REPORT

Project Title:

Determining the Carbon Footprint intensity of different maize farming systems within the summer rainfall crop production area in South Africa

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1. PROJECT BACKGROUND

The environmental impact of agricultural supply chains is increasingly being scrutinized by consumers, NGO's and governments. South Africa's commitment to the international community to reduce its carbon footprint has recently focussed on carbon emissions policy and the introduction of a carbon tax.

On the global stage, improved cropland management has been highlighted as a practical and viable carbon emission mitigation option. Conservation Agriculture (CA) is currently promoted by many role players in the agricultural industry, including Grain SA. An in-country, or regional, study is, however, required to assess the carbon sequestration potential of different farming systems when applied to local, South African, climate and soils.

Sequestration of atmospheric carbon into soil organic matter (SOM) through improved cropland management with Conservation Agriculture (CA) can be a practical and viable option to mitigate the effect of carbon emissions on *inter alia* climate change. This study aims to predict the potential of CA to sequester carbon in the summer-rain grain production regions (SG-regions) of South Africa. This modelling exercise has also collected information on crop rotations, tillage- and agronomic practices that play a role in optimising potential carbon sequestration in soils.

Accurate carbon sequestration assessment tools and calculators of the carbon budgets will be important to demonstrate the impacts of different, or improved farming systems. It will be possible to determine the impact of various management options on the net carbon budget and show how this can lead to improved farming efficiency, reduced emissions and alignment with the future carbon tax. The proposed carbon tax legislation also contains mechanisms for selling agricultural carbon credits to other South African organisations to reduce their carbon tax exposure. This project will take the first steps towards understanding the potential of this farm-based carbon credit income stream.

2. PROJECT GOAL AND OBJECTIVES

The long-term goal of this project is to determine the carbon sequestration potential of selected maize-based farming systems across key agro-ecological regions of the summer rainfall crop production area of South Africa.

The study objective is to predict the effect of CA with reduced tillage and an ideal but realistic future CA with no tillage on the C-sequestration potential for the various summer-rain grain production regions. This country study should provide essential information that will eventually facilitate improved farm production systems, reductions in the carbon budget and increased carbon sequestration rates.

The project's short-term objectives of Phase 2 are:
1. To collect or generate C-sequestration model input data;
2. To conduct C-sequestration modelling in the summer rainfall crop production area based on data provided by Grain SA;
3. To analyse and integrate modelling results;
4. To report and communicate C-sequestration assessment results for Phase 2.

3. PROJECT APPROACH

The project described and quantified maize-based farming systems in the summer grain production regions for the assessment of carbon stocks (balance) and potential carbon sequestration. The project scope includes three farming systems across six regions that fall in the summer rainfall climate.

The three farming systems are:

- Conventional agriculture (CT); with full tillage
- Current Conservation agriculture (CCA); with reduced tillage
- Future CA (FCA): with no tillage, an ideal but realistic CA system (based on assumptions).

The seven summer rainfall regions are:

- KwaZulu Natal
- Mpumalanga Highveld
- Eastern Free State
- Northern Free State
- North western Free State
- North West Province
- Smallholder farmers.

Phase 2 forms part of a longer-term project where the carbon footprint methodology and results can be used within the grain industry as an adaptive management tool (Figure 1).

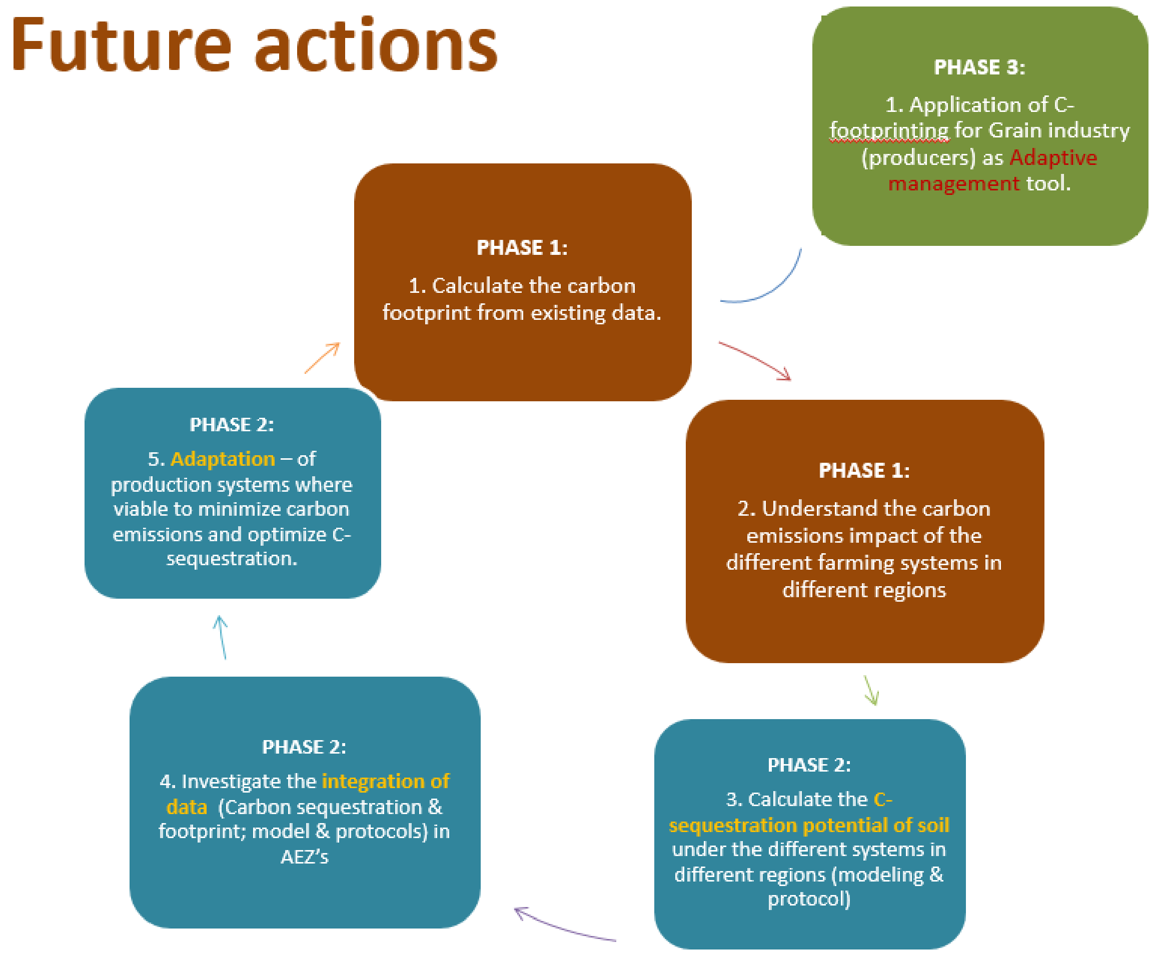

Figure 1: Carbon footprint project phases envisaged by Grain SA.

For each region, the IPCC carbon balance assessment tool was used to obtain an estimate of initial soil carbon conditions. The IPCC tool is a coarse conceptual model that cannot accurately predict the effects of changes in farming systems. Carbon sequestration assessments were carried out by modelling processes that occur in the soil profile using the EPIC model, which is a detailed, process based numerical model.

The results of these assessments were collated and were used to identify Carbon footprint trends associated with variations in farming systems, climate and soils. The long-term goal of the project is to determine the C-footprint (emissions, removals and sequestration) of farming systems across the summer 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.

This project will continue the process to provide novel (new) data on and create awareness in the entire agricultural value chain (from farmers to markets) on their carbon footprint (with the emphasis on C-sequestration) and provide information on which farming systems to implement in order to improve soil health and farming efficiency and reduce the impact on climate change. In the long term this will lead to improved land management, healthier natural resources and a reduction in greenhouse gas emissions. Furthermore, if carbon tax, or any other incentive scheme is implemented in the future, this information, followed by a rigorous monitoring and implementation process, will be useful for this sector. Determining the impact of various farming systems on carbon budgets also has long term policy implications as the information can be used to assist government in focussing their mitigation strategies for the agriculture sector.

4. CARBON SEQUESTRATION ASSESSMENT APPROACHES

4.1 IPCC carbon sequestration tool

4.1.1 Methodology

The methodology used in the development of the 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); and
- National Carbon Sinks Assessment (Dept. of Environmental Affairs, 2015a).

The methodologies consider 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; 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 tC/ha 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 (**Error! Reference source not found.**).

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: 3.17). 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; and
- 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: 3.20).

The cropland system carbon stock changes in this study covers the flows from the Nett Primary Production (NPP) 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.

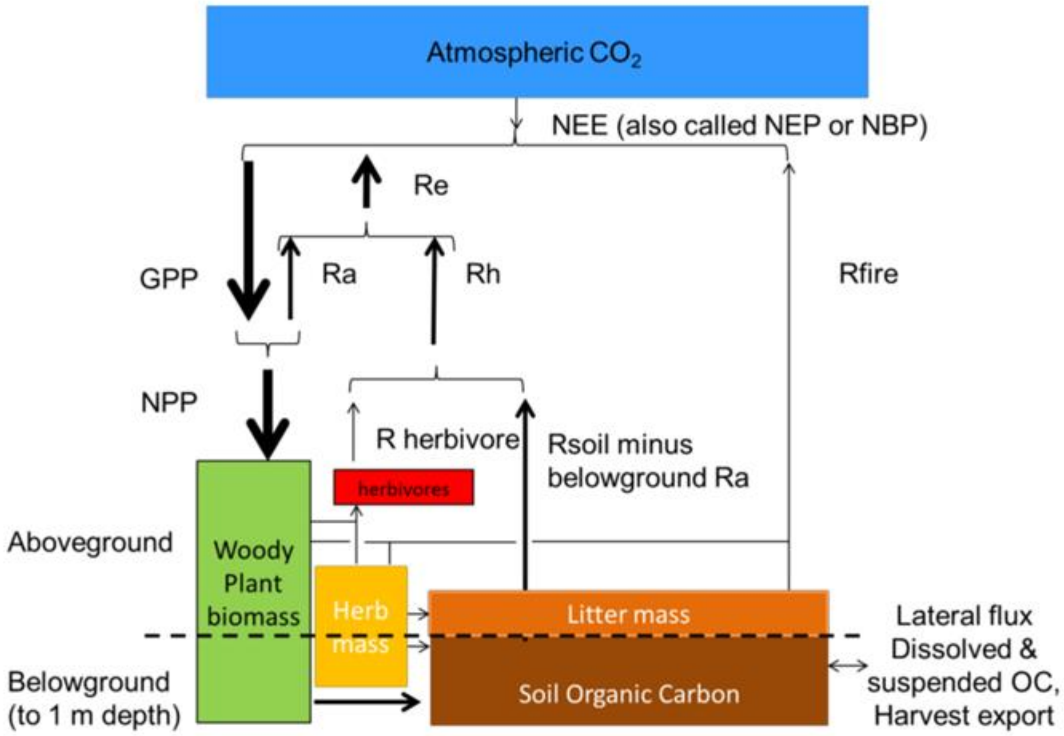

Figure 2: Components of a generalised terrestrial carbon cycle.

Terminology: NEE – Net Ecosystem Exchange, NEP – Net Ecosystem Productivity, N BP – Net Biome Productivity, GPP – Gross Primary Production, NPP – Net Primary Production, Ra – autotrophic respiration (respiration by plants) , Rh – heterotrophic respiration (herbivores, carnivores and microbes), Re – ecosystem respiration (the combined respiration from all sources), Rfire – fire emissions (Department of Environmental Affairs, 2015a).

4.1.2 Carbon stock accounting in cropland

Emissions and removals from cropland remaining cropland include two subcategories of CO_2 emissions and removals. Equation 1 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/year

ΔC_{LB} = annual change in carbon stocks of living biomass in tonnes C/year

ΔC_{Soils} = annual change in carbon stocks in soils tonnes C/year

Equation 1: Annual Change in Carbon Stocks in Cropland Remaining Cropland.

4.1.3 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: 189):

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

Equation 2: Above ground biomass (AGBcrop) as a function of at harvest above ground biomass (AGBharvest), crop duration and year round residue left in stalks (AGBresidue).

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 crop duration is the average number of days between planting and harvest of the crop. The crop duration values in Table 1 are the ratio of the number of days in relation to the number of days in a year for each crop and were thus used. The Harvest Index (HI) is the ratio of harvested yield to above ground biomass. The HI values for all the crops except cover crops were derived from Table 2 which is used by Grain SA and sourced from Stöckle *et al.*, (2001), as these values were more representative of the specific crops used than those in Table 1. For dry beans a HI value of 0.33 was used, the same as that for soybeans. This value is much lower to that shown in Table 2 (0.45-0.55) for beans. According to a study by Pinto Júnior *et al.* (2018) the harvest index values for beans is often overestimated as the procedures used may not include leaves or pods that are dropped and are close to the plant. The study by Pinto Júnior *et al.* (2018) included the dropped leaves and pods and results from the study also showed an average HI value for beans of 0.33. The HI values used per crop are indicated in

Table 3. Cover crops were classified as fodder crops and thus had a HI factor of 1 according to Table 1. Intercrops were classified as legumes with a grain yield of 1.2 t/ha (Hendrik Smith, *Personal communications*, 19 June 2020).

