WINTER CEREAL TRUST

PROGRESS REPORT for 2018

Carbon Footprint for Western Cape – Phase 2 (2018)

1. INSTITUTE & TITLE:

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Years' Experience:	25

2. PROJECT DETAILS:

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ANNUAL PROGRESS REPORT FOR PHASE 2

Project title:

Determining the Carbon Footprint intensity of different winter grain farming regimes in the Western Cape

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1 Introduction

Increasingly the environmental impact of agricultural supply chains is being scrutinised by consumers, NGO's and governments. South Africa made a commitment to the international community to reduce its carbon footprint (C-footprint), hence the recent focus on carbon emissions, policy and the introduction of a carbon tax.

Improved cropland management has been highlighted as a practical and viable carbon emission mitigation option. Conservation Agriculture (CA) is promoted by many role players in the agricultural industry, including Grain SA, to *inter alia* reduce the C-footprint of agriculture. It is important to conduct an in-country, or regional, study to assess the C-footprint of farming systems, soil health and soil carbon sequestration (C-sequestration). This will provide essential information to facilitate reduction in carbon budget (C-budget).

It will be important to demonstrate the impacts of farming systems on the C-budget through assessment tools and models. The impact of farming systems and management options on the C-budget can be determined from a combination of C-footprint-, soil health-, and C-sequestration assessments, and a farm carbon calculator (or protocol). The assessments and carbon calculator will also demonstrate how C-budgets can lead to improved efficiency in farming systems, reduced C-emissions and alignment with future carbon tax. The proposed carbon tax legislation also contains mechanisms for trading agricultural carbon credits to other organisations to reduce their carbon tax exposure. The project is a first step towards understanding the potential of farm-based carbon credit income. The actions and deliverables for each phase of the overall Winter Grain Carbon emission and sequestration project are shown in Figure 1.

In **Phase 1 (2017)** the C-footprints were calculated for farming systems for the seven regions in the Swartland and Southern Cape. The C-footprint results of three farming systems were weighted for each region to calculate the regional C-footprint. The regional C-footprints were extrapolated to calculate a snapshot winter grain region C-footprint. Soil samples were also analysed for soil health tests on representative farms and practices for each region.

Phase 2 (2018) of the project aimed to determine the carbon sequestration potential of cropping systems and offset these results with the carbon emission results from Phase 1 in the winter grain farming regions in the Western Cape.

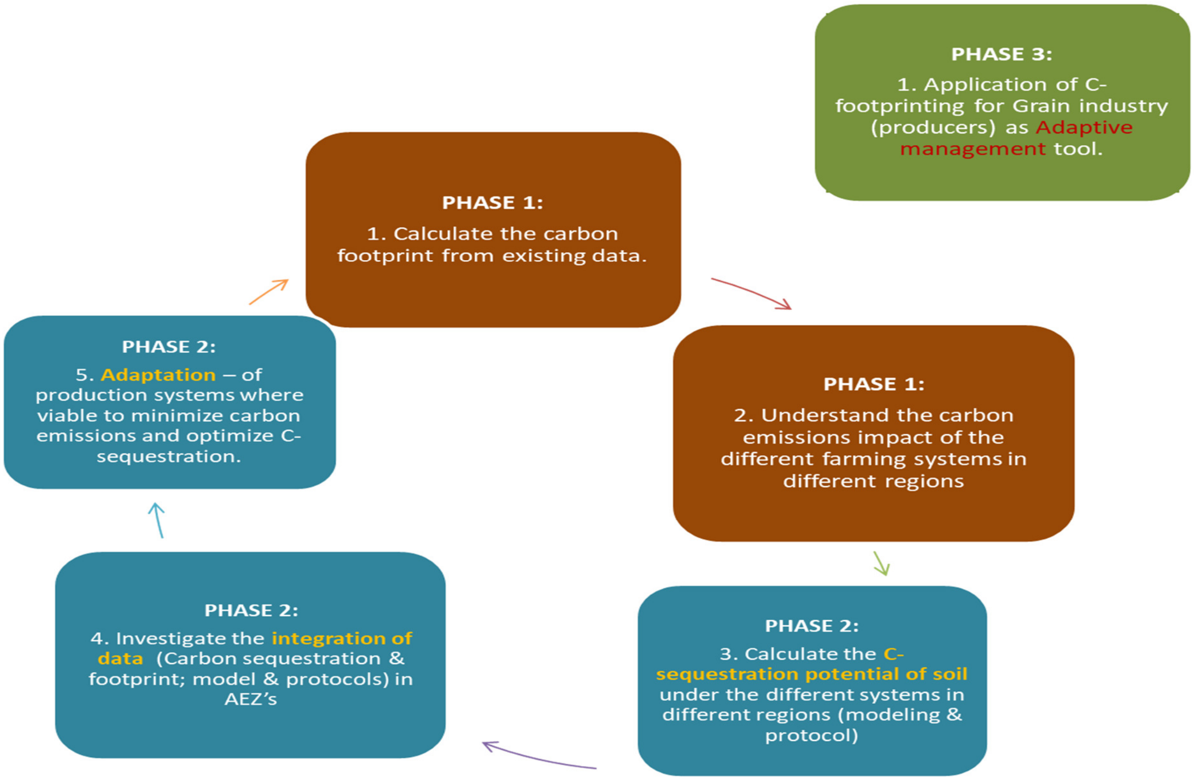

Figure 1: Phases and deliverables of Winter Grain Carbon emission and sequestration project.

2 Long term goal

The long-term goal of the project is to determine the C-footprint (emissions, removals and sequestration) of farming systems across the winter grain regions. The C-footprint will provide farmers with benchmark data and tools that can lead to improved efficiency in farming systems, reduced C-emissions and alignment with the future carbon tax.

3 Short-term objectives

The short-term objectives for Phase 2 (2018) are:

1. To evaluate, select or built soil carbon sequestration (C-sequestration) models or tools for application with annual crops in the Western Cape*;*
2. To collect data for C-sequestration modelling in the Western Cape*;*
3. To model C-sequestration for annual cropping systems in the Western Cape*;*
4. To analyse, report and integrate modelling results*;*
5. To communicate C-sequestration assessment results for Phase 1 and Phase 2.

4 Progress report

4.1 Objective 1: To evaluate, select or built soil carbon sequestration models or tools for application with annual crops in the Western Cape

4.1.1 Evaluation of numerical models to predict soil carbon sequestration

Theoretical evaluation

Numerical soil organic matter models were evaluated to predict C-sequestration based on simulation of the processes (process-based models) involved in C-sequestration at the detail level (farmers' field).

Fourteen (14) numerical models were evaluation theoretically that predict C-sequestration. The models were evaluated for their suitability to predict the impact of grain farming systems on C-sequestration for the Western Cape grain regions. Aspects that were considered include:

- Model complexity and extent that the model is user friendly for running the software;
- Data requirements and extent that data are readily available or can be determined with routine analytical methods;
- Modelling time resolution (daily or monthly); and
- Extent that conventional and conservation agriculture grain farming land management practices of the Western Cape can be accounted for.

The following models were not selected for this study:

- DOS-based models, namely CANDY, DAISY, NCSOILS, SOMM, CENTURY and DayCent. DOS-based models were considered to be not very user friendly;
- Windows-based models for which model codes are not easily accessible. The models include ROTH-C, CENTURY-4, CYCLES and C-Store. These models have no dedicated home page, model developers require motivation for use, and/or the codes are not easily available.

The following models were rated to be suitable for application for this study:

- Windows-based models, namely DNDC, DSSAT, EPIC and APEX;
- The DSSAT (Hoogenboom *et al.,* 2017) and EPIC (Gerik *et al.,* 2013) models were selected from the theoretical evaluation. The advantages and disadvantage of DSSAT and EPIC models are listed in Table 1.

Table 1: Advantages and disadvantages of selected numerical models.

Advantages	Disadvantages
DSSAT model	
• History of model support; • Comprehensive suite of models on crop production and related aspects: - SA calibrated CERES-Maize, Ceres-Wheat and Canegro; • Based on CENTURY C-sequestration model - Detail, process-based, - Predict effect of farming systems in detail e.g. tillage, crop and crop rotation; • Default data to work form; • Ability to upscale.	• Complex, time- and data intensive; • Requires expertise of soils, climate-soil-vegetation continuum and cropping systems; • Not user friendly for routine application: - Take time to learn and understand the comprehensive model, - The manual and tutorial on C-sequestration are not available; • Calibration is required before scenarios can be predicted.
EPIC model	
• Long history of model support; • Based on CENTURY C-sequestration model - Detail, process-based, - Predict effect of farming systems in detail e.g. tillage, crop and crop rotation; • Default data to work from that can be used to initially to refine specific input parameters; • Comprehensive data files included tillage and tillage implements, crop parameters and crop rotation, and farming / cropping systems; • User-friendly program to prepare large climate data files that are data-error corrected, can import South African climate station data; • Daily climate data can be changed into monthly climate statistics; • Has ability to upscale e.g. up-scaling example in US from local to national; • An extensive array of land management practices can be simulated e.g. crop rotations, tillage systems and fertilisation, etc.	• More time intensive, higher data requirements and more complex than IPCC protocol; • Requires expertise of soils and cropping systems.

The use of DSSAT was discontinued for the following reasons:

- The time required to learn and use the complex model. This is an indication that it is not meaningfully user-friendly for application to this study;
- DSSAT has not a manual and tutorial on C-sequestration modelling. The user has to consult academic articles to learn the C-sequestration model routine;
- Requires calibration of the C-sequestration component against (long-term) monitored data before scenarios can be predicted;
- DSSAT would require a dedicated modeller or be used in post graduate studies to simulate the C-sequestration for the winter grain regions, which is beyond the scope of the application required for the study.

The WinEPIC numerical software was applied to predict C-sequestration for conventional- and conservation agricultural farming systems for the winter wheat regions. WinEPIC was applied for the study for the following reasons:

- WinEPIC is a freeware, downloadable numerical model;
- Model code is easy accessible and downloadable from a dedicated home page;
- The model is well documented with tutorials to learn the model in a user-friendly manner;
- WinEPIC enables quick and easy simulation of various farming practices of the winter grain regions; and
- The process-based model is ideal software for simulating C-sequestration for the various farming regimes in the winter wheat regions in detail.

WinEPIC Model description

WinEPIC (Environmental Policy Integrated Climate) is a process-based computer model that simulates the physico-chemical processes that occur in soil and water under agricultural management. Application of WinEPIC in the study is summarised in Table ***2***.

The C-sequestration module of WinEPIC is based on the CENTURY C-sequestration model (Parton *et al.,* 1992) that simulates the soil organic matter processes and dynamics to predict C-sequestration. The C-sequestration model accounts for two forms of litter, namely metabolic and structural litter. The model also accounts for three forms of soil organic matter, namely active, slow and passive, that is also referred to as labile, intermediate and stable soil organic matter fractions. C leaving the active organic matter fraction is partitioned into either CO_2 or slow forms C. The CENTURY model produced consistently low errors for all datasets in a comprehensive study in a comparison of the performance of soil organic matter models using data from long-term experiments (Smith et al., 1997).

The important processes and components simulated by the CENTURY model, which WinEPIC C-sequestration component is based on, is shown in Figure 2.

Table 2: Summary of WinEPIC model.

