of sampling	164
4.4.	Conclusions and perspectives	166
4.4.1.	Spatial variability in soil-carbon stocks in similar apple orchard blocks of different ages	166
4.4.2.	Suitability of a chrono-sequence to observe a statistically significant change of soil-carbon stocks over time in apple orchard blocks	167
4.4.3.	Practical and economic feasibility of a standard protocol to measure and monitor soil-carbon stocks in apple orchards	168
4.5.	References	173

**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**

5.1.	Introduction	177
5.1.1.	The carbon footprint of New Zealand apples	178
5.1.2.	Apple orchard block life cycle, replacement and end of life implications	179
5.1.2.1.	Planting	179
5.1.2.2.	Trees' first years and establishment	180

5.1.2.3.	Full production	180
5.1.2.4.	Orchard block removal or replacement	181
5.1.3.	Data and variability	183
5.1.3.1.	Dearth of data	184
5.1.3.2.	Types of data required for quantification on an area basis	185
5.1.3.3.	Woody biomass estimates at the orchard block scale	185
5.1.3.4.	Guidelines and uncertainty at large scales	186
5.1.4.	Key parameters for LCA and CF	188
5.1.5.	Timing of emissions & GWP accounting methods	190
5.1.6.	Objectives of this Chapter	190
5.2.	Materials and methods	191
5.2.1.	Measurements	191
5.2.1.1.	Measurements of apple trees woody biomass	191
5.2.2.	Scenarios for end of life	192
5.2.3.	Timing of emissions and temporary storage	193
5.2.4.	Statistical considerations	194
5.3.	Results & discussion	194
5.3.1.	Woody biomass	194
5.3.2.	Woody biomass dry weight and TCA	196
5.3.3.	Calculation of dry woody biomass for the orchard block	198
5.3.4.	End of life of the orchard block	199
5.3.4.1.	Assumptions common to all scenarios	200
5.3.4.2.	Description of the scenarios	201
5.3.4.3.	End-of-life scenarios results	203
5.4.	Conclusions	209
5.5.	References	214

## **Chapter 6: Summary, discussion and conclusions**

6.1.	Introduction	219
6.1.1.	Objectives	221
6.2.	Objective 1: Spatial variability and sampling requirements	222

6.3.	Objective 2: Change in soil carbon stocks	225
6.4.	Objective 3: estimating biogenic carbon stocks and implications for the carbon footprint of NZ apples.	226
6.5.	Objective 4: standard protocols	228
6.6.	Discussion and conclusions	229
6.7.	References	233
<b>Appendix A1.1 General principles of LCA</b>		234
<b>Appendix A1.2 Soil-carbon stocks: Inventory and reporting under IPCC guidelines</b>		238
<b>Appendix A1.3: Documents that aim at being a globally recognised product carbon footprint standard</b>		244
<b>Appendix 3.1 Engine driven drill soil corer description and validation</b>		248
<b>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.</b>		254

## List of figures

Figure 1. 1	Changes in the atmospheric CO <sub>2</sub> concentration at the Mauna Loa Observatory, Hawaii, August 2013. Source: NOAA (2013)	4
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)).	12
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.	13
Figure 1. 4	Framework for the ecosystem services delivered by the soil. Source: Dominati et al. (2010).	15
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).	33
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).	55
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.	83
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.	89
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.	89
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.	93
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).	94

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).	95
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).	96
Figure 3. 8	Cumulative soil carbon stock as a function of depth for the tree row and the grass alley. 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.	97
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).	98
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.	103
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	108
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.	108
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.	110
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	110
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.	111
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.	111
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.	112
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 $\alpha$ is the statistical significance level and $\beta = 1$ -statistical power.	114

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.	115
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 $\alpha$ is the statistical significance level and $\beta = 1$ -statistical power.	116
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.	119
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.	120
Figure 4. 1	Expected trend in the change in soil carbon stocks following re-development of an apple orchard.	135
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.	142
Figure 4. 3	The soil texture chart showing the texture results 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 (① + ②), while larger differences exist below 70cm soil depth (③). Source: adapted from Thien (1979).	144
Figure 4. 4	Trend 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.	151
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.	159
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	161

samples per site for the 6 year old orchard block. NB: Scales of variance axes are different.