The yield values (in tonnes /ha) from Phase 1 were used and were provided by Grain SA on a per hectare basis, obtained from the Crop Estimates Committee (CEC, 2020) and trial results from the CA Farmer Innovation Programme. These yield values were converted to dry mass (DM) yield (Y) per crop in each crop rotation and farming system. The carbon fraction and fraction moisture per crop group is presented in Table 1. No error information was available for these factors and therefore no error was assumed.

The above ground residue left in the stalks is calculated from 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. reduced tillage in the Eastern Free State has a crop residue removal of 40% therefore R_{AGB} is 0.6. For systems with cover crops residues were consumed via grazing until only 50% residues remained. 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.

Table 1: 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

[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*

Table 2: Unstressed harvest index values for various crops used by Grain SA (adapted from Stöckle et al., 2001)

Crop	Harvest Index
Orzo (Primavera)	0.40 - 050
Beans (Dry)	0.45 - 0.55
Lentils	0.45 - 0.55
Maize	0.40 - 0.55
Peas (Dry)	0.45 - 0.55
Oats	0.40 - 0.55
Sorghum	0.40 - 0.55
Soybean	0.25 - 0.35
Sunflower	0.30 - 0.35
Wheat	0.40 - 0.55

Table 3: Harvest index values used per crop type

Crop	Harvest Index
Maize	0.48
Soybeans	0.33
Dry beans	0.33
Sunflower	0.33
Cover crops	1

4.1.4 Soils

The soils of the summer maize regions are not categorised as organic soils (i.e. peat soils) and the formula for carbon stock changes in mineral soils were thus used. Changes in carbon stocks in mineral soils were determined by the formulae in Equation 6 (IPCC, 2003: 3.75).

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

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 per year

SOC_0 = soil organic carbon stock in the inventory year, tonnes per hectare

$SOC_{(0-T)}$ = soil organic carbon stock T years prior to the inventory, tonnes C per hectare

T = inventory period, year (default is 20 years)

A = land area of each parcel, ha

SOC_{REF} = the reference carbon stock, tonnes /ha; see carbon stock in soil forms per site under low activity clay soils/ sandy soils in Section 5.1.3

F_{LU} = stock change factor for land use or land-use change type, dimensionless; see Department of Environmental Affairs (2015b: 188)

F_{MG} = stock change factor for management regime, dimensionless; see Appendix 1

F_I = stock change factor for input of organic matter, dimensionless; see Appendix 1

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

The parameters used for each of the variables for management (F_{MG}) and inputs (F_I) are included in Appendix 2. The F_{LU} parameter used for dry land agriculture in South Africa (Department of Environmental Affairs, 2015b: 188) is 0.5 and was used instead of the Tier 1 factor of the IPCC (Appendix 2).

4.2 Soil carbon sequestration modelling

4.2.1 Modelling approach

A field-scale numerical model was applied rather than following a GIS-modelling approach which could require large spatially distributed data sets for which data may not be readily available. The field-scale modelling approach was based on spatial units with relative homogeneous climate, soil and farming system practices which represent a production region. This approach has the advantage that the effects of crop rotation-, agronomic- and tillage practices and the biophysical (climate, soil and crop) properties of a production region could be accounted for and simulated in greater detail.

4.2.2 Selection of suitable model

Fourteen (14) soil C-sequestration numerical models were evaluated in a previous study to identify suitable models for the grain production regions of South Africa (de Kock, van Zyl and Smith, 2019). The Windows interface (WinEPIC) of the EPIC (Environmental Policy Integrated Climate) model was selected as a suitable model for this study for the following reasons:

- It is a freeware, and model code is easily downloadable from a dedicated home page;
- It is well documented with tutorials to learn the model;
- Ability to predict the effect of crop rotation, cultivation- and agronomic practices of the conventional- and conservation agriculture farming systems of the SG-regions;
- It is user friendly for setting up model input files and simulating various farming systems;
- It has an extensive database on crop growth and development, tillage implements, agronomic- and cultivation systems that could be used as guidance on appropriate values in setting up model input files for the SG-regions. This provided the additional advantage that the minimum data required by EPIC to simulate C-sequestration are readily available or could be determined / calculated from readily available data in the SG-regions; and
- The model includes a capability for up-scaling from field-scale to regions with *inter alia* the use of GIS in potential future studies.

4.2.3 Model description

The C-sequestration module of WinEPIC is based on the CENTURY C-sequestration model of Parton *et al.* (1992). The CENTURY model simulates the soil organic matter processes and dynamics to predict the extent of C-sequestration. 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 in the CENTURY model, which the WinEPIC C-sequestration component is based on, is shown in Figure 3. Application of the WinEPIC model in this project is summarised in Table 4.

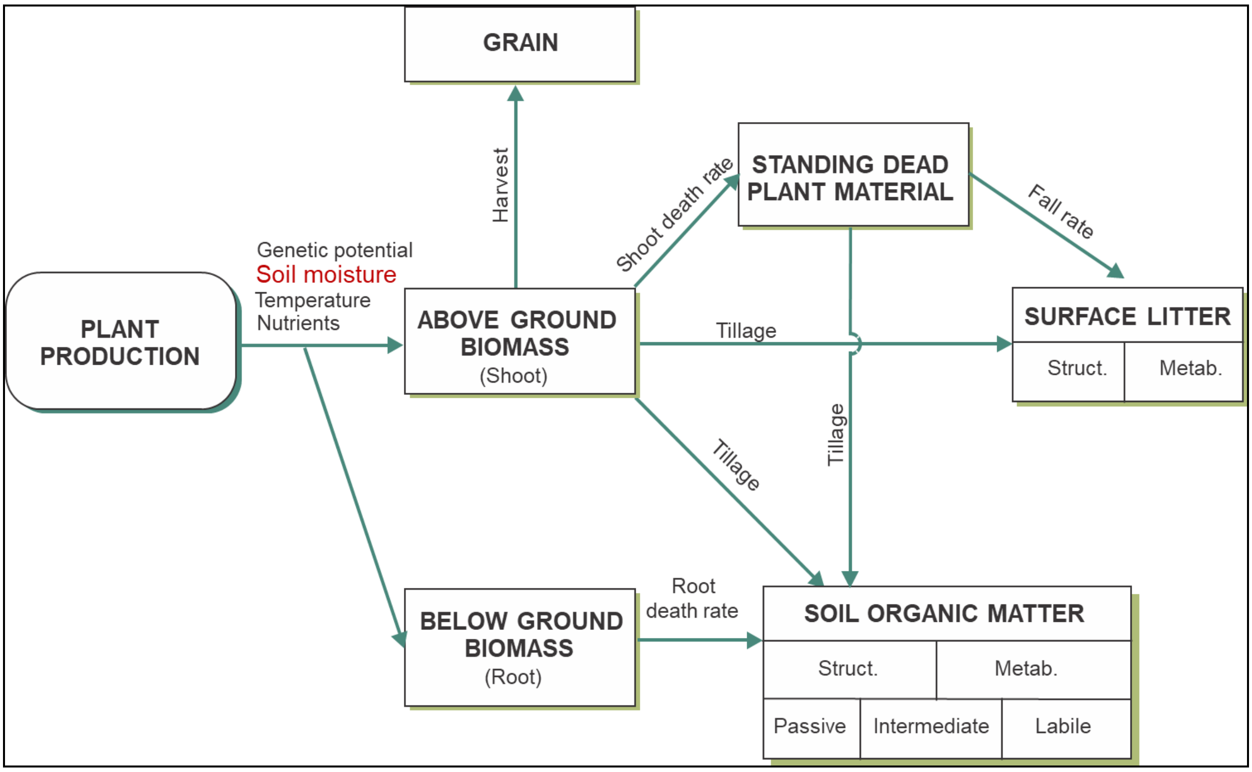

Figure 3: Summary of WinEPIC C-sequestration modelling components.

Table 4: Summary of the application of WinEPIC model in the project

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 impact of crop, land management practices and tillage systems in considerable detail

5. INPUT DATA

5.1 Study regions

Seven production regions have been identified as a framework for the assessment:

- KwaZulu Natal
- Mpumalanga Highveld
- Eastern Free State
- Northern Free State
- North western Free State
- North West Province
- Smallholder farmers.

The North West Province region was split in eastern- and western subregions for the purposes of the C-sequestration modelling to better represent the large range in precipitation and climate across the region (Figure 4).

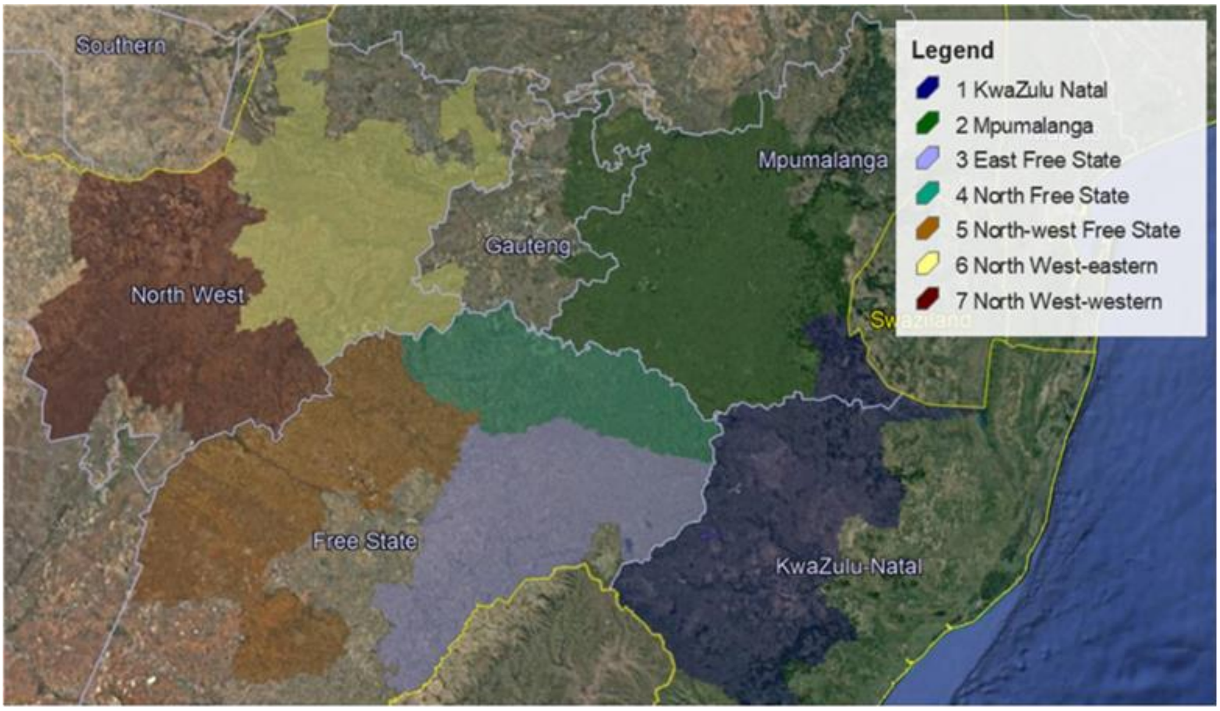

Figure 4: Summer Grain Production Regions for South Africa.

The regions represent the range in climatic and specific land management practices, such as rotation systems, cultivation and fertilisation of grain farming systems of the summer rainfall grain production area of South Africa. Soil carbon sequestration potential was predicted with the IPCC tool and extrapolated from field-scale to a typical likely conditions case scenario for each of the six broad production regions.

5.2 IPCC carbon stocks and sequestration inventory

Data required for the carbon stocks and calculations were sourced from:

- IPCC Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC GPG LULUCF) for Tier 1 values;
- National Terrestrial Carbon Sinks Assessment (Department of Environmental Affairs, 2015b; von Maltitz, 2016); and
- Data from Crop Estimates Committee (2020) and the CA Farmer Innovation Programme (Mahlathini) provided by Grain SA.

Grain SA provided the yield values and crop rotations for the FCA systems. The carbon sequestration methodology with data inputs and outputs is shown in **Error! Reference source not found.**.