Aspect	Description
Model type	Continuous process-based
Spatial scale	Field-scale, can simulate field, farm or small/agricultural catchment
Spatial unit	Units with homogeneous climate, soil, topography, land use and crop management system
Temporal scale	Daily time step predicting over decades (long-term)
Evaluate impact of conservation agriculture	Simulate crop, land management practices and tillage systems in considerable detail

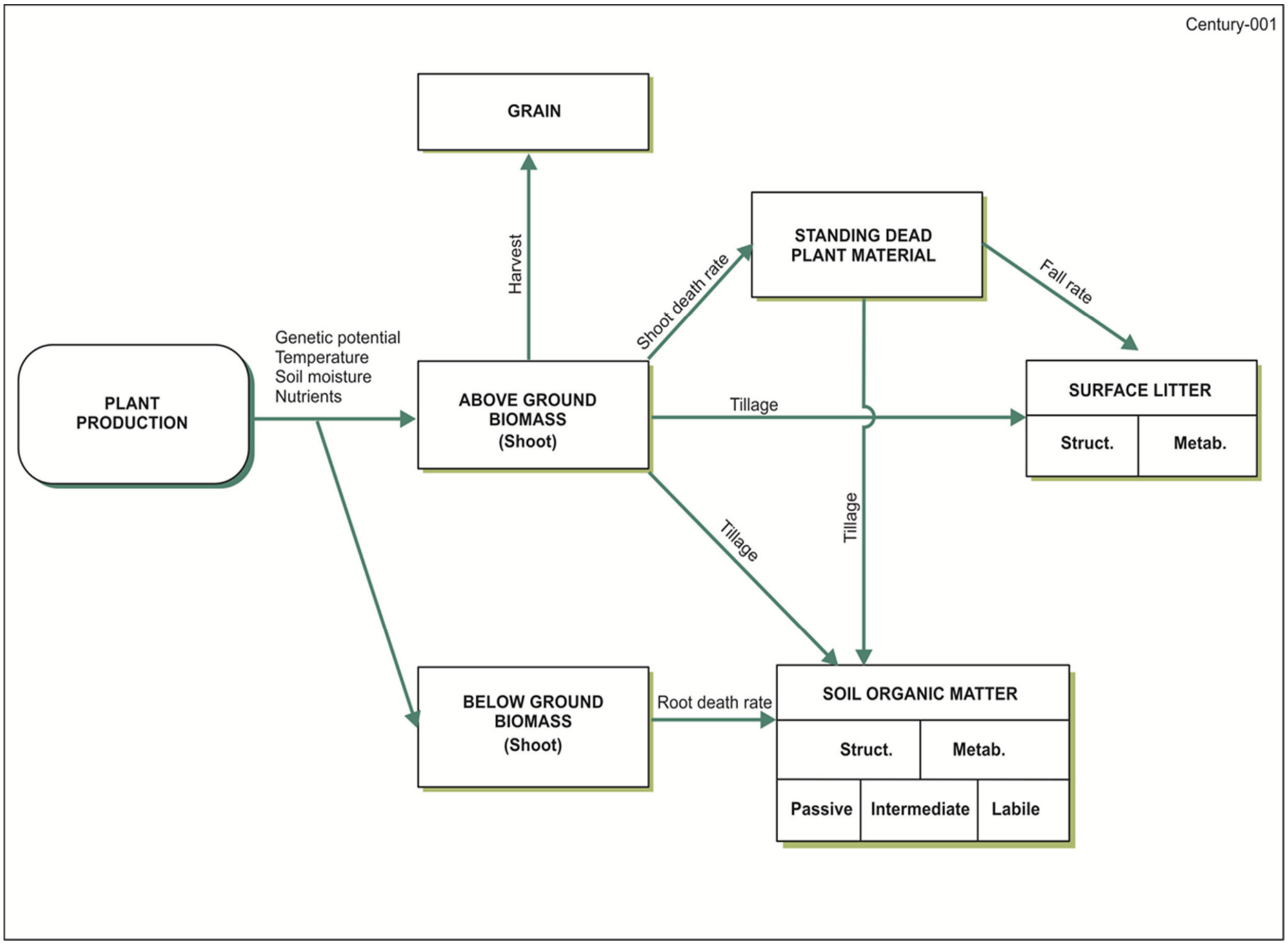

Figure 2: Summary of WinEPIC C-sequestration modelling components.

4.1.2 Evaluation of IPCC tools - coarse, conceptual-based level

This section discusses the IPCC tools used firstly to determine the carbon sequestration potential of the winter grain region per farming system before integrating these results with the carbon emission results from Phase 1 to obtain the nett C-footprint (balance) results for the region per farming system.

Carbon stock accounting in Cropland

The methodology used in the development of the carbon sequestration tool was the following:

- IPCC Good Practice Guidance for Land Use & Land Use Change & Forestry (IPCC GPG LULUCF) (IPCC, 2003);
- IPCC Guidelines 2006: Volume 4, Chapter 5 for Croplands (IPCC, 2006);
- National Carbon Sinks Assessment (Department of Environmental Affairs, 2015a)

The methodologies take into account current land use and land use change taking place during a certain period. The land uses classified in the IPCC documents are as follows:

- Forestland;
- Cropland;
- Grassland;
- Wetlands;
- Settlements and;
- Other.

The land use covered in this study is for cropland remaining cropland where no land use change occurs during the period. The results indicate the *change* in carbon stocks in t.ha^{-1} per year for each scenario. Carbon stocks in a predefined system consists of a set of linked and interacting sub-stocks (called 'pools') which change over time: slowly in the case of soil carbon, moderately quickly in the case of woody biomass, and rapidly in the case of herbaceous and litter carbon (Department of Environmental Affairs, 2015a). The carbon flows between the pools, and between the land and the atmosphere, land and ocean, and land and human systems are called fluxes (Figure 3).

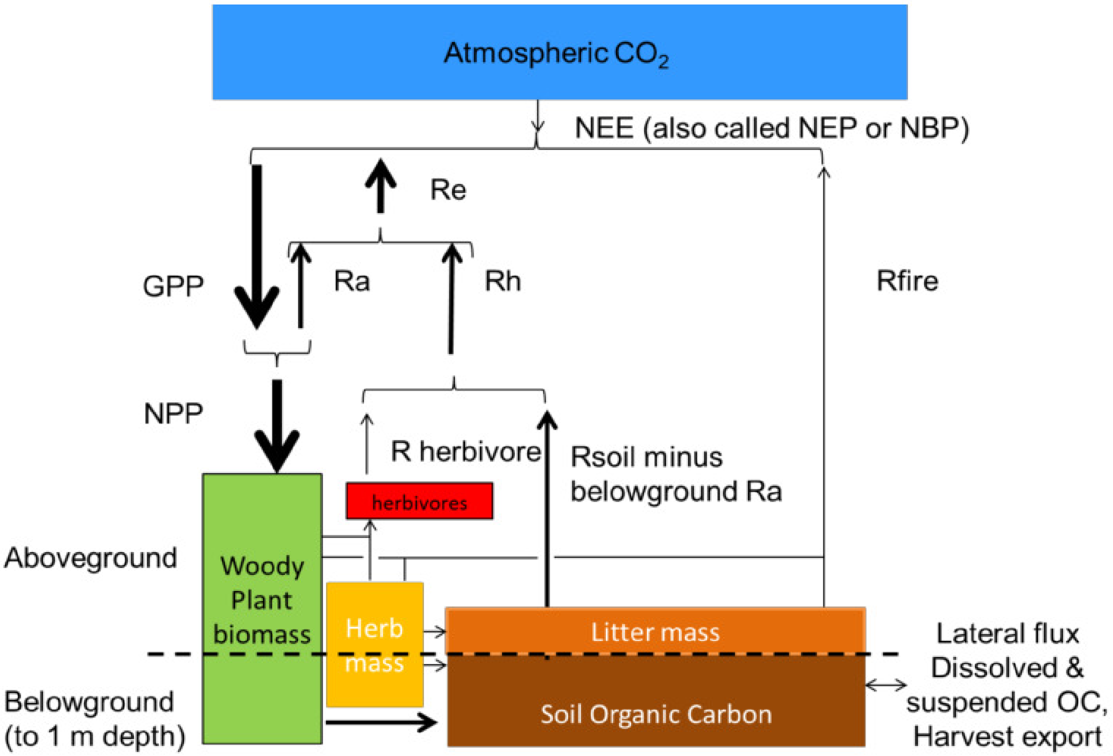

Figure 3: Components of a generalized terrestrial carbon cycle.

Terminology: *NEE = Net Ecosystem Exchange*
NEP = Net Ecosystem Productivity,
NBP = Net Biome Productivity,
GPP = Gross Primary Production,
NPP = Net Primary Production,
Ra = autotrophic respiration (respiration by plants),
Rh = heterotophic respiration (herbivores, carnivores and microbes),
Re = ecosystem respiration (the combined respiration from all sources),
Rfire = fire emissions

(Department of Environmental Affairs, 2015a)

The IPCC classifies the methodologies and data used to determine carbon sequestration potential of natural systems into Tiers/levels. These Tiers correspond to a progression from the use of formulae with default data to country specific data in more complex national systems (IPCC, 2003).

There are 3 Tier levels summarised as follows:

- Tier 1: Methods and parameters provided in IPCC guidelines. Activity data that is spatially coarse i.e. national or global estimates of deforestation rates, agricultural production statistics etc.
- Tier 2: same methodological approach as Tier 1 but with emission factors and activity data defined by country for land use/activities.
- Tier 3: models and inventory measurement systems for national circumstances repeated over time using high resolution and disaggregated activity data.

Carbon emissions (decrease in carbon stock) are reported as positive values (+) and sinks or removals (increase in carbon stock) are reported as negative values (-). To convert the C stock results to CO_2 removals the C stock results are multiplied by the factor 44/12 (IPCC, 2003).

The cropland system carbon stock changes in this study covers the flows from the Nett Primary Production of biomass (removals), specifically annual crops, the lateral movement of the NPP to litter mass and SOC and the respiration (emissions) of plants and soil.

Emissions and removals from cropland remaining cropland include two subcategories of CO_2 emissions and removals. **Error! Reference source not found.** summarises nett emissions or removals of carbon stock from cropland remaining cropland for the subcategories: changes in carbon stocks in living biomass (above and below ground) and changes in carbon stocks in soils.

$$\Delta C_{CC} = \Delta C_{LB} + \Delta C_{Soils}$$

Where:

ΔC_{CC} = *annual change in carbon stocks in cropland remaining cropland in tonnes C* yr^{-1}
ΔC_{LB} = *annual change in carbon stocks of living biomass in tonnes C* yr^{-1}
ΔC_{Soils} = *annual change in carbon stocks in soils tonnes C* yr^{-1}

Equation 1: Annual change in carbon stocks in cropland remaining cropland.

Above and below ground biomass

Above and below ground biomass of the different crops is accounted for using the formulae in Equation 2 from the South African Carbon Sink Assessment (Department of Environmental Affairs, 2015):

$$AGB_{crop} = AGB_{harvest} \times 0.5 \times \frac{crop\ duration}{365} + AGB_{residue}$$

Equation 2: Above ground biomass (AGB_{crop}) as a function of at harvest above ground biomass ($AGB_{harvest}$), crop duration and year round residue left in stalks ($AGB_{residue}$)

Where:

$$AGB_{harvest} = \frac{Y\left(\frac{tC}{ha}\right)}{HI}$$

and:

$$Y = yield \times (1 - fraction\ moisture)$$

Equation 3: At-harvest above ground biomass determine from the Harvest Index (HI) and Yield (tC/ha).