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),. “ $\alpha$ ” is the statistical significance level and “ $\beta$ ” = 1-statistical power.	162
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.	165
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).	178
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 <a href="http://www.winehawkesbay.co.nz/images/pdf/story-of-hawkesbay.pdf">http://www.winehawkesbay.co.nz/images/pdf/story-of-hawkesbay.pdf</a> .	184
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 (R <sup>2</sup> ) show the relatively good capacity of TCA to estimate both tree trunk dry weight and whole tree dry woody biomass.	197
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.	205
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)	245
Figure A3.1.2	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.	249
Figure A3.1.3	Nathan Arnold (left) and the author testing the drill soil corer in the apple orchard.	249

## List of tables

<b>Table 2. 1</b>	<b>Examples of factors affecting soil-carbon stock levels and temporal changes in land based systems.</b>	<b>58</b>
<b>Table 3. 1</b>	<b>Representative soil texture profile of the top metre of soil in the apple orchard block, in 10 cm depth increments.</b>	<b>85</b>
<b>Table 3. 2</b>	<b>Carbon content (% or g carbon/ 100g soil) for the 0-50cm and 50-100cm soil layers.</b> (n: number of samples, Avg: Average, SD: Standard Deviation, SE: Standard Error, CV: Coefficient of Variation)	<b>100</b>
<b>Table 3. 3</b>	<b>Difference in carbon contents outside versus between the wheel-tracks for the orchard block and their statistical significance</b>	<b>101</b>
<b>Table 3. 4</b>	<b>Soil carbon stock for the 0-50cm, 50-100cm and 0-100cm depth layers.</b> (n= number of samples; Avg= average; SD= standard deviation; SE= standard error; CV= coefficient of variation).	<b>106</b>
<b>Table 3. 5</b>	<b>The cost assumptions for sampling.</b>	<b>118</b>
<b>Table 4. 1</b>	<b>Main characteristics of the four apple orchard blocks of the chrono-sequence.</b>	<b>138</b>
<b>Table 4. 2</b>	<b>Soil profile descriptions of the four orchard blocks</b>	<b>142</b>
<b>Table 4. 3</b>	<b>Carbon content (% or g carbon/ 100g soil) and bulk density (BD, g/cm<sup>3</sup>) for the 0-50 cm soil layer in each of the orchard blocks of the chrono-sequence.</b> 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)	<b>144</b>
<b>Table 4. 4</b>	<b>Carbon content (% or g carbon/ 100g soil) and bulk density (BD, g/cm<sup>3</sup>) for the 50-100cm soil layer in each of the orchard blocks of the chrono-sequence.</b> 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)	<b>148</b>
<b>Table 4. 5</b>	<b>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.</b> Different letters indicate statistically significant differences at the 5% level within each individual column separately. ESM <sub>min</sub> (0-50 cm) = 5806 tons of soil/ha. ESM <sub>min</sub> (50-100 cm) = 6076 tons of soil/ha. (FD: Fixed Depth method, ESM: Equivalent Soil Mass method, SD: Standard Deviation).	<b>153</b>
<b>Table 4. 6</b>	<b>Soil-carbon stocks (t-C/ha) of the 0-100 cm soil layer for the four orchard blocks.</b> 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).	<b>155</b>

Table 5. 1	Literature woody biomass estimates and characteristics of the trials. All trees are on an M.9 rootstock.	186
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.	184
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).	197
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.	205
Table A1.2.1	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 <a href="http://www.ipcc-nggip.iges.or.jp/public/2006gl/worksheets/3B2a_CL%20Remaining%20CL.xls">http://www.ipcc-nggip.iges.or.jp/public/2006gl/worksheets/3B2a_CL%20Remaining%20CL.xls</a> . Equation 2.25 is from IPCC (2006)	242

## List of abbreviations

%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