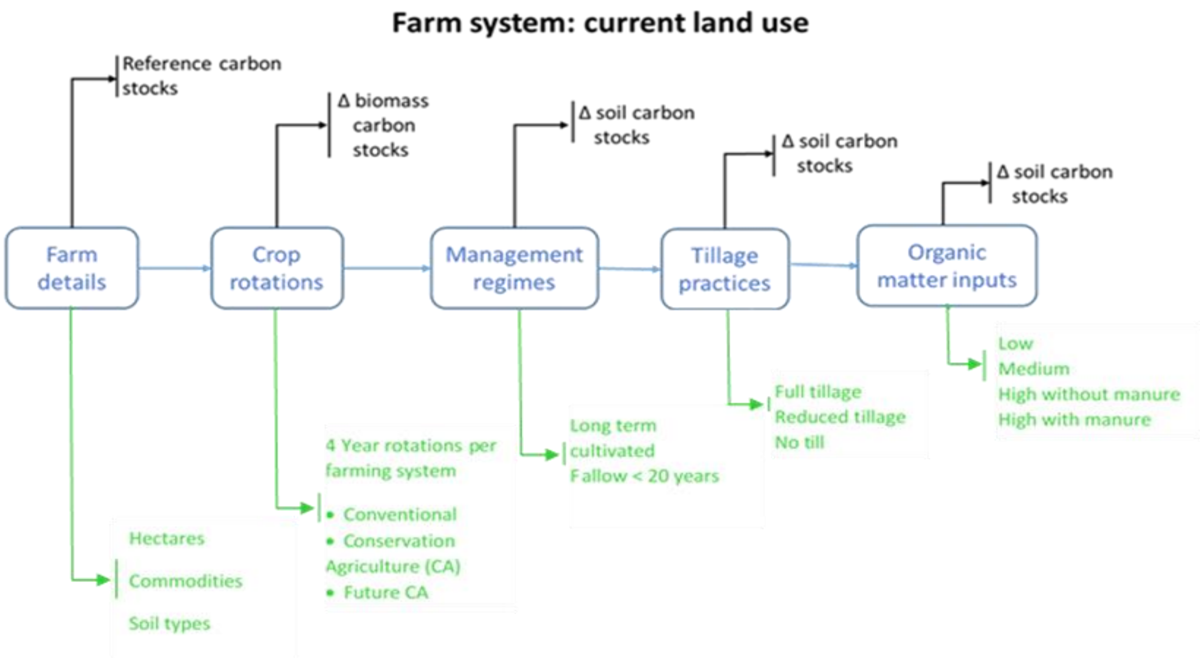

Figure 5: Data collection process map for carbon sequestration methodology input data inventory.

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

- Soil forms in various regions;
- Reference carbon stocks of these soils under native vegetation; and
- Crop rotations of different commodities;
- Farming regimes (CT, CCA, FCA). Currently there are 4 regimes (Hendrik Smith, Personal communications,13 March 2020)
    - Zero till - almost 0% soil disturbance (using a disc seeder)
    - No till: < 20% soil disturbance (using a no-till tine seeder)
    - Reduced 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.

The farming systems per region were defined as follows:

Eastern Highveld and KZN

- CT: Conventional till with up to 80% crop residues removed;
- CCA: Reduced till with up to 10% crop residues removed; and
- FCA: No till with a maximum of 50% crop residues removed for cover crops and cash crops along with cover crops.

Eastern Free State

- CT: Conventional till with up to 80% crop residues removed;
- CCA: Reduced till with up to 40% crop residues removed; and
- FCA: No till with a maximum of 10% of crop residues removed for cash crops only, and 50% for cover crops and cash crops along with cover crops.

Northern Free State

- CT: Conventional till with up to 80% crop residues removed;
- CCA: Reduced till with up to 30% crop residues removed; and
- FCA: No till with a maximum of 10% of crop residues removed for cash crops only, and 50% for cover crops and cash crops along with cover crops.

North Western Free State

- CT: Conventional till with up to 80% crop residues removed;
- CCA: Reduced till with up to 20% crop residues removed; and
- FCA: No till with a maximum of 10% of crop residues removed for cash crops only, and 50% for cover crops and cash crops along with cover crops.

North Western Province

- CT: Conventional till with up to 80% crop residues removed;
- CCA: Reduced till with up to 10% crop residues removed; and
- FCA: No till with a maximum of 10% of crop residues removed for cash crops only, and 50% for cover crops and cash crops along with cover crops.

Smallholders Future CA 1

- CT: Conventional till with up to 100% crop residues removed;
- CCA: Reduced till with up to 80% crop residues removed; and
- FCA: No till with a maximum of 80% of crop residues removed.

Smallholders Future CA 2

- CT: Conventional till with up to 100% crop residues removed;
- CCA: Reduced till with up to 80% crop residues removed; and
- FCA: No till with a maximum of 50% of crop residues removed.

Smallholders Future CA 3

- CT: Conventional till with up to 100% crop residues removed;
- CCA: Reduced till with up to 80% crop residues removed; and
- FCA: No till with a maximum of 50% of crop residues removed.

Organic matter inputs into soil (e.g. crop residues, green manures): The organic matter inputs were provided via Grain SA and were assumed to be the same per specific farming system, for all the regions. For the past land use, the organic matter inputs were low for all the farming systems, for all the regions. See the definitions of the organic matter inputs in Section.

Table 5: Organic matter inputs per farming regime

Region	Farming System	Organic matter inputs
All regions	CT	Low
	CCA – Reduced till	Medium
	FCA – No till	High – Without Manure

5.2.1 Tillage practices and crop rotations

The crop rotations and farming regimes per region were provided by Grain SA and are represented in Table 6.

Table 6: Commodities per farming regime per region.

Regions	Farming regime			
	Year	CT – Full Till	CCA – Reduced Till	FCA– No Till
KwaZulu-Natal and Eastern Highveld	1	Maize	Maize	Maize; cover crops (winter)
	2	Soybeans	Soybeans	Cover crops (summer + winter)
	3	Maize	Maize	Soybeans; cover crops (winter)
	4	Soybeans	Soybeans	Cover crops (summer + winter)
Eastern Free state	1	Maize	Maize	Maize
	2	Soybeans	Soybeans	Cover crops (summer + winter)
	3	Maize	Maize	Soybeans; Cover crops (winter)
	4	Dry beans	Dry beans	Cover crops (summer + winter)
Northern Free state	1	Maize	Maize	Maize
	2	Soybeans	Soybeans	Cover crops (summer+winter)
	3	Maize	Maize	Soybeans; Cover crops (winter)
	4	Soybeans	Soybeans	Cover crops (summer+winter)
North western Free State	1	Maize	Maize	Maize
	2		Soybeans	Cover crops (summer)
	3		Sunflower	Sunflower
	4		Maize	Cover crops (summer)
North West Province	1	Maize	Maize	Maize
	2			Cover crops (summer)
	3	Sunflower	Sunflower	Sunflower
	4	Maize	Maize	Cover crops (summer)
Smallholders (KZN) FCA 1	1	Maize	Maize	Intercropping (maize + beans in the summer season)
	2			
	3			
	4			
Smallholders (KZN) FCA 2 (50% residues remain)	1	Maize	Maize	Intercropping (maize + beans in the summer season)
	2			
	3			
	4			
Smallholders (KZN) FCA 3	1	Maize	Maize	Intercropping (maize + beans in the summer season) + Relay intercropping with winter cover crops
	2			
	3			
	4			

5.2.2 Biomass

The annual mean biomass yield of each crop per hectare per year within the cropping systems at the regions was provided by Grain SA in Phase 1 and were derived from the Crop Estimates Committee (Department of Agriculture, Forestry & Fisheries, 2020). Biomass is determined just before harvesting by sampling the above ground plant material (including the grain). Values for the FCA systems were based on assumptions by Grain SA.

Equation 2 is used to determine the carbon content of the above and below ground biomass for each crop. Maize was classified as a summer cereal, soybeans and dry beans were classified as legumes, sunflower as oil seeds and cover crops as fodder crops. The parameters for each crop type in Table 1 is accounted for in the calculation using Equation 2, with the exception of the HI values which were accounted for in Table 3.

5.2.3 Soil types

Only two dominant soil types were identified by Grain SA: The North Western Free State region has a sandy soil type, while all the rest of the regions in typically have low activity clay (LAC) soils. The summer maize regions all have a warm temperate, dry climate regime. Grain SA provided the reference SOC values at a depth of 0-30cm under native vegetation for each of the regions. Please refer to Appendix 2 for the reference SOC values provided by Grain SA for each region.

5.2.4 Organic matter inputs

The organic matter inputs varied per farming system, but not per commodity or per crop rotation. The inputs pertaining to each crop is included in Table 4 and were provided by Grain SA. 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 (Hendrik Smith, Personal communications, 01 April 2020).

5.3 Data files for carbon sequestration modelling

5.3.1 Climate

The SG-regions are characterised by warm to hot summers and cool to warm winters with frost. Most of the rain occurs during late spring and summer as thunderstorms late in the afternoon.

SG-regions generally have a semi-arid climate, ranging from an arid climate in the far western regions to a dry sub-humid climate in the east (Table 7). The mean annual precipitation (MAP) varies between about 475 mm/yr at Vryburg in the west to about 840 mm/yr at Bergville in the east. The onset of the summer rain season characteristically occurs towards end September in KwaZulu Natal, October in Mpumalanga, east- and the north Free State, and towards end November in Western Free Sate and the western region of North West Province.

In general, a decreasing trend in temperature, evaporation and aridity index (precipitation to evaporation ratio) occurs from the west to the east, with a resulting increasing trend in higher (wetter) soil moisture regime, biomass production and C-sequestration potential to the east (Table 7).

Table 7: Climate of production regions

Region	**Mean daily temperature** (^{0}C)	**Mean annual precipitation** (mm/yr)	**Aridity index**	
KwaZulu Natal	17.3	805	0.46	Semi-arid/ dry sub-humid
Mpumalanga	15.1	725	0.38	Semi-arid
East Free State	14.5	715	0.37	
North Free State	15.7	680	0.31	
North-west Free State	18.3	545	0.22	
Eastern North-West	16.3	625	0.26	
Western North-West	18.7	520	0.18	Arid/semi-arid

Climate datasets with daily rainfall, minimum- and maximum temperature, relative humidity, solar radiation and wind speed were prepared for the SG-regions. The North-West region was split into western- and eastern subregions to better represent the large range in rainfall, temperature and solar radiation across the region.

The daily values of each variable were adjusted to represent the monthly mean distribution of the maps included in the South African Atlas of Agrohydrology and Climatology by Schulze *et al.* (1997) for the SG-regions. The daily rainfall was adjusted to represent the mean annual precipitation of the SG-regions to represent an average rainfall year for modelling purposes.

5.3.2 Soil

Information on selected soil properties included in the ARC-ISCW Digital National Soil Profile Database (Soil Survey Staff, 1972-2010) was obtained. The database includes descriptions and analyses of a considerable number of soil profiles for all the SG-regions of this study.

Soil profiles consisting of apedal B soil horizons were identified from the comprehensive list of soil types included in the database to represent suitable soils for crop production for the purposes of this study.

Soil textural data on the selected soil profiles was analysed to determine the dominant textural classes of the A- and apedal B soil horizons for each SG-region. This information was used to determine two representative soils per region for the purposes of the modelling exercise. Soil texture was used as the basis to identify representative soils are consistent with the following required criteria for the modelling exercise:

- Texture does not vary significantly over time;
- Is not significantly affected by cultivation and agronomic practices;
- Is a primary soil property that considerably effects the range of soil physical and chemical properties important to C-sequestration; and
- Data is readily available or can be determined from readily available data.

The representative soils identified for each SG-region are summarised in Table 8.

Table 8: Soil textures of representative soils

<table>
<tr><th rowspan="2">Region</th><th colspan="2">Dominant soil texture</th><th colspan="2">Sub-dominant soil texture</th></tr>
<tr><th>A-horizon</th><th>B-horizon</th><th>A-horizon</th><th>B-horizon</th></tr>
<tr><td>KwaZulu Natal</td><td>Clay
(C)</td><td>Clay
(C)</td><td rowspan="2">Sandy clay loam
(SCL)</td><td rowspan="2">Sandy clay loam
(SCL)</td></tr>
<tr><td>Mpumalanga</td><td rowspan="3">Sandy loam
(SL)</td><td rowspan="3">Sandy clay loam
(SCL)</td></tr>
<tr><td>East Free State</td><td rowspan="5">Loamy sand
(LS)</td><td rowspan="3">Sandy loam
(SL)</td></tr>
<tr><td>North Free State</td></tr>
<tr><td>North-west Free State</td><td>Sand
(S)</td><td>Loamy sand
(LS)</td></tr>
<tr><td>Eastern North-West</td><td rowspan="2">Sandy loam
(SL)</td><td rowspan="2">Sandy clay loam
(SCL)</td><td rowspan="2">Sandy clay loam
(SCL)</td></tr>
<tr><td>Western North-West</td></tr>
</table>

Soil properties, such as dry bulk density, wilting point, field capacity and saturated hydraulic conductivity, were predicted from the sand-, silt- and soil organic matter (SOM) contents for the selected soils with the Soil Water Characteristics utility. The utility uses pedo-transfer functions and a soil hydraulic properties database that includes over 3000 soils for which the hydraulic properties have been determined. The utility was developed by the United States Department of Agriculture Agricultural Research Service and Department of Biological Systems Engineering of the Washington State University. Soil fertility properties such as soil organic carbon (SOC) content, pH, cation exchange capacity and base cation saturation were obtained from the ARC-ISCW Digital National Soil Profile Database (Soil Survey Staff, 1972-2010).

5.3.3 Cropping systems

WinEPIC's cropping system files requires the crop rotation and crop sequence as model input. The crop rotations that were simulated for the conventional cultivation (CT), conservation agriculture (CA) and future conservation agriculture (FCA) farming systems are based on the data provided by Grain-SA for the SG-regions and are summarised in Table 6.