The Harvest Index (HI) is the ratio of harvested yield to above ground biomass. Yield (in tonnes C/ha) was determined from the trials at Langgewens and Tygerhoek for winter grain cereals (Labuschagne, 2017; Strauss, 2017) as well as legume and fodder crops (Strauss, 2005a,b, 2006) and is the total average yield (grain) per crop in each crop rotation and farming regime multiplied by the carbon fraction of the biomass dry matter. The carbon fraction and fraction moisture per crop group is presented in Table 3. No error information was available for these factors and therefore no error was assumed. The carbon fraction for each crop in Smith (2014) and Cooper (2016) for the Tygerhoek and Langgewens sites was between 40% – 50% which is aligned with the value of 0.47 in Table 3.

Table 3: Calibration factors used for agricultural crops to determine biomass carbon content.

Crop group	HI[1]	Moisture	Below ground fraction[2]	Carbon fraction	Residual fraction of A_{GB} (R_{AGB})	Crop duration[3]
Summer cereals[4]	0.5	0.13	0.2	0.47	0.2 (dry) 0.1 (irr)	0.66
Winter cereals[5]	0.4	0.11	0.2	0.47	0.2 (dry) 0.1 (irr)	0.5
Oil seeds	0.39	0.15	0.2	0.47	0.2 (dry) 0.1 (irr)	0.66
Legumes	0.85	0.15	0.2	0.47	0.2 (dry) 0.1 (irr)	0.5
Fodder crops	1	0.5	0.2	0.47	0.2 (dry) 0.0 (irr)	1
Sugar cane	1	0.2	0.2	0.47	0.1 (dry) 0.1 (irr)	1
Other crops	1	0.5	0.2	0.47	0.2 (dry) 0.0 (irr)	1
Vegetables	1	0.5	0.2	0.47	0.0 (irr)	0.83

Note: [1] *HI = Harvest Index: the ratio of harvested yield to total aboveground biomass*

[2] *as proportion of AGB*

[3] *as proportion of year*

[4] *based on maize which accounts for over 94% of this group*

[5] *based on wheat which accounts for over 85% of this group*

The above ground residue left in the stalks is calculated from the following formulae in Equation 4:

$$AGB_{residue} = (AGB_{harvest} - Y) \times R_{AGB}$$

Equation 4: Formula to determine above ground biomass residue ($AGB_{residue}$).

Where R_{AGB} is the residual aboveground biomass expressed as a proportion of the non-yield biomass. The amount of residue remaining on the land per farming regime will be used for this variable; e.g. zero tillage in Middle Swartland has crop residue removal of 30% therefore R_{AGB} is 0.7. The below ground biomass for annual crops is calculated as a fraction of the above ground biomass in Equation 5:

$$BGB_{crop} = 0.2 \times AGB_{crop}$$

Equation 5: Formula to determine below ground biomass of annual crop.

Soils

The winter grain region soils are not categorised as organic soils (i.e. peat soils) and the formula for carbon stock changes in mineral soils were used. Changes in carbon stocks in mineral soils was determined by the formulae in Equation 6 (IPCC, 2003)

$$\Delta C_{cc} = \frac{\left[\left(SOC_0 - SOC_{(0-T)} \times A\right)\right]}{T}$$

Where $$SOC = SOC_{REF} \times F_{LU} \times F_{MG} \times F_I$$

ΔC_{CC} = annual change in carbon stocks in mineral soils, tonnes C yr-1
SOC_0 = soil organic carbon stock in the inventory year, tonnes C ha-1
$SOC_{(0-T)}$ = soil organic carbon stock T years prior to the inventory, tonnes C ha-1
T = inventory time period, year (default is 20 years)
A = land area of each parcel, ha
SOC_{REF} = the reference carbon stock, tonnes C ha-1; see carbon stock in soil forms per site under fynbos/renosterbos in Section 0.
F_{LU} = stock change factor for land use or land-use change type, dimensionless; see Appendix A
F_{MG} = stock change factor for management regime, dimensionless; see Appendix A
F_I = stock change factor for input of organic matter, dimensionless; see Appendix A

Equation 6: Annual change in carbon stocks in mineral soils for a cropland system.

The parameters used for each of the variables F_{MG} and F_I are included in Appendix 2. The F_{LU} parameter used for dry land agriculture in South Africa (Department of Environmental Affairs, 2015b) is 0.5.

Nett C-footprint (C balance)

Carbon emissions per ton grain (kg CO_2e/ton) were determined for representative farms in all sub-regions under each farming system; Conventional (CT), Current conservation agriculture (Current CA) and Future conservation agriculture (Future CA) for all commodities. The results were then extrapolated to the current and future scenario for the Western Cape using the tonnages produced per system.

The carbon sequestration results in tonnes Carbon (tC) and tCO_2/hectare will be viewed as representative at a coarse level for the two sub-regions and will also be extrapolated to the Swartland and Southern Cape regions and finally to the Western Cape region as done for the carbon emission results in Phase 1.

However, a conversion process will need to take place in order to offset the emissions from the carbon sequestered. The results for the carbon emissions of the current and future scenarios have the functional unit of kg CO_2e/ton grain and the carbon sequestration values have the functional unit tCO_2/hectare. The functional unit of the carbon emissions will be converted to tCO_2e/ha using the yield per hectare for each grain commodity in order to integrate the carbon emission values with the CO_2 sequestration values.

Once the results of the carbon emissions and carbon sequestration are converted to a per hectare base, both values can be offset to obtain the nett C-footprint. The offset formula is presented in Equation 8 (IPCC, 2003).

$$Nett\ C - footprint = Total\ Carbon\ emissions + Total\ Carbon\ sequestered$$

Equation 7: Formula to determine nett carbon footprint (C-footprint)

4.2 Objective 2: To collect data for soil carbon sequestration modelling in the Western Cape

4.2.1 Numerical model data collation to predict soil carbon sequestration

Modelling approach

WinEPIC was used to predict C-sequestration as a function of the following:

- Climate for an experimental farm or region;
- Soil properties;
- Cropping system (crop rotation)
- Crop characterises;
- Crop and tillage management practices.

The predicted C-sequestration represents the net carbon included in the soil organic matter for a growing season, and the cumulative build-up or loss of soil organic carbon in the long-term (decades). The WinEPIC model used to predict C-sequestration is discussed in Section 4.4.1., and the components and processes of C-sequestration accounted for by WinEPIC is shown in Figure 2.

Data requirements

The type of data required for WinEPIC are summarised in Table 4 to predict C-sequestration.

Climate

Climate data files of dally recorded meteorological data were prepared for input to WinEPIC. The climate data files were prepared with a weather import utility to prepare climate files for import into WinEPIC. The utility was also used to scan imported data for data errors and missing days/data. Daily solar radiation was calculated from available temperature data.

Table 4: Type of model data required for WinEPIC.

Data type	Variable	Data requirement[1,2,3,4]
Site	Site / farm name Dryland or irrigated Latitude, longitude and elevation Slope and aspect	***Required***
Climate	Daily rainfall Daily minimum and maximum air temperature[1,2]	***Essential***
	Daily solar radiation	**Essential** **Calculated from temperature**
	Daily wind speed Daily relative humidity or dew point temperature	***Required***
Soil properties	Amount of soil layers Thickness % Sand % Silt	***Essential***
	% Coarse fragments / stones Soil organic carbon / matter	**Essential** **Must be included in routine soil analyses**
	Field capacity Wilting point Saturated hydraulic conductivity Bulk density	**Essential** **Can be determined from soil texture and %coarse fragments**
Crop systems (Crop and tillage management)	Cropping sequence Planting - date, depth, method and density Tillage - date, type, depth and disturbance Fertiliser application - dates, type, rates and depth Harvesting - date Row spacing and direction Residue application - material, depth of incorporation, amount and nutrient contents	***Essential*** ***Use GrainSA data for typical dates of planting, tillage, fertilisation and harvesting*** ***Use model default values for more detailed and less readily available data***
Crop characteristics	Cultivar Cultivar growth parameters Soil nutrient uptake / requirements	***Required*** ***Use model default values and refine with available data***

Note: [1.] *Essential data:* ***Minimum data required*** *to predict C-sequestration.*

[2] *Required data: Required to* ***improve accuracy of C-sequestration prediction****, but not essential to predict C-sequestration.*

[3.] ***Bold and Italics****: Data readily available or can be obtained with routine analyses.*

[4.] **Bold***: Data not readily available, but can be determined from readily available data.*

The following climate model input files of 40 years climate data were prepared:

- Data files for the Langgewens- and Tygerhoek research farms; The files were prepared from the data provided by the Western Cape Department of Agriculture;
- Data files for each of the winter grain regions. The files were prepared from data included in the web-based weather station network of NOAA National Climatic Data Centre (http://gis.ncdc.noaa.gov/map/viewer/#app=cdo&cfg=cdo&theme=daily&layers=111&node=gis). The data was used under the condition for non-commercial use without restriction. The climate data was converted to WinEPIC format using weather import utility.

The climate data files were prepared from daily recorded data to conserve the relation between daily rainfall and other climatic variables, as well as to account for the effect of rainfall distribution such as the amount of rainy days and consecutive days of rainfall.

Soil

Soil parameter (default) values of soil files included in WinEPIC with similar texture to the soils at the Langgewens- and Tygerhoek research farms were changed to the values reported by Cooper (2016) and Smith (2014) for the 0-5, 5-10, 10-20 and 20-40 cm layers for the soils at the experimental sites. The following soils data were used that is essential (minimum required) data to predict C-sequestration:

- Clay and sand contents, coarse fragments content and dry bulk density data reported by Cooper (2016) and Smith (2014);
- Wilting point, field capacity and saturation (also referred to as porosity), and saturated hydraulic conductivity were estimated from soil texture using pedo-transfer functions.

The soil files prepared for the Langgewens research farm were used for the winter grain sub-regions of the Swartland region, and that of Tygerhoek farm for the sub-regions of the Southern Cape / Ruêns region.

Cropping systems

Cropping systems are defined as the combination of crop rotation (crop order), as well as the type, timing, rate and method for each operation associated with the crop rotation. Nine cropping systems were prepared for the study based on the combinations between the three crop rotation systems and the three tillage systems considered for the study.

The *crop rotation systems* that were simulated include:

- Wheat monoculture (WWWW);
- Wheat-medics crop rotation (WMWM); and
- Wheat-canola-wheat-lupin (WCWL).

The *tillage systems* that were simulated for each crop rotation system include:

- Conventional till (CT) that involves scarifying the soil to a depth of 305 mm with a disc plough in late February followed by ploughing with a chisel to a depth of 300 mm in March before planting;
- Conservation agriculture:
  - Minimum till (MT) that involves scarifying the soil to a depth of 300 mm with a disc plough in late February; and
  - No till (NT), also referred to as zero till, that had no disturbance of the soil prior to planting.

All crops were planted with a gravity tine planter in late May.

The default cropping systems included in WinEPIC for dryland winter wheat, dryland clover and dryland winter canola for conventional till, reduced (minimum) till and no till were selected for the wheat monoculture-, wheat-medics- and wheat-canola-wheat-lupin crop rotation systems. The default file for clover was used for lupin as WinEPIC does not include a crop default file for lupin.

The type and date of cropping and tillage activities (planting, cultivation, fertilisation, harvesting) of the default cropping system files were edited by changing, deleting and or adding activities based on the information provided by GrainSA on the type and date of activities of the crop rotation- and tillage systems for the winter grain sub-regions.

Four-year crop rotation systems (WWWW, WMWM and WCWL) were prepared from the default dryland winter wheat, clover and canola cropping systems for each of the tillage systems (CT, MT and NT). Consequently, 9 four-year cropping systems were prepared from the combination of the three crop rotation- and three tillage systems. The four-year cropping systems were repeated to create cropping systems of 40 years.