Cover crops, such as grain sorghum as a summer crop, were included in the future CA cropping systems with the objective to increase SOC and C-sequestration potential by limiting soil disturbance with minimum- or no tillage and providing large root mass in addition to high crop residue rates. Intercropping of maize and cowpea or dry beans with the future CA scenario for the small holder farmers were simulated as a maize-cowpea/dry beans rotation for the purposes of the modelling exercise.

5.3.4 Crop properties

The crop characteristics file includes an extensive list of parameters relating to crop growth, leaf properties and development, root development, biomass production, plant nutrient uptake, harvest index and organic carbon and nitrogen contents of leaves, roots and grain. The parameter values represent the maximum potential growth rate, leaf area, nutrient uptake and harvest index that could possibly be attained under non-stressed conditions.

Parameter values should be based on experimental data where crop stresses related to climate and moisture- and plant nutrient availability have been minimised to allow the crop to attain its potential. Available crop parameter values, such as for the harvest index, grain yield and dry matter, were used to refine the values included in WinEPIC crop parameter files.

It should be noted that the effect of climate, moisture and plant nutrient stresses on plant growth, plant nutrient uptake and biomass production are accounted for in the model components related to soil water balance and plant available water, plant growth and C-sequestration. The soil water balance modelling component included in WinEPIC was imperative to predict changes in soil moisture, plant available water and crop stress (drought) during the growing season.

5.3.5 Agronomic- and Tillage Practices

The crop management file of WinEPIC requires that the type and schedule (timing) of agronomic- and tillage activities are specified for each cropping system. The agronomic- and tillage activities that were accounted for in the C-sequestration modelling include:

- Planting;
- Tillage before, during and after planting;
- Fertiliser and lime application; and
- Harvesting.

Activities and the scheduling of agronomic- and tillage activities for a cropping system are based on data provided by Grain SA for the SG-regions.

The following activities were not accounted for in the C-sequestration modelling:

Pesticide application. The frequency and specific pesticide to be used can vary between growth seasons. Minimum soil disturbance also occurs during pesticide application. Consequently, the activity of pesticide application was not included as it unnecessarily complicates modelling without having a significant effect on C-sequestration. C-sequestration modelling is therefore based on healthy crops that are not affected by pests.

- *Grazing and burning of crop residue after harvesting*. Livestock stocking rates and duration of grazing is highly variable. Consequently, the fraction (%) of crop residue removed during grazing and burning was accounted for with harvesting to simplify the modelling.

Information is also required that describes each agronomic- and tillage practice when an activity is scheduled in the crop management file. The information includes:

- *Implement type and properties*. The data provided by Grain-SA on the various implements used for the farming systems was applied as basis to select the implements from the extensive list of implements included in the WinEPIC database. Data included in WinEPIC database was used since it includes a detailed description on a tillage implement, including the tillage depth and extent of soil mixture and crop residue incorporation during tillage.
- *Planter type, properties and planting density*. Data provided by Grain-SA on the planters used for conventional, minimum- and no tillage was used as basis to select the specific planters from the implements list included in the WinEPIC database. Data included in database was applied since it includes detail description of the planters and their effect on extent of soil mixture during planting.
- *Fertilizer and lime application*. Data provided by Grain-SA on the nitrogen, phosphorus, potassium and lime (calcitic and/or dolomitic) application rate for the various cropping systems were applied to specify the amount fertiliser- and lime applied before, during and after planting for the cropping systems for each SG-region. The fertilizer and lime application rates are included in Appendix 3.
- *Harvesting*. A combine, self-propelled harvester was selected from the WinEPIC implements database. The amount of crop residue that was specified to be removed is based on the data provided by Grain-SA on residue removal through grazing after harvesting for the cropping systems for the various regions. The fraction of crop residue that is removed is included in Appendix 3.

6. PREDICTED CARBON STOCKS

According to the IPCC method, carbon stocks are reported as the average tonnes of soil organic carbon (SOC) content per hectare (tC/ha) for the 0-30 cm soil layer after a 20-year period. The carbon stocks predicted with the IPCC C-sequestration tool and numerical model are shown in Figure 6 and Figure 7 respectively.

The highest carbon stocks in each region was achieved in the FCA farming systems, as expected. A region's reference SOC influenced the level of carbon stocks it achieved, with regions that had higher reference SOC stocks achieving higher carbon stocks than those which had lower reference SOC stocks. The reference SOC stocks per region are included in Appendix 2 for the reference. The smallholders FCA 2 farming system showed an increase of 1 tC/ha in carbon stocks in comparison to smallholders FCA 1, while the smallholders FCA 3 farming system showed an increase of 3 tC/ha in carbon stocks in comparison to the smallholder FCA 1.

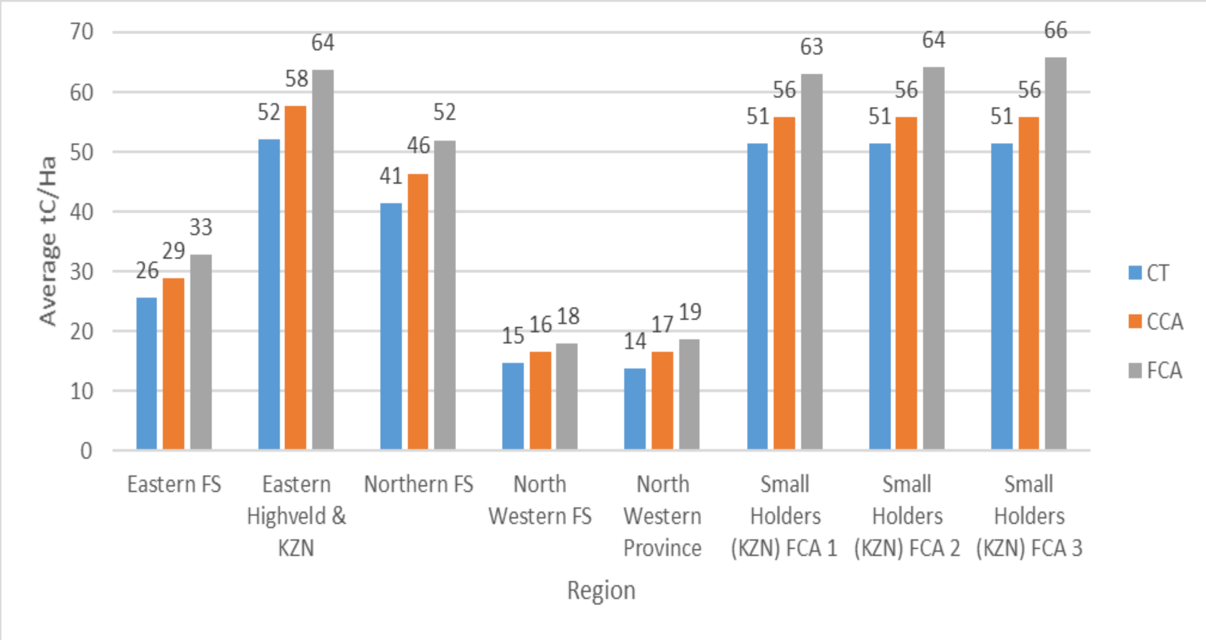

Figure 6:. Carbon stocks (tC/ha) predicted with IPCC method.

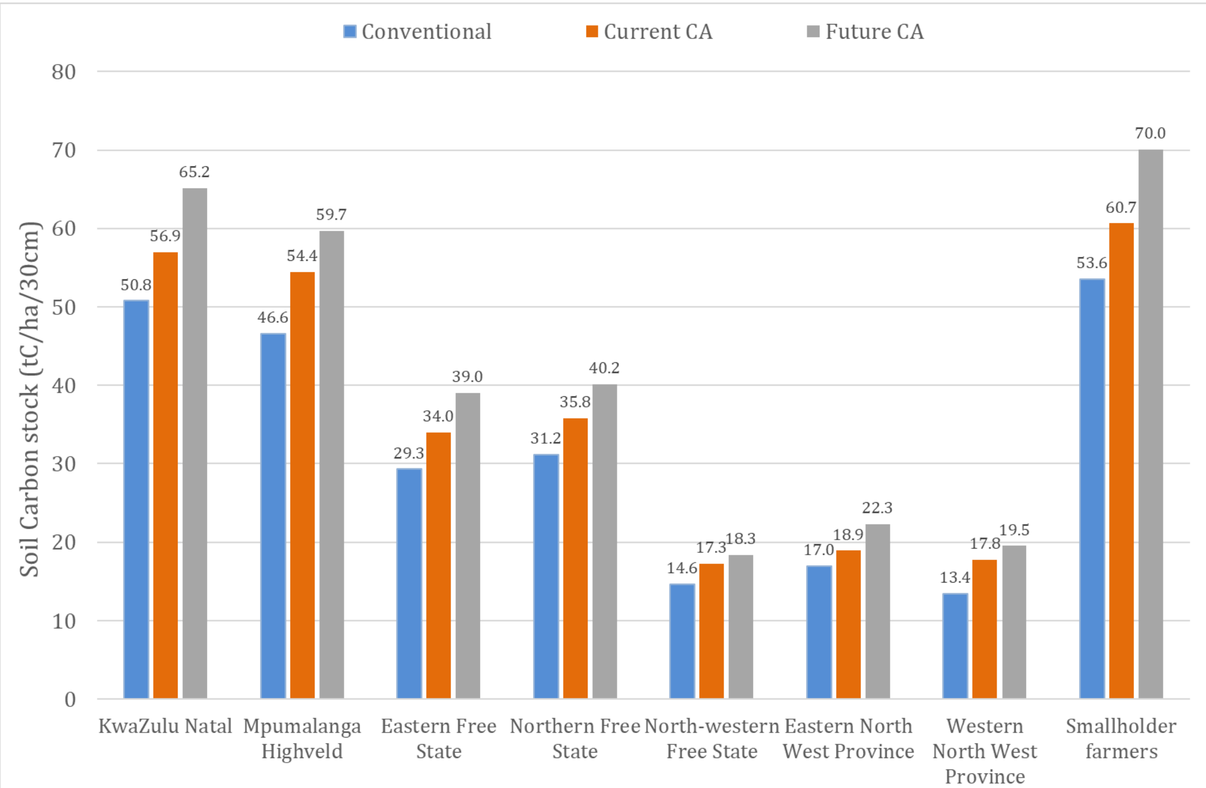

Figure 7: Carbon stocks predicted with C-sequestration numerical model.

The carbon stocks of the CT, CCA and FCA farming systems in comparison with the carbon stocks of natural veld prior to being cultivated are also shown in Figure 8. As expected, the natural systems show the highest soil organic carbon stock levels, while the CT systems showed the lowest soil carbon stocks for each of the regions. The transition to the CCA and FCA systems resulted in increases in the soil organic carbon stocks, with the FCA system showing higher levels of soil carbon stocks than the CCA system.

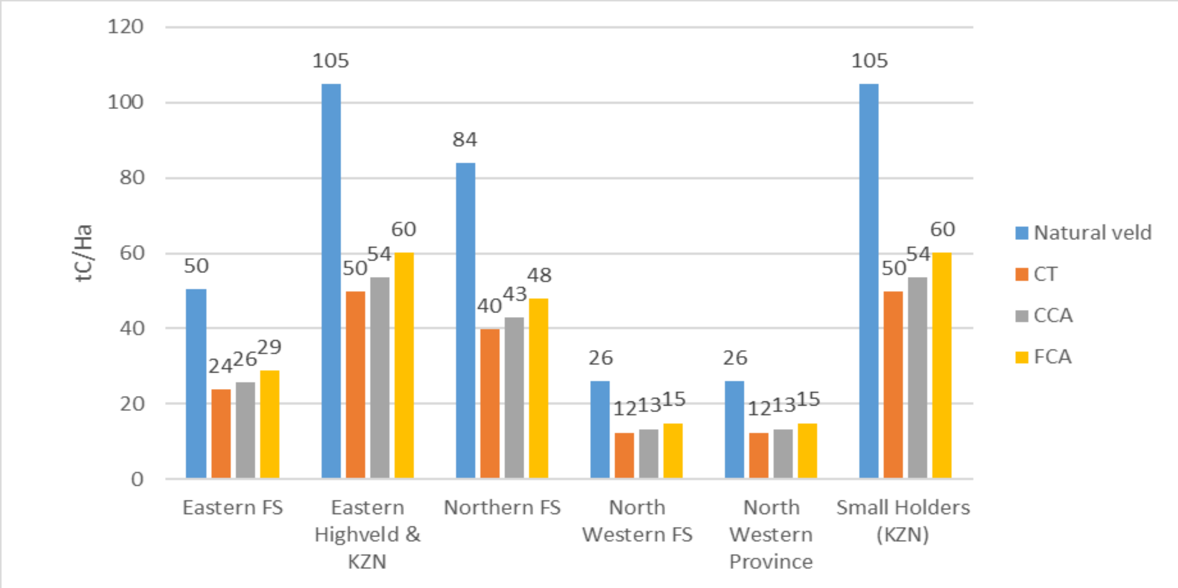

Figure 8: Carbon stocks predicted for farming systems and natural veld.