Crop characteristics

The default files included in WinEPIC for the crop characteristics on dryland winter wheat, clover and canola were used for the study due to the comprehensive list of data requirements for a crop data file. The crop data file include over 50 crop parameters relating to crop growth, root and leaf properties, biomass production, plant nutrient uptake and harvest index. Verification and/or calibration of crop characteristics and plant growth were beyond the scope of this study. The focus and aim of the study was to evaluate the application of numerical models to predict C-sequestration. Further refinement in the C-sequestration modelling should focus on verification and refining of crop parameter values, especially those parameters sensitive to crop growth and biomass production.

4.2.2 Carbon stocks and sequestration Inventory using IPCC tool

This section discusses the details of the raw data collected, the data collection process and the modelling of the activities and inputs at the experimental farms relevant to C-sequestration.

Raw data and data sources

Data required for the carbon stocks, CO_2 emissions and calculations was sourced from:

- IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC GPG LULUCF) for Tier 1 values
- Master's thesis by G.D. Cooper (Cooper, 2016)
- Master's thesis by J.D. Smith (Smith, 2014);
- National Terrestrial Carbon Sinks Assessment (Department of Environmental Affairs, 2015b; von Maltitz, 2016)
- Data from trials at experimental farms provided by Dr. Johann Strauss and Dr. Johan Labuschagne at the Western Cape Department of Agriculture (WCDoA).

The carbon sequestration methodology with data inputs and outputs is shown in Figure 4.

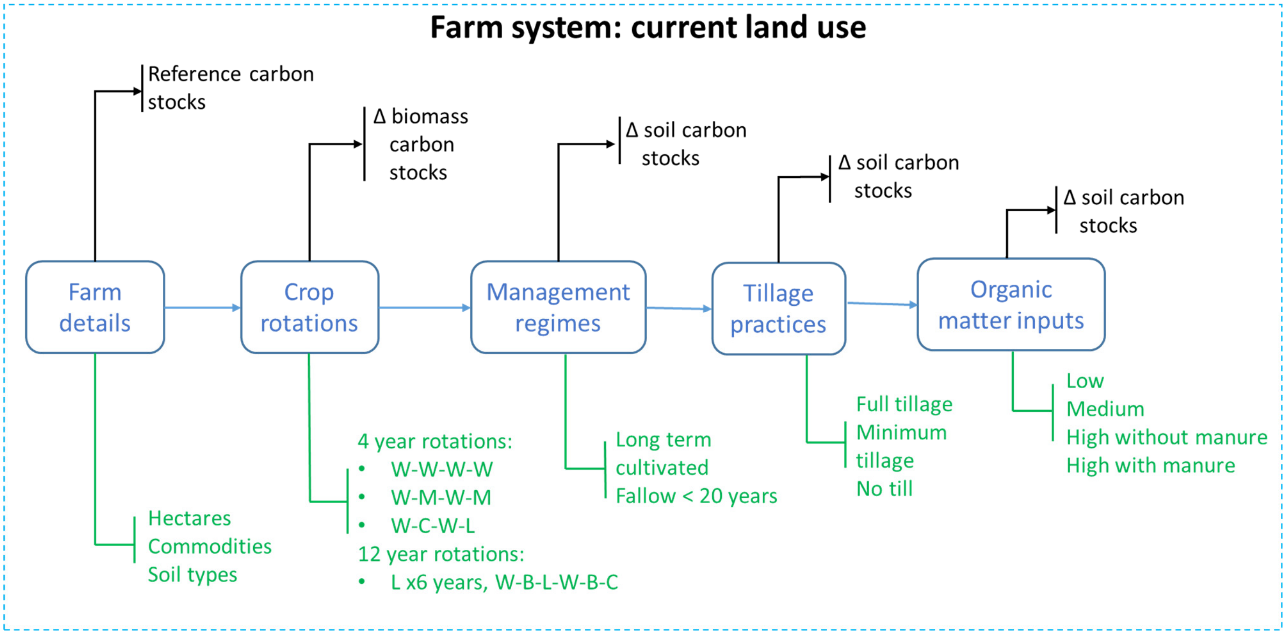

Figure 4: Data collection process map for carbon sequestration methodology.

Note: W-W-W-W: Wheat-Wheat-Wheat-Wheat
W-M-W-M: Wheat-Medics-Wheat-Medics
W-C-W-L: Wheat-Canola-Wheat-Lupines
L x 6: Lucerne over 6 years
W-B-L-W-B-C: Wheat-Barley-Lupines-Wheat-Barley-Canola

Input data inventory

In order to calculate the carbon sequestration potential per farming regime, crop rotation and region, data was gathered from literature, soil carbon databases and industry experts. The following data was required for the calculations:

- Soil forms at various farms.
- Reference carbon stocks of these soils under native vegetation; renosterbos and fynbos.
- Crop rotations of different commodities;
- Farming regimes (Conventional, Current CA, Future CA). Currently there are 4 regimes (personal communication Johan Labuschagne).
  - Zero (no) till - almost 0% soil disturbance (using a disc seeder)
  - No till: < 20% soil disturbance (using a no-till tine seeder)
  - Minimum till: more disturbance than no-till and less than conventional till
  - Conventional till: max disturbance, soil ploughed and inverted – no residues on surface after ploughing

To align with Phase 1 definitions the farming regimes are defined as follows:

- Conventional: Conventional till with up to 80% crop residues removed.
- Current CA: No till with up to 60% crop residues removed.
- Future CA: Zero (no) till with a maximum of 30% of crop residues removed.
- Organic matter inputs into soil (e.g. crop residues, green manures). See the definitions of the organic matter inputs in section 0 and the allocation per crop rotation and farming regime in Appendix 1.

Tillage practices & crop rotations

The inventory for the experimental farms Langgewens and Tygerhoek, had the following crop rotations and farming regimes as shown in

Table 5.

Table 5: Commodities per farming regime per region.

Region	Sub-region	Tillage regime	Crop rotations
Swartland	Middle Swartland	Conventional	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
		Current CA - No till	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
		Future CA - Zero till	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
Southern Cape (Ruens)	Western Ruens	Conventional	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
		Current CA - No till	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
		Future CA - Zero till	Wheat-Wheat-Wheat-Wheat
			Wheat-Medics-Wheat-Medics
			Wheat-Canola-Wheat-Lupin
		Future CA - Zero till	Lucerne-Lucerne-Lucerne-Lucerne-Lucerne-Lucerne-Wheat-Barley-Lupin-Wheat-Barley-Canola

Biomass

The annual mean biomass and yield of each crop within the cropping systems at the two sites over a 10 year period was provided by Dr Johann Strauss and Dr Johan Labuschagne at the Western Cape Department of Agriculture (WCDoA). Biomass is determined just before harvesting by sampling the above ground plant material (including the grain). At the Langgewens site no biomass is removed apart from the grain and no grazing is allowed so all crop residues after harvesting remained on the plots (personal communication, Dr Johan Labuschagne). The biomass and yield (grains) values were based on the specific conditions at this site. However, in order for the results to be more representative of the Middle Swartland farming practices, the organic matter inputs provided for the site were adjusted for the W-M-W-M system and approximate crop residue removal rates from Phase 1 of the project were used:

- Conventional tillage: 80%
- Minimum tillage: 70%
- No till: 30%

The same procedure was followed for the Overberg site (Tygerhoek), where no crop residues are removed and no grazing or manure inputs take place. Organic matter inputs and crop residue removal rates were adjusted to be more representative for the region. The crop residues removed per regime according to the carbon footprint datasets in Phase 1 were as follows:

- Conventional tillage: 70%
- Minimum tillage: 60%
- No till: 30%

For the 12 year crop rotation, the lucerne above ground biomass was calculated from data collected at the Tygerhoek site in 2005 and 2006 after harvest.

Equation 2 is used to determine the carbon content of the above and below ground biomass for each crop. All grain crops are classified as winter cereals, medics as legumes and lucerne as a fodder crop. The parameters for each crop type in Table 3 are accounted for in the calculation using Equation 2.

Soil types

The Langgewens experimental site in the Swartland region has dominant soil forms Swartland, Glenrosa and Klapmuts. The soil form under the natural vegetation renosterbos (*Elytropappus rhinocerotis*) is Swartland. Carbon stocks under renosterbos vegetation at Langgewens measured at depths of 40 cm was 27 tC ha^{-1} (Cooper, 2016) for bulk soil (coarse and fine fragments). The Tygerhoek site in the Southern Cape Ruens region had soil forms Glenrosa and Oakleaf. The dominant soil form for the cultivated land with crop rotations listed in

Table 5 is Glenrosa and under natural vegetation Oakleaf. Carbon stocks measured at this site under native vegetation for bulk soil (coarse and fine fragments) was 49 tC ha^{-1} at a depth of 0-30 cm (Smith, 2014). According to the National Terrestrial Carbon sinks assessment by the Department of Environmental Affairs (2015), the soil carbon content at 1m depth under land cover class fynbos nationally is 56.6 Mg ha^{-1}. The lower carbon stock result at the Langgewens site could be due to the warmer and dryer climate in the Swartland region.

Organic matter inputs

The organic matter inputs varied per site and commodity per crop rotation. The inputs pertaining to each crop is in Appendix 1 from Labuschagne (2018a,b) and personal communication with Johann Strauss. The organic matter inputs are described as follows in the IPCC GPG for LULUC&F (IPCC, 2003):

- **Low:** Low residue return due to removal of residues (via collection or burning), frequent bare-fallowing or production of crops yielding low residues (e.g. vegetables, tobacco, cotton)
- **Medium:** Representative for annual cropping with cereals where all crop residues are returned to the field. If residues are removed then supplemental organic matter (e.g. manure) is added.
- **High without manure:** Represents significantly greater crop residue inputs due to production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, frequent use of perennial grasses in annual crop rotations, but without manure applied.
- **Higher with manure:** Represents high input of crop residues together with regular addition of animal manure (see row above).

To account for organic inputs for past land use practices (before current), the low organic input is used (personal communication with Johann Strauss).

4.3 Objective 3: To model soil carbon sequestration for annual cropping systems in the Western Cape

4.3.1 Numerical soil carbon sequestration modelling

Research sites

Research sites at Langgewens and Tygerhoek Research Farms were selected to predict soil carbon sequestration (C-sequestration). The research sites were selected for the following reasons:

- Detail data on soil properties, crop rotation, and tillage systems were collected under a variety of land management practices;
- Data on the impact of conventional- and conservation agriculture tillage systems on the long-term dynamics of soil organic carbon/matter was collected;
- Advantage of detailed data to assess the effect and implications of non-readily available data on modelling results; and
- Research sites represent the range in climatic and soils, and specific land management practices, such as rotation systems, cultivation and fertilisation of grain farming systems in the Western Cape Province to some degree.

The WinEPIC numerical model was applied to the research sites to *determine the application, potential shortcomings and ability to simulate the long-term C-sequestration potential for the grain farming systems.* WinEPIC was applied at the field-scale representing a farmers' field. Nine cropping systems were predicted based on the combination of the three crop rotation- and three tillage systems.

The *crop rotation systems* that were simulated include:

- Wheat monoculture (WWWW);
- Wheat-medics crop rotation (WMWM); and
- Wheat-canola-wheat-lupin crop rotation (WCWL).

The *tillage systems* that were simulated for each crop rotation system include:

- Conventional till (CT);
- Minimum till (MT); and
- No till (NT).

The cropping systems that were predicted are discussed in more detail in Section 4.2.1.

The impact of the crop rotation, conventional- and agricultural tillage systems on soil organic carbon over 40 years are shown in Figure 5 to Figure 7. The effect on soil organic nitrogen is shown in Figure 8.

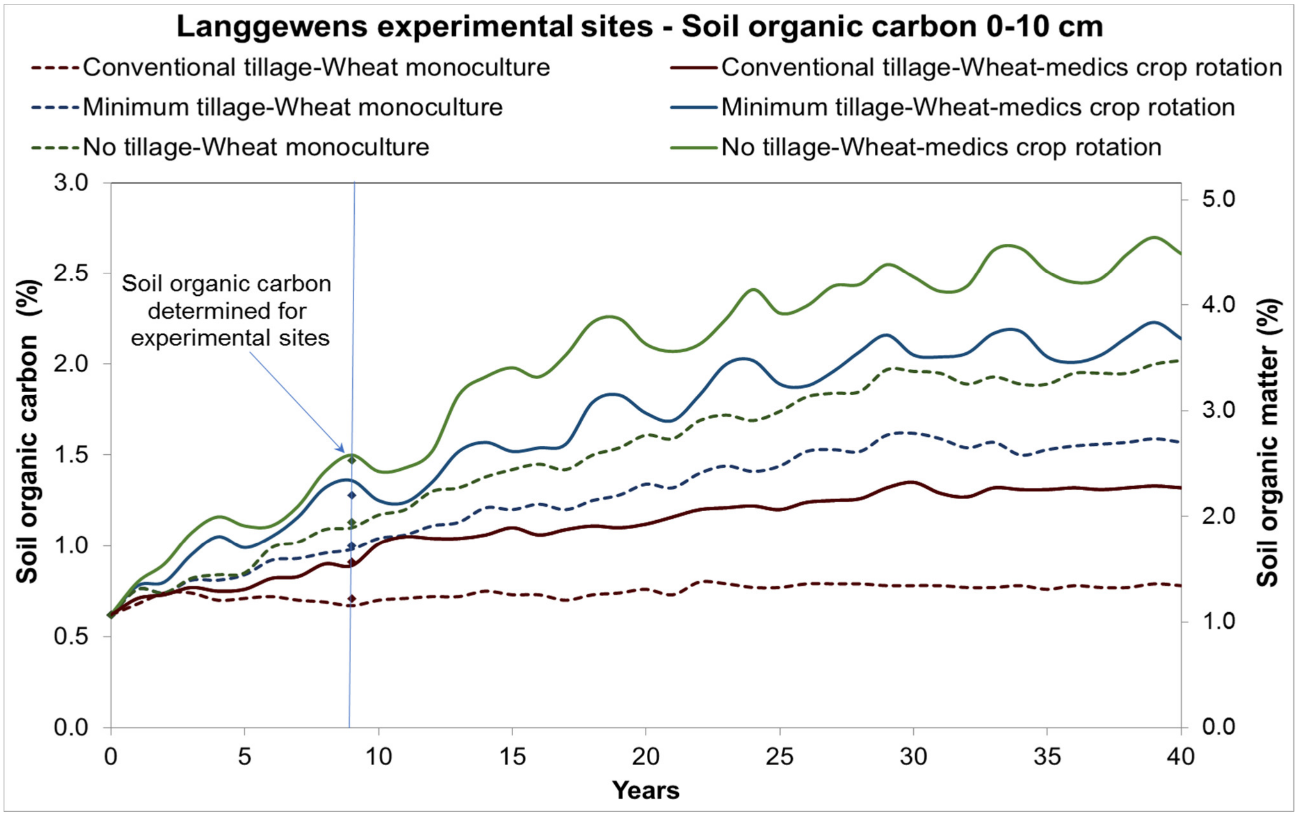

Figure 5: Predicted impact of tillage and crop rotation on soil carbon at 0-10 cm soil depth.

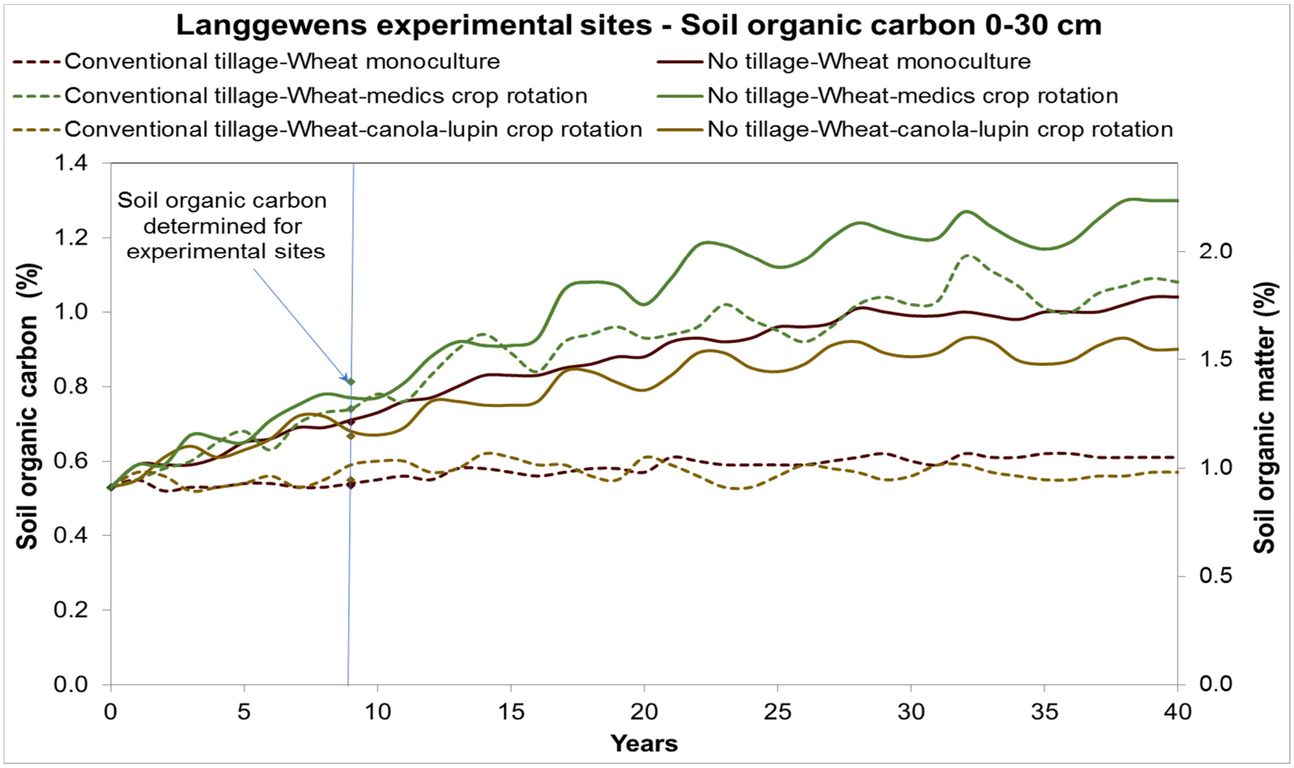

Figure 6: Predicted impact of tillage and crop rotation on soil carbon at 0-30 cm soil depth for the Langgewens experimental sites.

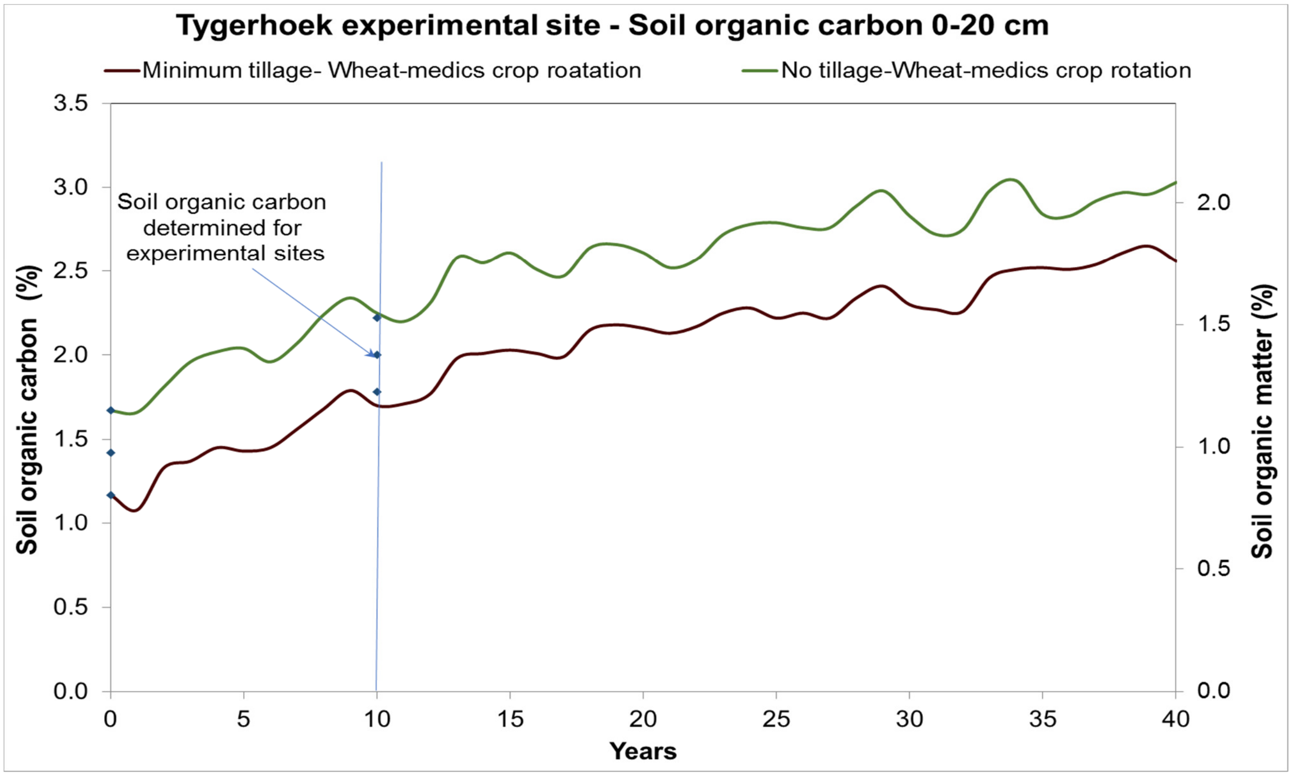

Figure 7: Predicted impact of tillage and crop rotation on soil carbon at 0-30 cm soil depth for the Tygerhoek experimental farm.