6.1 Carbon stocks compared per region

6.1.1 Eastern Highveld and KZN, Northern FS and Eastern FS

The Eastern Highveld and KZN region had the highest carbon stock values for the CT and CCA systems out of all the regions (Figure 9 and Figure 10). The high yields of the Eastern Highveld and KZN in these two systems contributing to its high carbon stocks in comparison to the other regions. Furthermore, the Eastern Highveld and KZN had very low residue removals in the CCA system in comparison to the rest of the regions (with the exception of the North Western Province), further contributing to its high carbon stocks in the CCA farming system. The Eastern Highveld and KZN had the third highest carbon stocks for the FCA system, coming in third place after the smallholders FCA 2 and the Smallholders FCA 3. The reasons for these differences will be discussed when looking at the smallholders below.

The Northern FS had the fifth highest carbon stocks overall (Figure 9 and Figure 10). When looking specifically at the CCA system, the Northern FS had higher yields, and thus carbon stocks than the Eastern FS. The reason for the higher yields in the Northern FS compared to the Eastern FS was due to the incorporation of soybeans rather than drybeans in the CCA system. Lower residue removals further contributed to the higher carbon stocks achieved in the Northern FS compared to the Eastern FS for the CCA farming system. The combination of higher yields due to the use of soybeans instead of sunflower, and the more prominent use of cover crops by the Northern FS were the primary reasons for higher carbon stocks achieved in the FCA farming system in comparison to the North Western FS and North Western Province.

The Eastern Free State (FS) had the third lowest carbon stocks overall (Figure 9 and Figure 10).

Higher reference SOC stocks and higher yields in the CCA farming systems contributed to the Eastern FS having higher carbon stocks to the North Western FS and the Northern FS, despite the former region having higher residue removals than the two latter regions. The more prominent use of cover crops played a significant role in the higher yields and thus carbon stocks achieved per hectare in the Eastern FS for the FCA farming system.

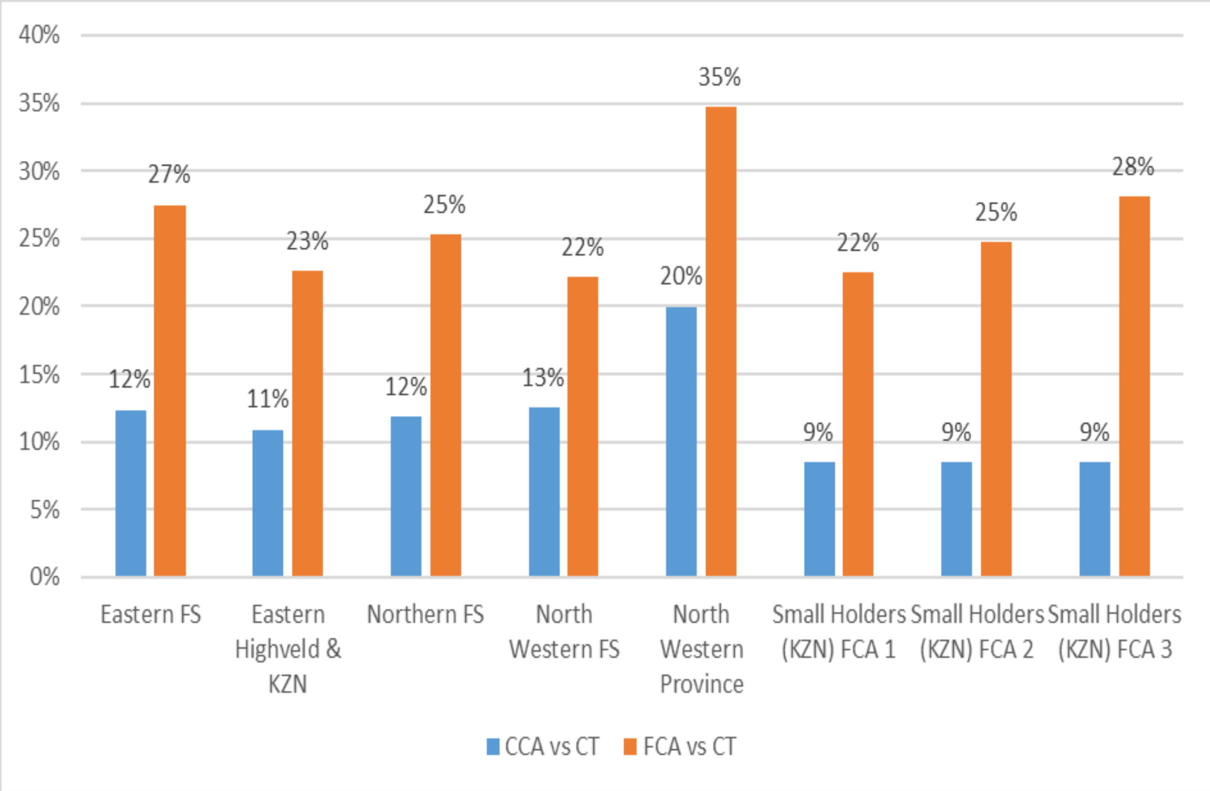

Figure 9: Change in carbon stocks predicted with IPCC method.

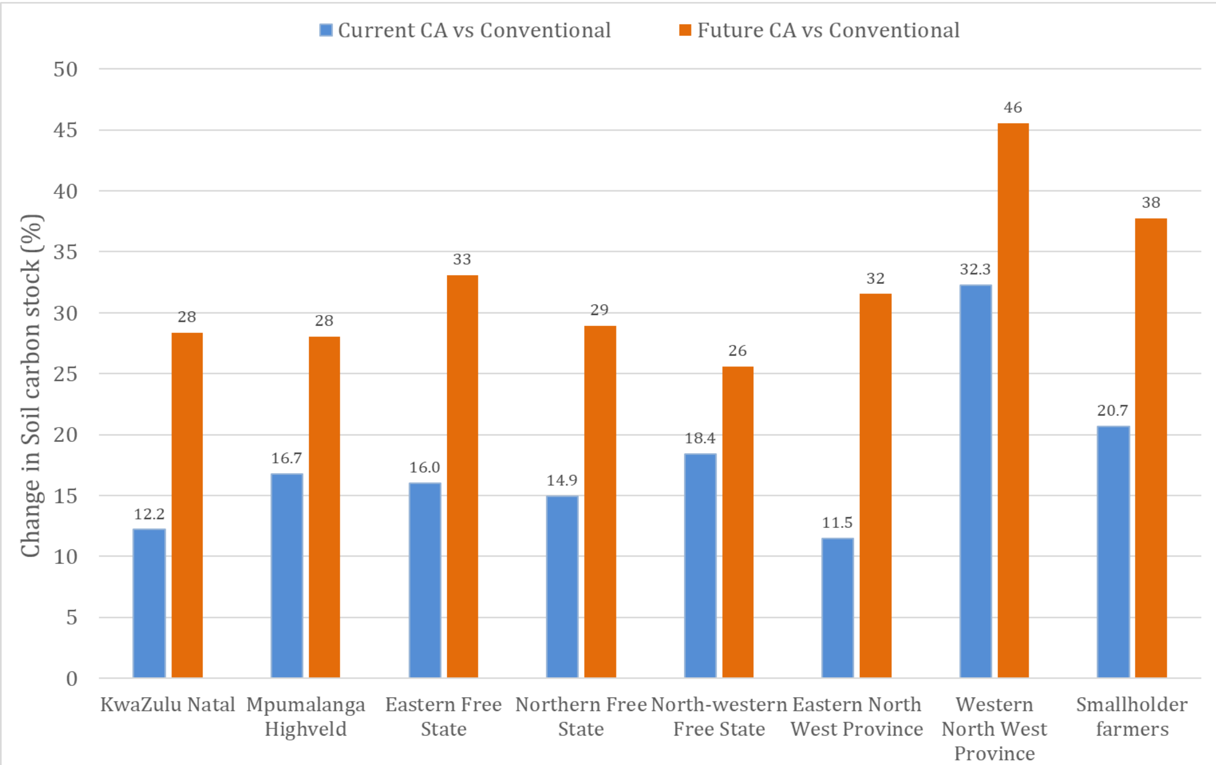

Figure 10: Change in carbon stocks predicted with C-sequestration numerical model.

6.1.2 North Western Free State and North Western Province

The North Western FS and the North Western Province had the lowest carbon stocks overall refer to (Figure 9 and Figure 10). The North Western FS had the lowest yields for the CCA and FCA farming systems and thus the lowest carbon stocks for these farming systems. The North Western Province had the lowest yields in the CT farming system and thus lowest carbon stocks for this system. The incorporation of sunflower instead of soybeans, and summer cover crops without winter cover crops contributed to the low carbon stocks achieved in the FCA farming system by both these regions. The North Western Province had higher carbon stocks than the North Western FS for the CCA and FCA farming systems due to the former region having lower residue removals in these two systems.

6.1.3 Smallholder farmers

The smallholders had the second highest carbon stocks for the CCA and FCA farming systems out of all the regions (Figure 9 and Figure 10). The smallholders had the highest residue removals out of all the regions, but due to its high reference SOC stocks the carbon stocks were much higher than for the other regions (with the exception of the Eastern Highveld and KZN). Lower yields and higher residue removals contributed to the original smallholders (FCA 1) having lower carbon stocks than the Eastern Highveld and KZN. Reducing the residues removed to 50% (FCA 2), smallholders achieved significant increases in carbon stocks (refer to Figure 4). These increases were even more significant when combining this reduction in residue removal with maize intercropping in summer followed by relayed intercropping with winter cover crops (FCA3) (Figure 9 and Figure 10). The smallholders FCA 3 farming system showed the highest carbon stocks achieved out of all FCA systems overall. Thus, reducing residue removals and using intercropping in summer and relayed intercropping with cover crops in winter will cause gains in carbon stocks for smallholders.

6.2 Carbon stocks gains achieved per farming system

The Eastern FS, Eastern Highveld and KZN and Northern FS had similar gain values for carbon stocks in the transition from the CT to CCA farming system (Figure 9 and Figure 10). These regions all had similar cropping systems for the CT and CCA systems, consisting of maize and soybeans primarily. The gains in carbon stocks achieved in the CCA farming system for these four regions were the result of reduced residue removals from the CT system. The differences between these three regions for the gains achieved in the transition to the FCA farming system from the CT system were the result of differences in yields, residue removals and crops used per rotation for each of these regions. The replacement of drybeans in the CT system with soybeans in the FCA system caused the yields of the Eastern FS and thus its carbon gains to be slightly higher to that of the Eastern Highveld and KZN, Northern FS and North Western FS for this transition.

The North Western FS had the lowest gains in carbons stocks for the transition from the CT to the FCA farming system, along with smallholders FCA 1 (Figure 9 and Figure 10). The low level of gains achieved by the North Western FS for the transition to the FCA system is due to there being only a small increase in yields from the CT farming system.

Despite its low carbon stocks, the North Western Province showed the highest increases in stocks for the transition to both the CCA and FCA farming systems from the CT system (refer to Figure 5). These gains primarily resulted from a major reduction in the level of residues that were removed in the CCA and FCA farming systems in companion to the CT system. The increase in yields per hectare resulting from the use of summer cover crops further contributed to the high gains in carbon stocks achieved in in the transition from CT to the FCA farming system for the North Western Province (Figure 9 and Figure 10).

The smallholders had the lowest gains overall for the transition from the CT to CCA system, due to high residue removals for both these farming systems. For the FCA farming system, smallholders FCA 1 had the lowest increase in carbon stocks (along with the North Western FS), also due to high residue removals. When reducing the level of residues removed to 50%, the FCA system of the smallholders (FCA 2) increased by 3% (Figure 9 and Figure 10). When combining this reduction in residue removal with the use of maize intercropping in summer followed by relayed intercropping with cover crops in winter (FCA 3), an additional 3% increase in carbon stocks was achieved in comparison to the smallholder FCA 1 system (Figure 9 and Figure 10). This is in agreement with the conclusion in section 6.1.3, that a reduction in residue removals and more prominent use of intercropping will assure the greatest carbon gains for smallholders.

6.3 Comparison with results from literature

Conceição et al. (2013) found that the carbon stocks for a No Till (NT) cropping system with a LAC soil type at a depth of 0-20 cm and a cropping system of maize in summer and black oats with vetch cover cropping in winter, was 31.1 tC/ha in comparion to a CT system which had a value of 27.8 t C/ha. Thus a 12% increase in carbon stocks was achieved in the transion from CT to NT in the study by Conceição et al. (2013). The carbon stock values achieved by Conceição et al. (2013) is signficantly lower than those found for FCA systems making use of cover cropping in both summer and winter in this project (31.1 tC/ha vs 33 tC/ha – 64 tC/ha), with the Eastern FS having carbon stocks most similar to those found by Conceição et al. (2013) at 33 tC/ha. The percentage increase in carbon stocks found in this project for the transition from CT to NT (FCA) was signficantly higher to those found by Conceição et al. (2013) (12% vs 22-35%), whereas the increases due to transition from the CT to CCA in this project system were more in range with those found by Conceição et al. (2013): 11-13%.