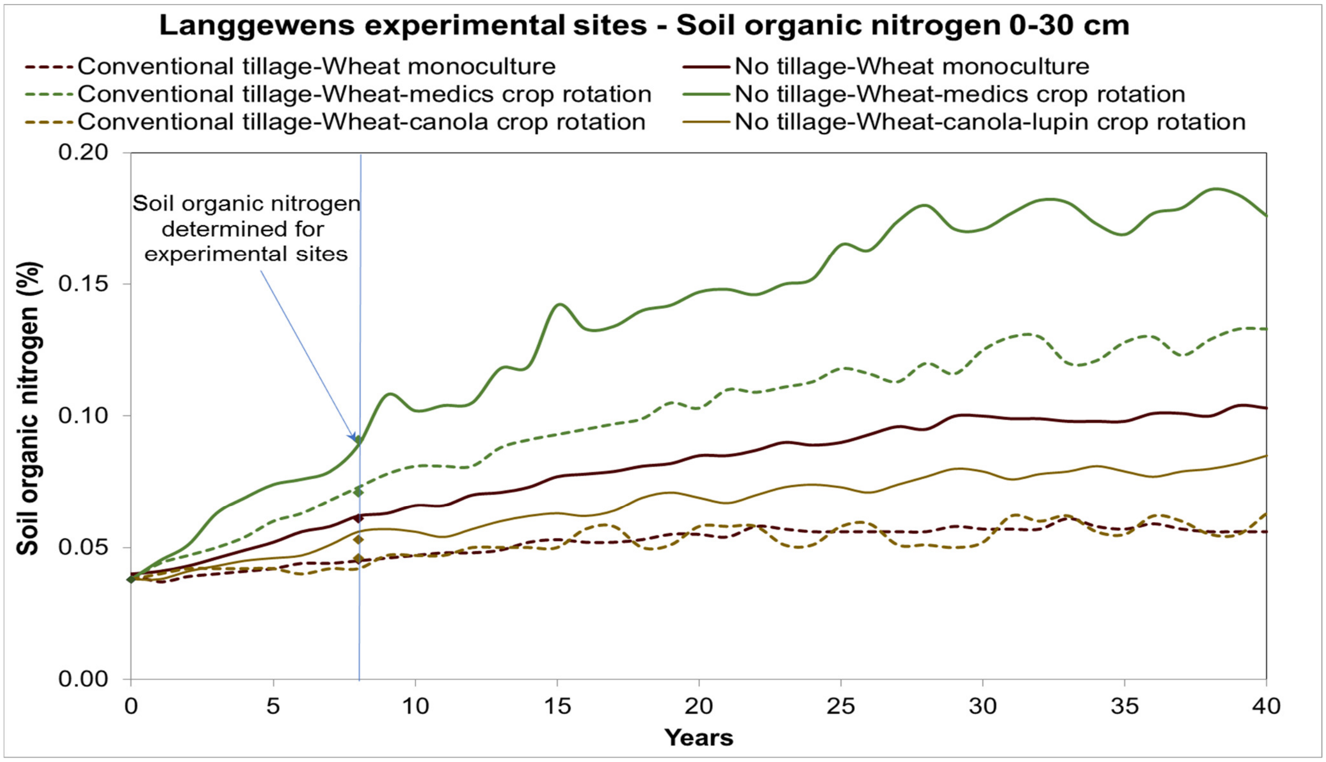

Figure 8: Predicted impact of tillage and crop rotation on soil organic nitrogen at 0-30 cm soil depth for the Langgewens experimental sites.

The following inferences were made from the predicted C-sequestration:

- *Model verification* (Langgewens Experimental Farm):
  - Low soil organic carbon contents were used as model input for the initial carbon contents based on the assumption that conventional tillage system was used for some time before commencing with the field trials. Consequently, decline in SOC contents with cultivation of virgin land did occur before commencement of the field trials;
  - Predicted soil organic carbon (SOC) contents at 8 years are comparable to the SOC contents reported by Cooper (2016) for the 8-year field trials.
- *Long-term trends*:
  - Highest increase in SOC content is in the upper 10 cm of the soils. SOC increases less noteworthy with soil depth,
  - Highest temporal variability (fluctuations) in SOC content occurs in the upper 10 cm of the soils. Temporal variability in SOC build-up decreases with increasing soil depth;
- Effect of *tillage systems*:
  - Predicted increases in SOC contents over 40 years occurs in the following order: No till > reduced till > conventional till,
  - An increase in SOC content was predicted for the no till and reduced till systems until a new equilibrium is reached with higher SOC contents in the long-term,
  - SOC content of conventional tillage stay the same over the long-term. However, there is a slow increase in SOC contents with the inclusion of a nitrogen fixing crop in the cropping system until a new equilibrium is reached,
  - Similar trends in soil organic nitrogen contents were predicted than SOC;
- Effect of *crop rotation*:
  - Higher SOC contents were predicted for crop rotation systems that includes nitrogen fixing crops compared to a wheat monoculture system,
  - The increase in SOC was predicted for clover, which can be ascribed to the higher root weight in the soil,
  - Similar trends in soil organic nitrogen contents were predicted than SOC.

Winter Grain regions

WinEPIC was applied to the Winter Grain regions to *assess the capability to predict C-sequestration potential at field-scale (farmers' fields to farms) for the regions*. The C-sequestration modelling did *not involve spatially distributed C-sequestration modelling for the regions, which would require a GIS systems approach*. C-sequestration modelling in a GIS environment is beyond the scope of this project.

C-sequestration at the field-scale level was predicted for the regions based on the use of a "driver" meteorological station in a region. The preparation of the climate data files from the web-based weather station network of NOAA National Climatic Data Centre is discussed in Section 4.2.1. The "driver" stations used for the various regions are listed in Table 6.

Table 6: Climate stations and soils data used for Winter Grain regions.

Winter Grain Region		Climate station used	Soils data files used
Swartland	Sandveld area	Langebaan	Langgewens Experimental Farm
	Middle Sandveld area	Langgewens	
	Red Karoo area	Vredendal	
	High rainfall area	Malmesbury	
Rûens	Western Rûens	Robertson	Tygerhoek Experimental Farm
	Southern Rûens	Overberg	
	Eastern Rûens	Riversdal	

The soils-, cropping systems- and crop data files prepared for the Langgewens research farm were used as model files for the Swartland winter grain region to predict C-sequestration as the spatial distribution of soils data was not readily available for the sub-regions. The soils-, cropping- and crop data files prepared for the Tygerhoek research farm were used for the Rûens (Southern Cape) sub-regions. The soil data files used for the sub-regions are listed in Table 6.

4.3.2 IPCC carbon sequestration tool modelling results

The results per sub-region are reported in tC stocks changes and CO_2 sequestered per hectare per year over the default 20 year period for each crop rotation and farming regime combination.

Middle Swartland (Langgewens)

The C stock changes per hectare over 20 years for Langgewens showed on average, for all crop systems, a 166% increase from the conventional farming regime to the Future CA regime. The W-M-W-M crop rotation with the Future CA regime had the highest C stock over a year at 1.18 tC/ha. Compared to the other crop rotations with Future CA regimes, this crop system had the highest C stock change over a year due to the high biomass production of the wheat crop and the high organic inputs allocated to medics from livestock grazing. Figure 9 shows the tonnes of C accumulated per year for each cropping system and farming regime.

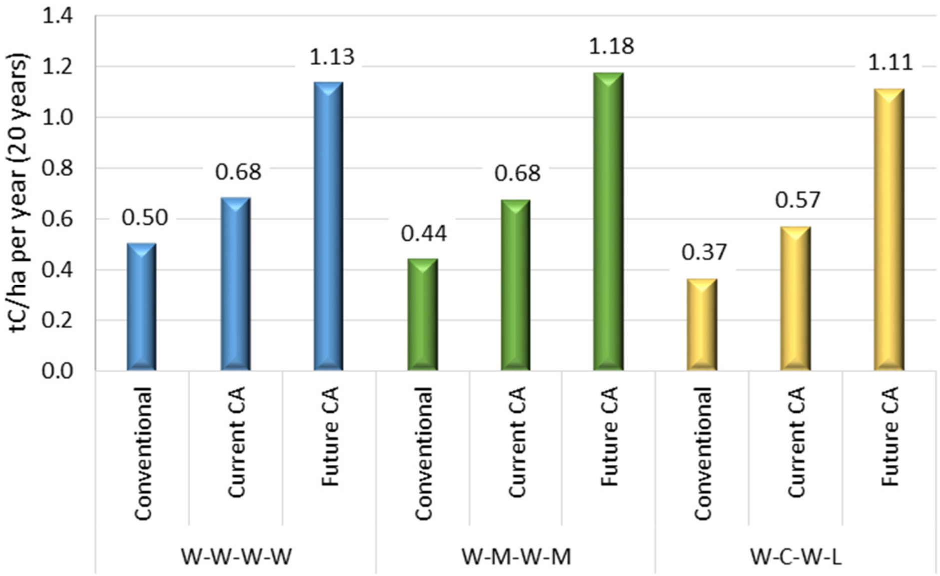

Figure 9: Carbon stock change per year for crop rotation and farming regime combinations at Langgewens.

The tC accumulated is converted to tCO_2 by multiplying by the factor 44/12. The CO_2 sequestered is a carbon sink which is reported as a negative value in Figure 10.

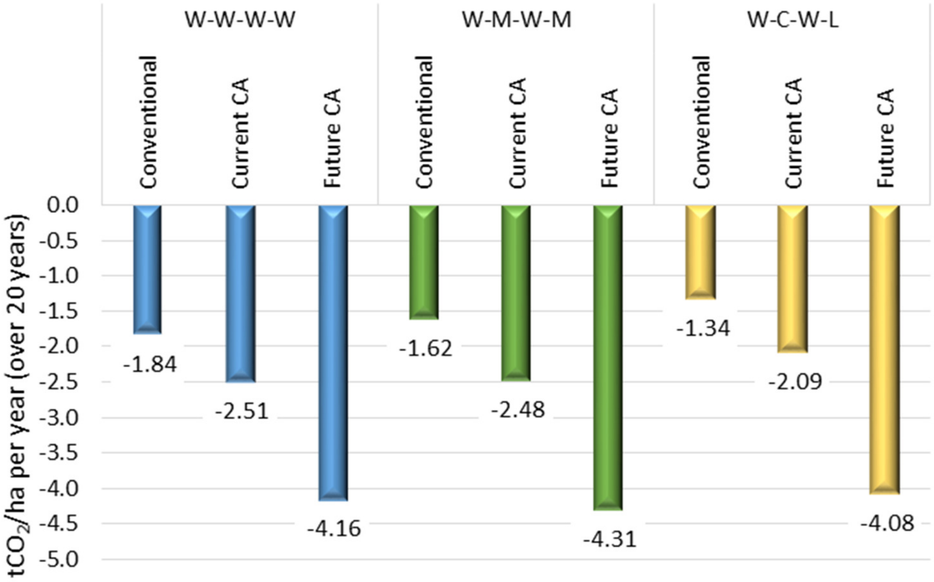

Figure 10: Tonnes CO2 sequestered per ha per year for crop rotation and farming regimes combinations at Langgewens.

Western Ruens (Tygerhoek)

The C stock changes per hectare over 20 years for Tygerhoek showed on average, for all crop systems, a 132% increase from the conventional farming regime to the Future CA regime. The W-W-W-W crop rotation under the Future CA regime had the highest C stock over a year at 1.47 tC/ha. Compared to the other crop rotations with Future CA regimes, this crop system had the highest C stock change over a year due to the high biomass production of the crop. Figure 11 shows the tonnes of C accumulated per year for each cropping system and farming regime. The 12 year Future CA rotation with lucerne had the lowest carbon stock change out of all the Future CA regimes due to all the lucerne biomass being harvested (through grazing or baling) with none left on the field according to the Harvest Index parameter in

***Table 3*3. This brought the average C stock for the 12 year crop rotation down even with the W-B-L-W-B-C rotation yielding the highest C stock at 1.60 tC/ha per year.

Figure 11: Carbon stock change per year for crop rotation and farming regime combinations at Tygerhoek.

The carbon sink values in terms of tCO_2 sequestered is in Figure 12.

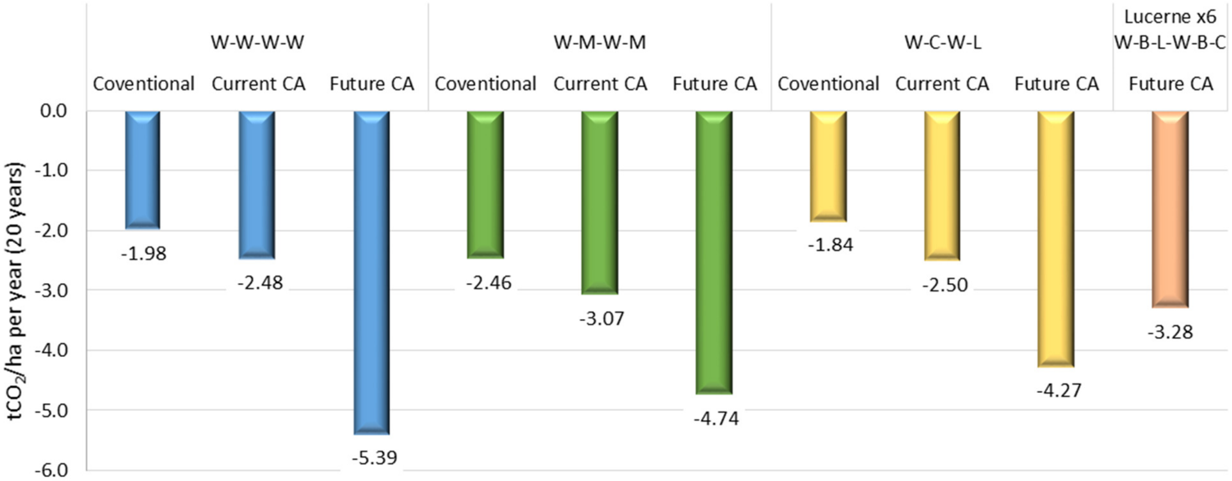

Figure 12: Tonnes CO2 sequestered per ha per year for crop rotation and farming regimes combinations at Tygerhoek.

Extrapolation to winter grain region

The average carbon stock results per farming regime for the sub-regions Western Ruens and Middle Swartland are presented in Figure 13 and these results duplicate the rising annual C stock accumulation from conventional to Future CA regimes.

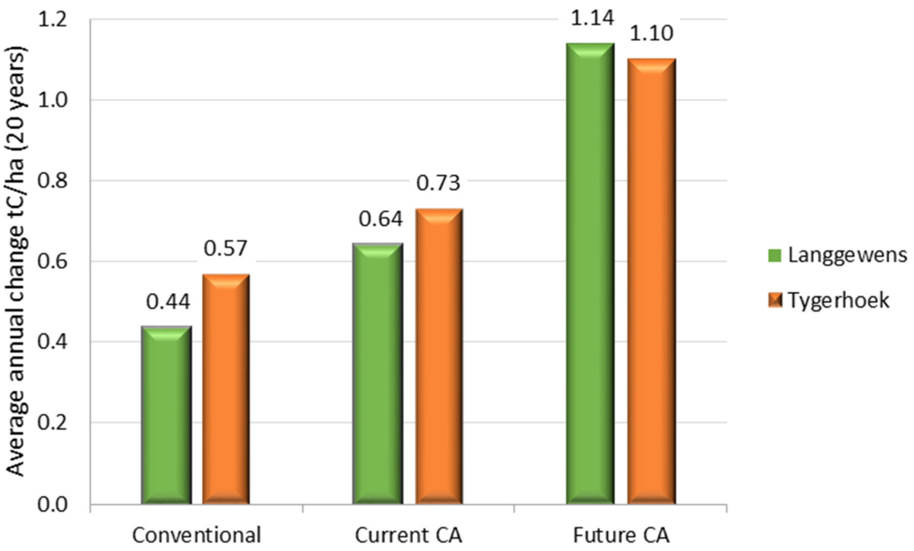

Figure 13: Average annual C stock change for each farming regime per site.

Current practices in the winter grain region include a combination of the conventional and Current CA regimes. In Phase 1 the total yield in tonnes was allocated as 10% to conventional and 90% to Current CA. This allocation was used (hectares per farming regime was unavailable) to determine the overall average carbon stock change per region under the **current scenario**. The same method was applied for the **future scenario** where it is predicted that Current CA practices will cover 20% and Future CA 80% of total hectares. The results per region between the current and future scenarios are presented in Figure 14.

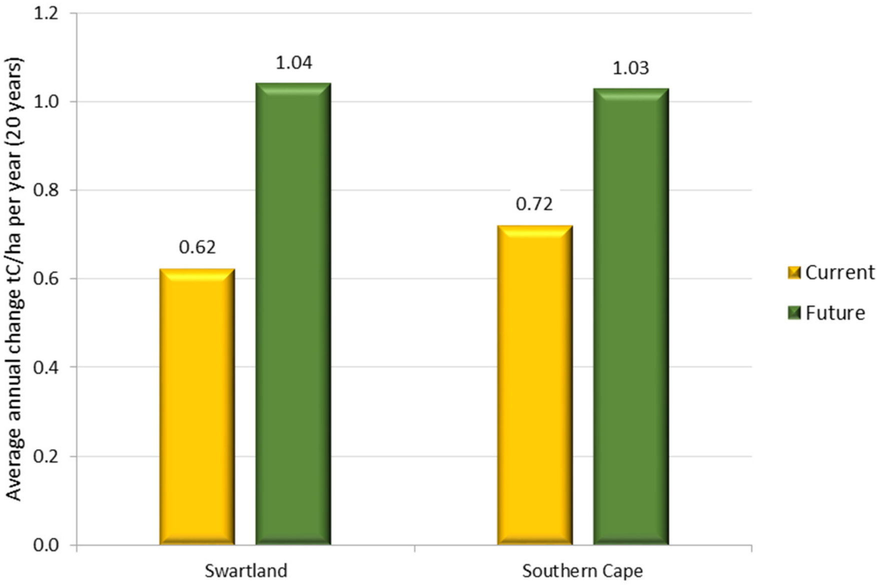

Figure 14: Annual C stock change for current and future scenario in winter grain regions.

The extrapolated results indicate a 67% and 44% increase in C stock accumulation per hectare from the conventional to the future scenario in the Swartland and Southern Cape regions respectively. The corresponding potential CO_2 sequestered per ha per year for the current and future scenarios is presented in Table *7*.

Table 7: CO2 sequestered potential of current and future scenario in tCO2e/ha/yr.

Regions	**Current scenario [tCO_2]**	**Future scenario [tCO_2]**
Swartland	-2.27	-3.81
Southern Cape	-2.64	-3.78

4.4 Objective 4: To analyse, report and integrate different modelling results

This section discusses the process followed to integrate the carbon sequestration results and the carbon emission results from Phase 1 as well as the final nett C-footprint for the winter grain region.

4.4.1 Comparison between C sequestration numerical model and IPCC tool

Carbon stocks gains were calculated from the C-sequestration predicted with WinEPIC. Comparison of the carbon stocks calculated from the EPIC-predicted C-sequestration and determined by the IPCC tool is summarised in Table 8.

The following inferences were made from the comparison in calculated carbon stock between WinEPIC numerical model and the IPCC tool:

- Carbon stocks calculated from WinEPIC predicted C-sequestration are comparable to the stock calculated with the IPCC tool for*:*
  - Swartland region: No tillage,
  - Rûens: Conventional and minimum tillage;
- Carbon stocks calculated from WinEPIC predicted C-sequestration is higher than the stock calculated with the IPCC tool for conventional- and minimum tillage for the Swartland region;
- Carbon stocks calculated from WinEPIC predicted C-sequestration is lower than the stock calculated with the IPCC tool for no tillage for the Rûens region;
- *Calculated carbon stocks are in general comparable between the two methods, considering the widely different methodologies used*.

Table 8: Carbon stocks calculated from numerical model and IPCC tool.

Region	**Tillage system**	**Crop rotation**	**Carbon stock[1] tC/ha/yr (+)**	
			IPCC tool	**WinEPIC model**
Swartland	Conventional	Wheat-Wheat-Wheat-Wheat	0.50	0.64
		Wheat-Medics-Wheat-Medics[2]	0.44	0.73
		Wheat-Canola-Wheat-Lupin	0.37	0.61
	Minimum till	Wheat-Wheat-Wheat-Wheat	0.68	0.81
		Wheat-Medics-Wheat-Medics[2]	0.68	0.94
		Wheat-Canola-Wheat-Lupin	0.57	0.71
	No till	Wheat-Wheat-Wheat-Wheat	1.13	0.98
		Wheat-Medics-Wheat-Medics[2]	1.18	1.07
		Wheat-Canola-Wheat-Lupin	1.11	0.96
Rûens	Conventional	Wheat-Wheat-Wheat-Wheat	0.54	0.46
		Wheat-Medics-Wheat-Medics[2]	0.67	0.77
		Wheat-Canola-Wheat-Lupin	0.50	0.45
	Minimum till	Wheat-Wheat-Wheat-Wheat	0.68	0.52
		Wheat-Medics-Wheat-Medics[2]	0.84	0.88
		Wheat-Canola-Wheat-Lupin	0.68	0.85
	No till	Wheat-Wheat-Wheat-Wheat	1.47	0.97
		Wheat-Medics-Wheat-Medics[2]	1.29	1.18
		Wheat-Canola-Wheat-Lupin		

Notes: [1] *Carbon stock calculated at 20 years and at 30 cm soil depth based on the IPCC method.*

[2] *C-sequestration modelling with WinEpic based on vegetation default file for clover.*

4.4.2 Conversion process using the IPCC tool data

The Phase 1 carbon emissions per ton grain for the Middle Swartland and Western Ruens were converted from kg CO_2e/ton grain to tonnes CO_2e/hectare using the yields per commodity per hectare in   The conversion was only done for the Middle Swartland and Western Ruens as the carbon sequestration results per hectare were only available for these two sub-regions.

Table 9: Conversion of carbon emissions from kg CO_2e/ton grain to tCO_2e/ha

Sub region	Grain	Yield / ha			tCO_2e/ton grain			tCO_2e/ha		
		CT	Current CA	Future CA	CT	Current CA	Future CA	CT	Current CA	Future CA
Middle Swartland	Wheat	3.0	3.0	3.0	0.56	0.56	0.26	1.69	1.67	0.79
	Barley			3.1			0.18			0.54
	Canola			1.7			0.35			0.57
Western Ruens	Wheat	3.0	3.0	3.3	0.63	0.63	0.35	1.90	1.88	1.17
	Barley		3.0	3.3		0.59	0.33			1.10
	Canola		1.6	1.8		1.07	0.56			0.98

It is clear from the results in Table 9 that the Future CA system is less carbon intensive than the other two systems as discussed in the findings on Phase 1. The tCO_2e/ha for the Western Ruens for all systems is also higher than the Middle Swartland due to the higher yields in the Western Ruens. The weighted average in tCO_2e/ha was calculated for the Middle Swartland Future CA system and the Current CA and Future CA systems in the Western Ruens based on the tonnages per hectare.

The results for Phase 2 per crop rotation and farming system is in Table 10

Table 10: Carbon sequestration and carbon dioxide sequestration results per crop rotation and farming system [per hectare]

Sub-region	**Crop rotation**	**tC/ha**			**tCO_2/ha**		
		CT	**Current CA**	**Future CA**	**CT**	**Current CA**	**Future CA**
Middle Swartland	W-W-W-W	0.50	0.68	1.13	-1.84	-2.51	-4.16
	W-M-W-M	0.44	0.68	1.18	-1.62	-2.48	-4.31
	W-C-W-L	0.37	0.57	1.11	-1.34	-2.09	-4.08
	Average	***0.44***	***0.64***	***1.14***	***-1.60***	***-2.36***	***-4.18***
Western Ruens	W-W-W-W	0.54	0.68	1.47	-1.98	-2.48	-5.39
	W-M-W-M	0.67	0.84	1.29	-2.46	-3.07	-4.74
	W-C-W-L	0.50	0.68	1.17	-1.84	-2.50	-4.27
	Lucerne x 6			0.19			-0.70
	W-B-L-W-B-C			1.60			-5.87
	Average	***0.57***	***0.73***	***1.14***	***-2.09***	***-2.68***	***-4.19***

The average values per farming system per sub-region is across the different crop rotations. All results are per hectare and an average of the results across crop rotations was calculated.