A study by Cheesman et al. (2016) found that the increase in carbon stocks between a CT and CCA maize cropping system was approximately 2 Mg/ha (1 Mg = 1 t/ha). From Figure 6 it can be seen that the increases in carbon stocks achieved in the transition from CT to the CCA system ranged from 2 tC/ha to 6 tC/ha, which is higher to that found by Cheesman et al (2016). Cheesman et al. (2016) suggested that a possible reason for this low increase in carbon stocks may be due to limited carbon inputs in the CCA system, that resulted in a bottleneck for the increase in carbon. Thus, increasing organic matter inputs per region for the CCA in this project would potentially have resulted in significant increases in carbon stocks. The study by Cheesman et al. (2016) was conducted in various sites across Mozambique, and for various soil types at a depth of 0-30cm. Cheesman et al. (2016) found that a NT farming system with a maize-legume crop rotation had mean carbon stocks of 46.1 tC/ha in comparison to 41.4 tC/ha found for CT practice where residue burning takes place. Thus an 11% increase in carbon stocks was achieved in the transition from the CT to the No till farming system in the study by Cheesman et al. (2016), which is much lower to that found in this project for the transition to the FCA (NT) system (22%-35%).

Du point et al. (2010) found the SOC for an annual crop rotation consisting of soybeans, sorghum and wheat at a soil depth of 10-20 cm to be 27.03 tC/ha in the transition to a No-till farming system, which is much higher to the SOC values found for the FCA (NT) farming systems of the North West Province and North West FS in this study (15 tC/ha), but much lower than the SOC stocks found for the FCA systems of all the other regions in this study (29 tC/ha - 60 tC/ha). The Eastern FS had the most similar SOC stocks to that found by Du point et al. (2010) for the transition from the CT to the FCA system (29 tC/ha).

When looking at a study specific to South Africa by (Nyambo et al., 2020), it was found that maize cropping systems in a warm temperate climate and high activity clay soils had significantly higher soil organic carbon stocks (approximately 14 Mg/ha) under a no-till farming system in comparison to a CT farming system (approximately 10.5 Mg/ha) regime. This indicates an increase in SOC stocks of 40% in the transition from the CT to the NT system in the study by (Nyambo et al., 2020). In this project, SOC stocks for CT farming systems ranged from 12 Mg/ha to 50 Mg/ha, while the SOC stocks for FCA (NT) systems ranged from 15 Mg/ha to 60 Mg/ha. The increase in SOC stocks found in this project with the transition from a CT to FCA system specifically was 20%, which is significantly less than that found by Nyambo et al. (2020), despite the SOC stocks in this project being higher to those found by Nyambo et al. (2020). The North Western Province and the North Western FS had the most similar carbon stocks to those found by Nyambo et al. (2020) for the CT and FCA farming systems (12 Mg/ha and 15 Mg/ha respectively).

Thus, for each of the abovementioned studies, carbon stocks were mostly found to be significantly lower for CT and No Till farming systems than those found in this project. It is important to take not that various factors influenced the results per study e.g. differences in soil type, climate, inputs, crop rotations, soil depth etc. and thus the results cannot be used for comparison purposes.

7. PREDICTED CARBON SEQUESTRATION POTENTIAL

According to the IPCC method, carbon sequestration is reported as the average tonnes of soil organic carbon sequestrated per hectare per year (tC/ha/yr) for the 0-30 cm soil layer for a 20-year period. The predicted carbon sequestration potential of the IPCC (2003) methodology, EU Red Methodology and the WinEPIC carbon sequestration model are discussed in subsequent sections.

7.1 IPCC method

The carbon sequestration potential predicted with the IPCC (2003) methodology is shown in Figure 11. Negative values indicate carbon sinks or removals (increase in carbon stock).

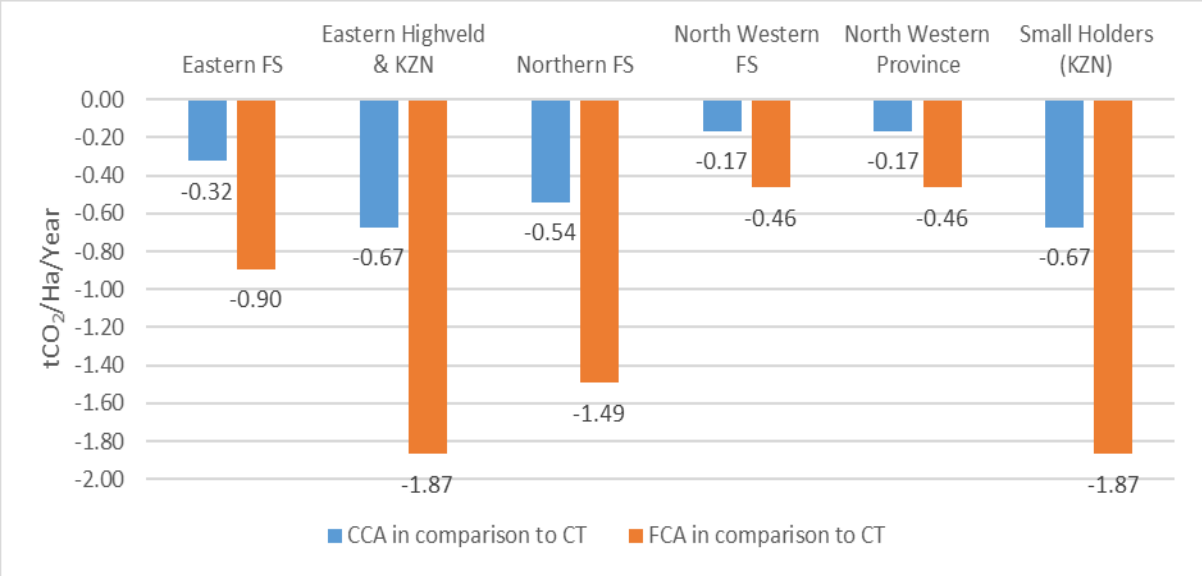

Figure 11: CO2 sequestration potential of CCA and FCA systems in each region when applying the IPCC methodology.

The carbon sequestration potential ranged from 0.17 tC/ha/year to 0.67 tC/ha/year for the transition from the CT farming system to the FCA farming system, while an even greater carbon sequestration potential ranging from 0.46 tC/ha/year - 1.87 tC/ha/year was achieved in the transition from the CT to the FCA farming system.

Figure 10 depicts the soil carbon sequestration (Cveg for the Natural system was excluded) potential of the CT system in comparison to the natural veld, and the soil carbon sequestration potential of the CCA and FCA systems in comparison to the CT system respectively for each region. The CT system showed soil carbon emissions instead of sequestration, as is expected with a transition from a natural system to a cultivated system with full tillage and low organic matter inputs. The transition from the CT to the CCA and FCA systems each showed soil carbon sequestration potential, with the FCA systems showing the greatest carbon sequestration potential.

7.2 EU RED model

Figure 12 shows the carbon sequestration potential when applying the EU RED methodology. The EU RED results show slightly improved carbon sequestration abilities ranging between 0.27 tC/ha/year-1.08 tC/ha/year for the transition to the CCA farming system and 0.74 tC/ha/year – 2.99 tC/ha/year for the transition to the FCA farming system. The higher values are due to a higher land use factor (FLU) used in the EU RED model (0.8) compared to a value of 0.5 from the Department of Environmental Affairs (2015b: 188) used in the IPCC model.

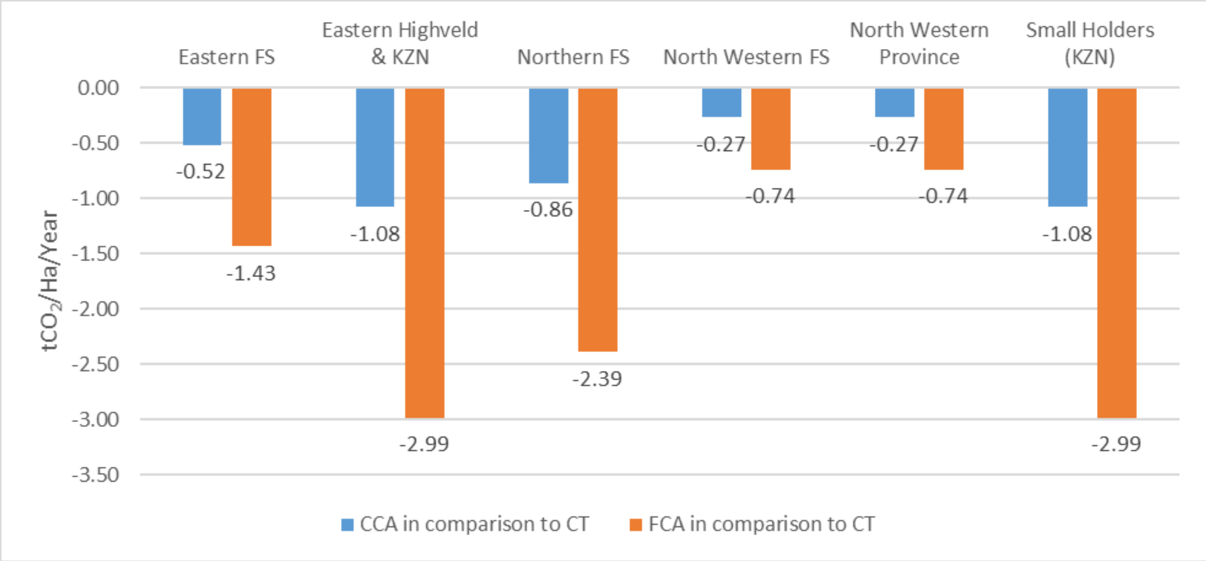

Figure 12: CO2 sequestration potential of CCA and FCA systems in each region when applying the EU Red methodology

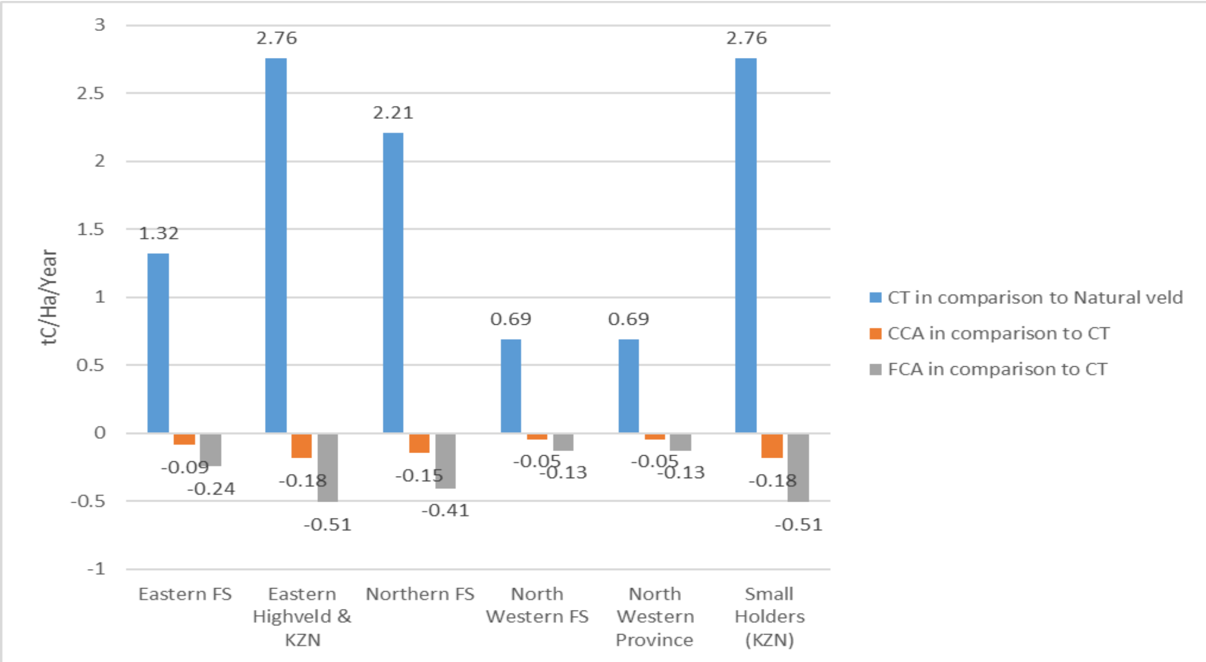

Figure 13: Soil carbon sequestration potential of CT, CCA and FCA systems (excluding Natural veld Cveg).

7.3 Numerical carbon sequestration model

Figure 13 shows the carbon sequestration potential predicted with a carbon sequestration numerical model. The sequestration of carbon is predicted as the average increase in the soil organic carbon contents over 20 years in the 0-30 cm soil layer, and is expressed in tC/ha/yr. The predicted sequestrated carbon (tC/ha/yr) for the higher rainfall areas are comparable to literature values of annual values of about 0.43 through CA in Africa (Gonzalez-Sanchez et al., 2019). The World Bank (2012) reported that for Africa soil C-sequestration rates (tC/ha/yr) for crop residues of 0.374 mean; mulches of 0.377 mean; for cover crops of 0.406; and for no-till of 0.370.