4.4.3 Carbon sequestration and Nett C-footprint

Nett C-footprint results

To obtain the Nett carbon footprint (Nett C-footprint) result for the region the carbon sequestration results are offset against the carbon emission results as presented in Equation 1:

$$Nett\ C - footprint = Total\ Carbon\ emissions + Total\ Carbon\ sequestered$$

Equation 8: Formula to determine nett carbon footprint (C-footprint)

The Phase 1 carbon emissions per ton grain for the Middle Swartland and Western Ruens were converted from kg CO2e/ton grain to tonnes CO2e/hectare using the yields per commodity per hectare in Table 11 The conversion was only done for the Middle Swartland and Western Ruens as the carbon sequestration results per hectare were only available for these two sub-regions.

Table 11: Conversion of carbon emissions from kg CO2e/ton grain to tCO2e/ha

Sub region	**Grain**	**Yield / ha**			**tCO_2e/ton grain**			**tCO_2e/ha**		
		CT	**Current CA**	**Future CA**	**CT**	**Current CA**	**Future CA**	**CT**	**Current CA**	**Future CA**
Middle Swartland	Wheat	3.0	3.0	3.0	0.56	0.56	0.26	1.69	1.67	0.79
	Barley			3.1			0.18			0.54
	Canola			1.7			0.35			0.57
Western Ruens	Wheat	3.0	3.0	3.3	0.63	0.63	0.35	1.90	1.88	1.17
	Barley		3.0	3.3		0.59	0.33			1.10
	Canola		1.6	1.8		1.07	0.56			0.98

The weighted average in tCO_2e/ha was calculated for the Middle Swartland Future CA system and the Current CA and Future CA systems in the Western Ruens based on the tonnages per hectare.

Table 12 shows the carbon emissions and carbon sequestered per hectare for the two sub-regions and scenarios.

Table 12: Carbon emissions and sequestration per hectare for current and predicted future farming system scenarios.

Sub-regions	**Current scenario (CT & Current CA)**		**Future scenario (Current CA & Future CA)**	
	C-emissions [tCO_2e/ha]	**C-seq [tCO_2e/ha]**	**C-emissions [tCO_2e/ha]**	**C-seq [tCO_2e/ha]**
Middle Swartland	1.67	-2.28	0.85	-3.82
Western Ruens	1.81	-2.62	1.24	-3.89

Using the formula in Equation 8, the nett C-footprint extrapolated per region and farming system scenario is in Figure 15. These results per hectare are extrapolated (weighted average based on hectares) to the entire winter grain region for the current and future scenarios and are presented in Figure 16.

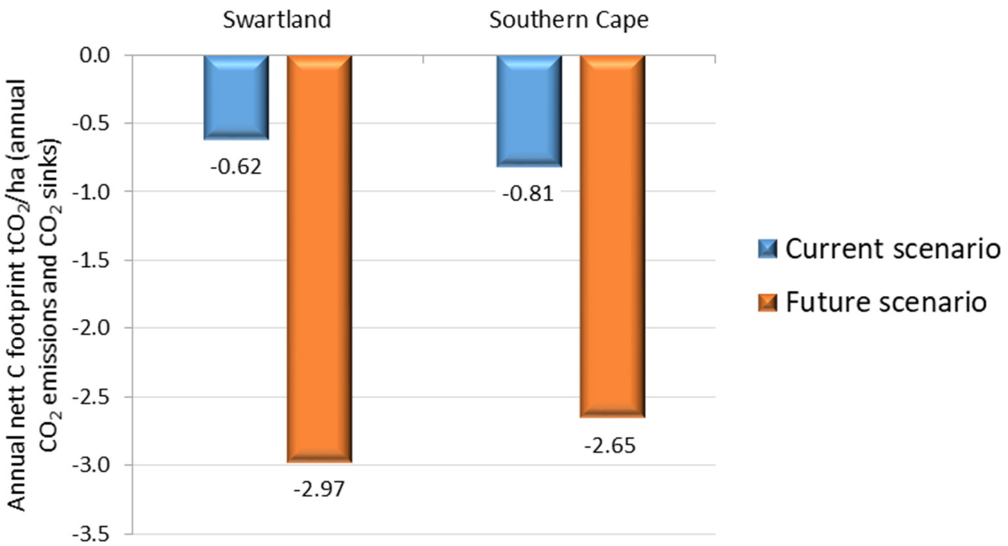

Figure 15: Nett C-footprint per region

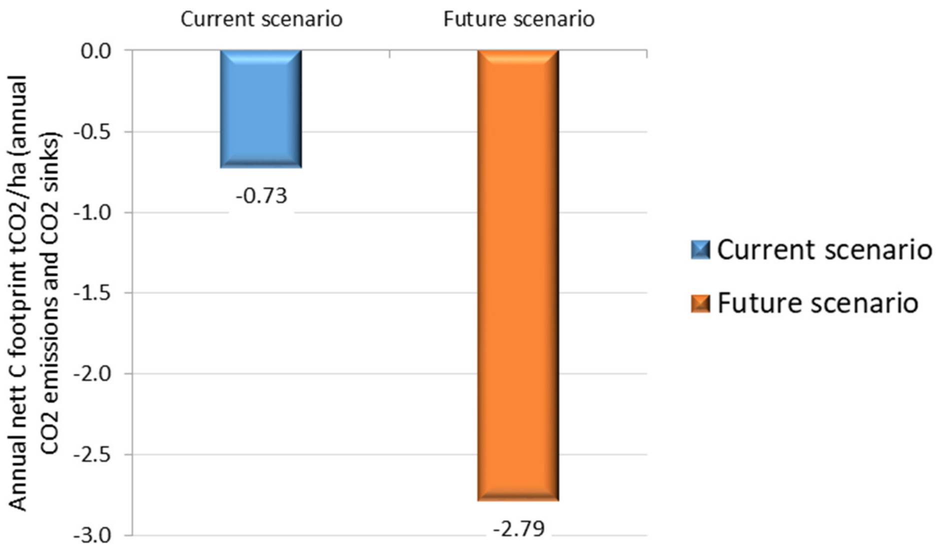

Figure 16: Nett C-footprint for the South African winter grain region

Both scenarios result in a negative nett C-footprint which indicates that both the current and future scenarios sequester carbon. There is however a significant difference in the magnitude of carbon sequestration potential between the two scenarios with a 382% increase in sequestration capacity in the Swartland and a 227% increase in the Southern Cape with the transition from the current to the future scenarios.

At the regional level (all regions in the Western Cape) the differences in carbon sequestration potential indicates a potential 282% increase in carbon sequestration capacity with the transition from the current farming system scenario to an ideal future farming system scenario.

5 Conclusions

The following conclusions were made from the numerical carbon sequestration modelling:

- The WinEPIC process-based numerical C-sequestration model was selected for application to the project. WinEPIC is downloadable freeware, well documented and could simulate the cultivation- and cropping systems for the winter grain regions from available data.
- Predicted soil organic carbon (SOC) contents are within the range of the contents determined from long-term field trials at the experimental sites.
- Highest increase in SOC content occurred is in the upper 10 cm of the soils.

- Predicted increases in SOC contents over 40 years occur in the following order for cultivation systems: No tillage > reduced tillage >> conventional tillage.
- An increase in SOC content was predicted for the no till and reduced till systems until a new equilibrium is reached with higher SOC contents over the long-term.
- Higher SOC contents were predicted for crop rotation systems that include nitrogen-fixing crops compared to a wheat monoculture system.
- Similar trends in soil organic nitrogen contents were predicted than SOC.
- Calculated carbon stocks are generally comparable to the stocks calculated with the IPCC tool, considering the widely different methodologies used.

The following conclusions were made from the coarse, conceptual-based level carbon sequestration (C-sequestration) and net C-footprint assessments:

- The Future CA regime across all crop rotations yields the highest annual C stock accumulation in the system.
- The Langgewens site achieved the highest annual C stock accumulation with the W-M-W-M cropping system under Future CA at 1.18 tC/ha and CO_2 sequestration of -4.31 tCO_2/ha.
- The Tygerhoek site cropping system W-W-W-W had the highest annual C stock accumulation at 1.47 tC/ha and CO_2 sequestration potential of -5.39 tCO_2/ha.
- For sites Langgewens and Tygerhoek there was an average 166% and 132% increase in C stocks per hectare per year from the conventional to the Future CA farming regimes across all cropping systems.
- Soil type played a role with the initial C stocks under native vegetation which was coupled to the climate at the respective sites (rainfall and temperature), however it was the farming regime and cropping rotation practises that made the greatest contribution to the annual change in C stocks and CO_2 sequestration in the system.
- These results were extrapolated to the winter grain regional level (Swartland and Southern Cape) for the **current** (Conventional and Current CA) and **future** (Current CA and Future CA) scenarios.
- It was found that the Swartland and Southern Cape regions had a 67% and 44% increase in the C stock levels with the transition from the current to the future farming regime scenario.
    - Note: the results from the coarse (high level) methodologies give an indication of potential C stock changes and CO_2 sequestered and not accurate site specific results. In order to obtain site specific Tier 3 results, the WinEPIC process-based numerical C-sequestration model results are more appropriate. However, the results from these Tier 1 & 2 methods still indicate a higher trend in C stock accumulation from conventional to Future CA (zero till) regimes and in addition from the current scenario to the future farming regime scenario in the winter grain regions.

- The net C-footprint results for regions Swartland and Southern Cape and ultimately the entire winter grain region for the current and future scenarios indicate much larger differences than the stand alone results for carbon emissions and carbon sequestration per scenario. This is due to the current scenario having higher emissions (+) and lower sequestration potential (-) than the future scenario which leads to a much larger difference in the net C-footprint result.
- Both scenarios have a negative net C-footprint per hectare at a sub-regional and regional level, which could mean the potential participation of the winter grains industry in carbon offset markets. Various carbon offset mechanisms and standards are available such as Verra ("Verra", n.d.), the Clean Development Mechanism (CDM) ("Clean Development Mechanism", n.d.) and the Gold Standard ("Gold Standard", n.d.).
- It is therefore recommended that the future scenario, which includes the Future CA system, be adopted in the winter grain region as the benefits include higher soil organic carbon (SOC) levels, a decrease in input costs and an increase in overall system resilience to climate change.

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7 Budget Summary (by December 2018)

Project Task Description – C-footprint, Phase 2	**Total Actual YTD 2018**	**Total Budget YTD 2018**	**Available to use by Dec2018**
Data collection: GSA	4 979	10 000	5 021
Data collection: CCC	11 520	11 520	-
Data collection: TerraSim	13 000	13 000	-
Annual Corp System: CCC	27 000	27 000	-
Annual Crop System: TerraSim	60 000	60 000	-
Annual Report: CCC	42 000	42 000	-
Annual Report: TerraSim	17 000	17 000	-
Project close out: CCC	3 000	3 000	-
Project close out workshop: TerraSim	-	3 000	3 000
Travel & Accommodation CCC	7 764	2 700	-5 064
Travel & Accommodation GSA	12 860	20 000	7 140
Data purchase GSA	-	20 000	20 000
Evaluate Model: TerraSim	1 000	1 000	-
Evaluate Model: CCC	46 000	46 000	-
Communication: CCC	12 000	12 000	-
Total	**258 123**	**288 220**	**30 097**
Plus: Management fee (10%)	**25 812**	**28 822**	**3 010**
Grand Total	**283 935**	**317 042**	**33 107**