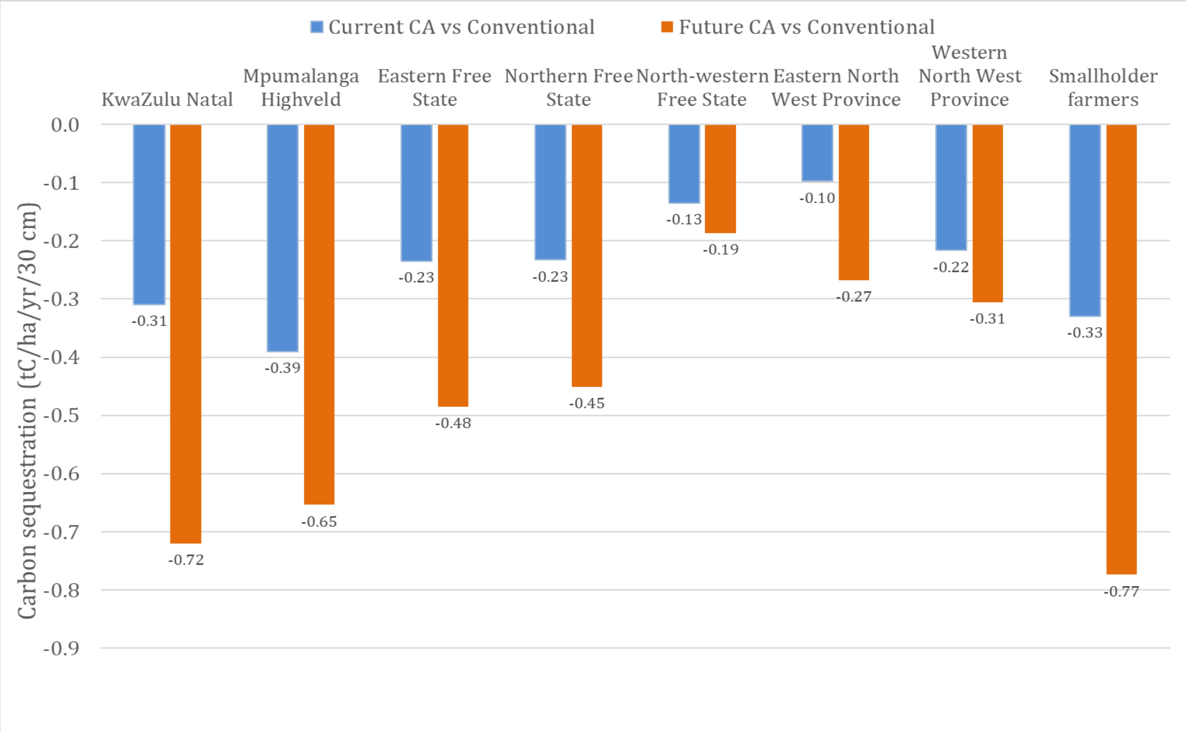

Figure 14: Soil carbon sequestration potential of CCA and FCA systems in each region predicted with the numerical model.

7.4 Comparison with results from literature

A study was done by Wiesmeier et .al (2014) on the carbon sequestration in the croplands of Germany for regions with low annual mean temperatures of 4 - 9 degrees Celsius and primarily high activity soil types at a depth of 0-10 cm. Wiesmeier et .al (2014) found CO2 sequestration values of 4.1 tCO2 per hectare per year, which is significantly higher than those found in this project (0.17 tCO2/ha/year – 1.87 tCO2/ha/year). The study by Wiesmeier et .al (2014) did not define crop rotations or regime, but just looked at croplands as a whole, this and differences in soil depth, soil type and climate make it impossible to compare the results to those found in this project.

Results for CO2 sequestered in the switch from CT to CCA farming systems (0.17 tCO2/ha/year and 0.67 tCO2/ha/year) in this project are significantly higher to those reported by Swan & Paustian (2017) (converted from t/acre/year) for croplands in the USA in dry/semiarid climate zones (0.04 tCO2/ha/year). The CO2 sequestered in the switch from CT to FCA farming system (0.46 tC/ha/year and 1.87 tC/ha/year) in this project was much higher to those found by Swan & Paustian (2017) for croplands in the USA (converted from t/acre/year) in dry/semiarid zones (0.09 tCO2/ha/year). Swan & Paustian (2017) did not define specific crops used. Once again due to differences in various variables e.g., soil type climate, soil depth etc. these values cannot be used for comparisons.

8. PREDICTED CO2 BUDGET

Farming systems in Phase 1 and Phase 2 were not identical, thus the results could not be compared directly. We can, however, in general compare the relative intensity of emissions and the sequestration potential of the farming systems. For each region, the current carbon emissions from Phase 1 is being compared to its future carbon sequestration results calculated in Phase 2 (**Error! Reference source not found.**). The carbon emission and sequestration values are depicted in kg CO_2/ha/year for each region.

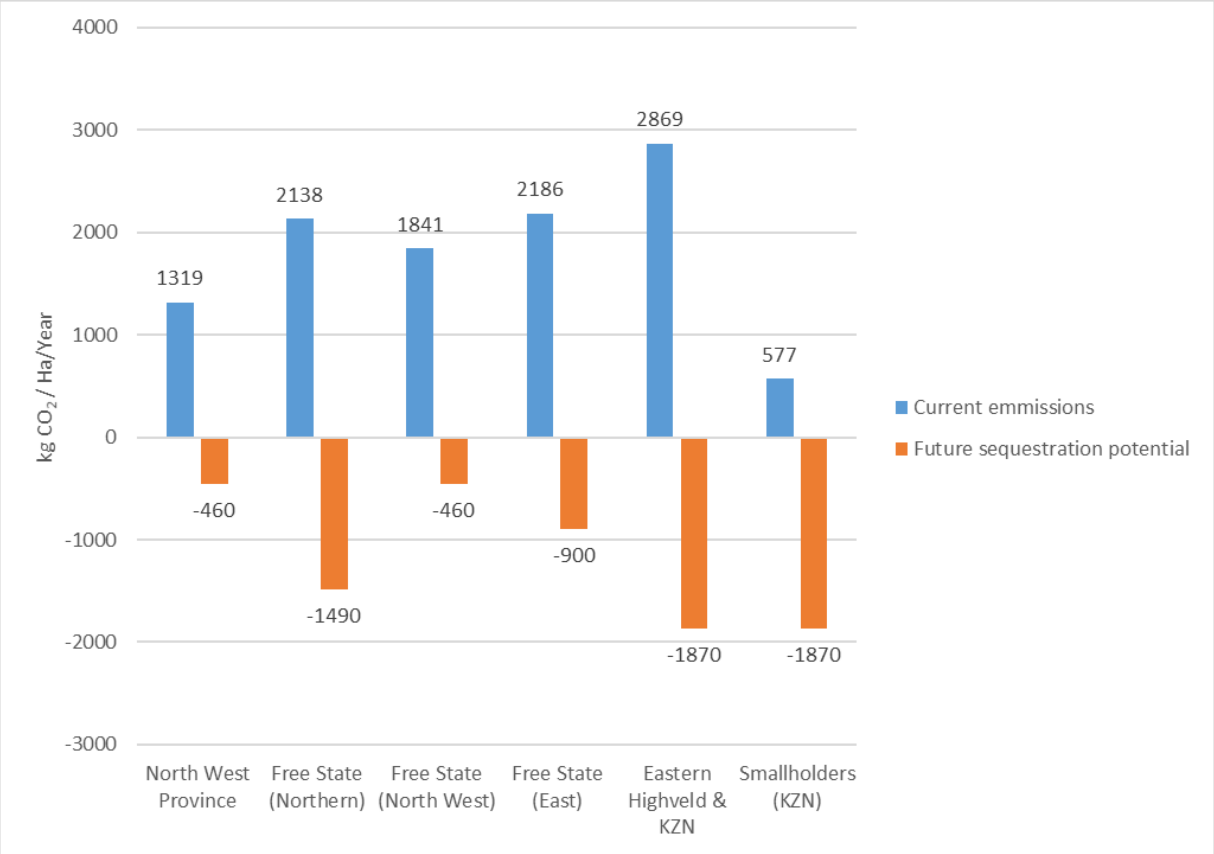

Figure 15: Comparison of Phase 1 Emissions with Potential Phase 2 Sequestration.

From **Error! Reference source not found.** it is evident that the CO_2 emissions from Phase 1 (except for smallholders) are much higher than the future (FCA) sequestration potential, as calculated by applying the IPCC (2003) methodology for all regions. Figure 16 shows the Nett kg CO2 calculated from the emission and sequestration values in Figure 15.

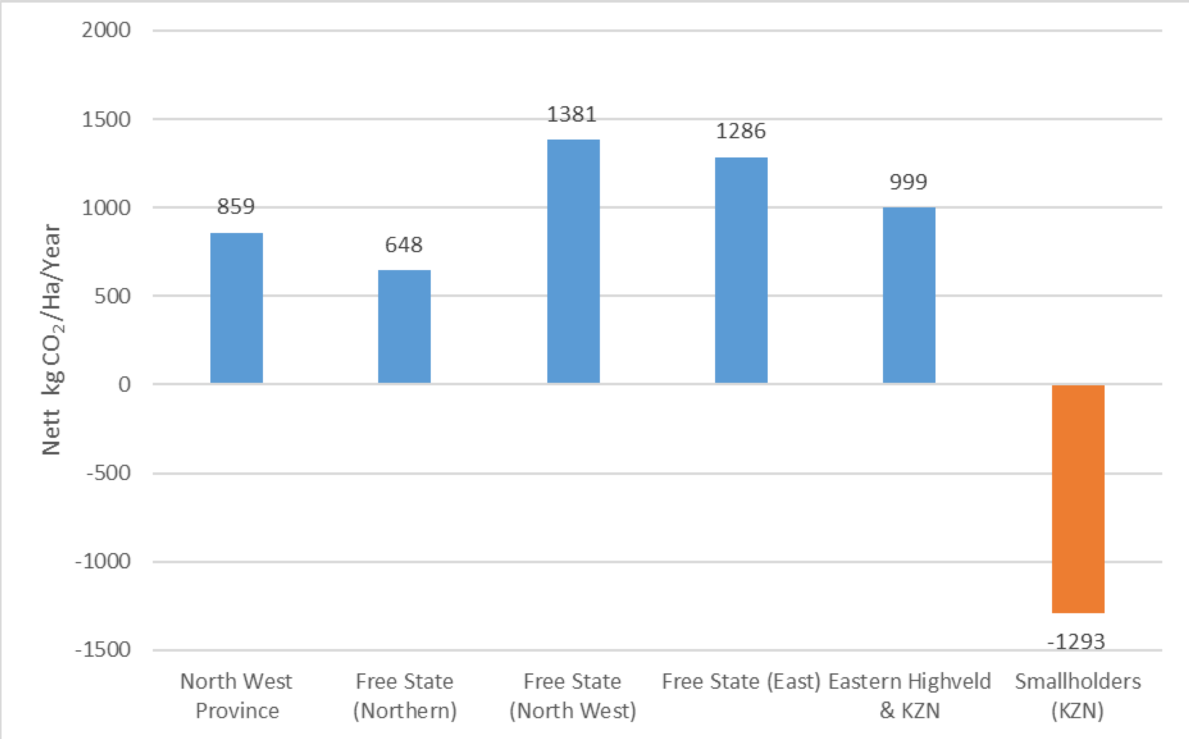

Figure 16: Comparison of Phase 1 Emissions with Potential Phase 2 Sequestration.

It can clearly be seen that farming systems in all regions (except for smallholders) are nett emitters of carbon. The smallholders were the only group which showed nett carbon sequestration.

8.1 Nett CO_2 of each region

All regions showed Nett CO_2 emissions, except for the smallholders. To look at a balance between emissions and sequestration, maize farmers would first need to look at reducing their emissions at farm level. To reduce emissions, there are two primary methods which can be applied. Firstly, the percentage of farmers that make use of CCA or FCA farming systems per region needs to be increased, which will reduce emissions in each of the regions. Secondly, each farmer needs to reduce their level of tillage to reduced or no-till, and their inputs per ha from the levels in the CT farming systems to the reduced levels in the CCA and FCA farming system as indicated in Phase 1. The primary inputs that need to be lowered per ha would be litres of diesel, kg of N, P and K applied, as well as the kg of fungicides, insecticides and herbicides applied.

The smallholders were the only region which showed nett carbon sequestration, resulting from a change in crop rotation from maize only in the CT and CCA systems to maize intercropping in the FCA system. The use of maize intercropping systems is therefore the way forward for ensuring carbon sequestration for smallholders, and through the additional incorporation of cover crops and reduced residue removals even higher levels of carbon sequestration can be achieved.

9. CONCLUSIONS

The use of the higher level methodologies (Tier 1 and Tier 2), clearly indicates that the transition from the CT to a CCA and FCA farming regime will increase the average carbon stocks per hectare and provide carbon sequestration benefits in each of the six summer maize regions.

FCA systems that make more prominent use of cover cropping per rotation will result in higher carbon stocks per hectare compared to FCA systems which make use of only cover crops in summer. Furthermore, the percentage of residues removed affects the average carbon stocks that a farming system can achieve, with lower residue removal resulting in higher carbon stock values for regions with similar cropping rotations. Higher yields will also contribute to higher carbon stocks per farming system.

An FCA smallholder farming system that makes use of maize intercropping in summer, followed by relayed intercropping with winter crops and reduced residue removal will result in the highest carbon stocks and high carbon sequestration potential for smallholders.

The sequestration potential calculated in Phase 2 was significantly less than the annual emissions of producing maize (calculated in Phase 1) for all regions except smallholders. A first step would thus be to focus on carbon emission reductions at farm level and start building the farm's sequestration potential. In many instances, this is a parallel process as practices that reduce carbon emissions also build the sequestration capability of the farm.

The results of Phase 2 support the thesis that reduced tillage practices, higher organic matter inputs, reduced residue removals and increased cover crop rotations positively impact the carbon stocks and carbon sequestration potential of a maize farming systems in South Africa.

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Appendix 1: Relative stock change factors over 20 years for different management activities on cropland (IPCC, 2006).

Default stock change factors provided in Table 5.5 in the IPCC GPG for LULUCF were computed using a global dataset of experimental results for tillage, input, set-aside, and land use. The land-use factor represents the loss of carbon that occurs after 20 years of continuous cultivation. Tillage and input factors represent the effect on C stocks after 20 years following the management change. Set-aside factors represent the effect of temporary removal of cultivated cropland from production and placing it into perennial cover for a period that may extend to 20 years.

Experimental data (see citations provided in reference list in IPCC GPG for LULUCF pg.144) were analysed in linear mixed-effects models, accounting for both fixed and random effects. Fixed effects included depth, number of years since the management change, and the type of management change (e.g., reduced tillage vs. no-till). For depth, data were not aggregated but included C stocks measured for each depth increment (e.g., 0-5 cm, 5-10 cm, and 10-30 cm) as a separate point in the dataset. Similarly, time series data were not aggregated, even though those measurements were conducted on the same plots. Consequently, random effects were used to account for the dependencies in times series data and among data points representing different depths from the same study. If significant, a country level random effect was used to assess an additional uncertainty associated with applying a global default value to a specific country (included in the default uncertainties). Data were transformed with a natural log transformation if model assumptions were not met for normality and homogeneity of variance (back-transformed values are given in the tables).

Factors represent the effect of the management practice at 20 years for the top 30 cm of the soil, with the exception of the land-use factor, which represents the average loss of carbon at 20 years or longer period following cultivation. Users of the Tier 1 method can approximate the annual change in carbon storage by dividing the inventory estimate by 20. Variance was calculated for each of the factor values and can be used with simple error propagation methods or to construct probability distribution functions with a normal density.

TABLE 5.5
RELATIVE STOCK CHANGE FACTORS (F_{LU}, F_{MG}, AND F_I) (OVER 20 YEARS) FOR DIFFERENT MANAGEMENT ACTIVITIES ON CROPLAND

Factor value type	Level	Temperature regime	Moisture regime[1]	IPCC defaults	Error[2,3]	Description
Land use (F_{LU})	Long-term cultivated	Temperate/ Boreal	Dry	0.80	± 9%	Represents area that has been continuously managed for >20 yrs, to predominantly annual crops. Input and tillage factors are also applied to estimate carbon stock changes. Land-use factor was estimated relative to use of full tillage and nominal ('medium") carbon input levels.
			Moist	0.69	± 12%	
		Tropical	Dry	0.58	± 61%	
			Moist/ Wet	0.48	± 46%	
		Tropical montane[4]	n/a	0.64	± 50%	
Land use (F_{LU})	Paddy rice	All	Dry and Moist/ Wet	1.10	± 50%	Long-term (> 20 year) annual cropping of wetlands (paddy rice). Can include double-cropping with non-flooded crops. For paddy rice, tillage and input factors are not used.
Land use (F_{LU})	Perennial/ Tree Crop	All	Dry and Moist/ Wet	1.00	± 50%	Long-term perennial tree crops such as fruit and nut trees, coffee and cacao.
Land use (F_{LU})	Set aside (< 20 yrs)	Temperate/ Boreal and Tropical	Dry	0.93	± 11%	Represents temporary set aside of annually cropland (e.g., conservation reserves) or other idle cropland that has been revegetated with perennial grasses.
			Moist/ Wet	0.82	± 17%	
		Tropical montane[4]	n/a	0.88	± 50%	
Tillage (F_{MG})	Full	All	Dry and Moist/ Wet	1.00	NA	Substantial soil disturbance with full inversion and/or frequent (within year) tillage operations. At planting time, little (e.g., <30%) of the surface is covered by residues.
Tillage (F_{MG})	Reduced	Temperate/ Boreal	Dry	1.02	± 6%	Primary and/or secondary tillage but with reduced soil disturbance (usually shallow and without full soil inversion). Normally leaves surface with >30% coverage by residues at planting.
			Moist	1.08	± 5%	
		Tropical	Dry	1.09	± 9%	
			Moist/ Wet	1.15	± 8%	
		Tropical montane[4]	n/a	1.09	± 50%	
Tillage (F_{MG})	No-till	Temperate/ Boreal	Dry	1.10	± 5%	Direct seeding without primary tillage, with only minimal soil disturbance in the seeding zone. Herbicides are typically used for weed control.
			Moist	1.15	± 4%	
		Tropical	Dry	1.17	± 8%	
			Moist/ Wet	1.22	± 7%	
		Tropical montane[4]	n/a	1.16	± 50%	

TABLE 5.5 (CONTINUED)
RELATIVE STOCK CHANGE FACTORS (F_{LU}, F_{MG}, AND F_I) (OVER 20 YEARS) FOR DIFFERENT MANAGEMENT ACTIVITIES ON CROPLAND

Factor value type	Level	Temper-ature regime	Moist-ure regime[1]	IPCC defaults	Error[2,3]	Description
Input (F_I)	Low	Tem-perate/ Boreal	Dry	0.95	± 13%	Low residue return occurs when there is due to removal of residues (via collection or burning), frequent bare-fallowing, production of crops yielding low residues (e.g., vegetables, tobacco, cotton), no mineral fertilization or N-fixing crops.
			Moist	0.92	± 14%	
		Tropical	Dry	0.95	± 13%	
			Moist/ Wet	0.92	± 14%	
		Tropical montane[4]	n/a	0.94	± 50%	
Input (F_I)	Med-ium	All	Dry and Moist/ Wet	1.00	NA	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. Also requires mineral fertilization or N-fixing crop in rotation.
Input (F_I)	High with-out manure	Tem-perate/ Boreal and Tropical	Dry	1.04	± 13%	Represents significantly greater crop residue inputs over medium C input cropping systems due to additional practices, such as production of high residue yielding crops, use of green manures, cover crops, improved vegetated fallows, irrigation, frequent use of perennial grasses in annual crop rotations, but without manure applied (see row below).
			Moist/ Wet	1.11	± 10%	
		Tropical montane[4]	n/a	1.08	± 50%	
Input (F_I)	High – with manure	Tem-perate/ Boreal and Tropical	Dry	1.37	± 12%	Represents significantly higher C input over medium C input cropping systems due to an additional practice of regular addition of animal manure.
			Moist/ Wet	1.44	± 13%	
		Tropical montane[4]	n/a	1.41	± 50%	

[1] Where data were sufficient, separate values were determined for temperate and tropical temperature regimes; and dry, moist, and wet moisture regimes. Temperate and tropical zones correspond to those defined in Chapter 3; wet moisture regime corresponds to the combined moist and wet zones in the tropics and moist zone in temperate regions.

[2] ± two standard deviations, expressed as a percent of the mean; where sufficient studies were not available for a statistical analysis to derive a default, uncertainty was assumed to be ± 50% based on expert opinion. NA denotes 'Not Applicable', where factor values constitute defined reference values, and the uncertainties are reflected in the reference C stocks and stock change factors for land use.

[3] This error range does not include potential systematic error due to small sample sizes that may not be representative of the true impact for all regions of the world.

[4] There were not enough studies to estimate stock change factors for mineral soils in the tropical montane climate region. As an approximation, the average stock change between the temperate and tropical regions was used to approximate the stock change for the tropical montane climate.

Note: See Annex 5A.1 for the estimation of default stock change factors for mineral soil C emissions/removals for Cropland.

Appendix 2: Reference soil organic carbon stocks at 0-30cm under native vegetation per region provided by Grain SA

Region	Reference Soil Organic Carbon Stocks (SOC) under native vegetation (tonnes C per ha for 0-30cm depth)
Eastern Free State	50,4
Eastern Highveld & KZN	105
Northern Free State	84
North Western Free State	26,1
North Western Province	26,1
Smallholders	105

Appendix 3: Inputs per hectare for farming regimes. The phase 2 data applicable is the crop residue data and rotations.

Region	Regime CT: Conventional CA: Conservation Agriculture	Commodity	Total fresh weight yield	Inputs			Crop Residue		
				Calcitic Lime	Dolomite Lime	Gypsum Lime	Dry matter	% Crop residue burnt	Crop residue removed
			tons/ hect	kg/ hect	kg/ hect	kg/ hect	kg/ hect	%/ hectare	%/ hectare
North West Province	CT	Maize	3.5	150	150	-	3,045.0	-	80%
		Maize	3.5	150	150	-	3,045.0	-	80%
		Sunflower	1.5	150	150	-	1,365.0	-	80%
	CA	Maize	4.5	150	150	-	3,915.0	-	10%
		Maize	4.5	150	150	-	3,915.0	-	10%
		Sunflower	1.5	150	150	-	1,365.0	-	10%
	Future CA	Maize	5.0	150	150	-	4,306.5	-	10%
		Sunflower	1.7	150	150	-	1,501.5	-	10%
		Cover crops (Summer & Wi	17.0	150	150	-	15,300.0	-	10%
Free State (Northern)	CT	Maize	5.0	200	750	-	4,350.0	-	80%
		Soybeans	1.6	-	-	250	1,456.0	-	0%
	CA	Maize	7.0	-	-	-	6,090.0	-	30%
		Maize	7.0	-	-	-	6,090.0	-	30%
		Soybean + WCC	2.0	-	-	-	1,820.0	-	30%
		Cover crops (Summer & Wi	17.0	-	-	-	15,300.0	-	30%
		Soybean + WCC	2.0	-	-	-	1,820.0	-	0%
	Future CA	Maize	7.7	-	-	-	6,699.0	-	10%
		Maize	7.7	-	-	-	6,699.0	-	10%
		Soybean + WCC	2.2	-	-	-	2,002.0	-	10%
		Cover crops (Summer & Wi	18.7	-	-	-	16,830.0	-	10%
		Soybean + WCC	2.2	-	-	-	2,002.0	-	10%
Free State (North West)	CT	Maize	5.0	250	250	-	4,350.0	-	80%
	CA	Maize	5.0	250	250	-	4,350.0	-	20%
		Soybeans	2.1	250	250	-	1,911.0	-	20%
		Cover crops (Summer & Wi	17.0	250	250	-	15,300.0	-	50%
		Sunflower	2.0	250	250	-	1,820.0	-	20%
	Future CA	Maize	5.5	250	250	-	4,785.0	-	10%
		Soybeans	2.3	250	250	-	2,093.0	-	10%
		Cover crops (Summer & Wi	18.7	250	250	-	16,830.0	-	10%
		Sunflower	2.2	250	250	-	2,002.0	-	10%

Free State (North West)	CT	Maize	5.0	250	250	-	4,350.0	-	80%
	CA	Maize	5.0	250	250	-	4,350.0	-	20%
		Soybeans	2.1	250	250	-	1,911.0	-	20%
		Cover crops (Summer & Wi	17.0	250	250	-	15,300.0	-	50%
		Sunflower	2.0	250	250	-	1,820.0	-	20%
	Future CA	Maize	5.5	250	250	-	4,785.0	-	10%
		Soybeans	2.3	250	250	-	2,093.0	-	10%
		Cover crops (Summer & Wi	18.7	250	250	-	16,830.0	-	10%
		Sunflower	2.2	250	250	-	2,002.0	-	10%
Free State (East)	CT	Maize	5.5	200	750	-	4,785.0	-	80%
		Soybeans	1.8	-	-	250	1,638.0	-	0%
		Maize	5.5	200	750	-	4,785.0	-	80%
		Drybeans	1.8	200	750	-	1,620.0	-	0%
	CA	Maize	5.5	167	233	-	4,785.0	-	40%
		Soybeans	2.0	167	233	-	1,820.0	-	40%
		Wheat	1.4	167	233	-	1,246.0	-	0%
		Sunflower	1.9	167	233	-	1,729.0	-	40%
		Cover crops (Summer & Wi	17.0	167	233	-	15,300.0	-	40%
	Future CA	Maize	6.1	167	233	-	5,263.5	-	10%
		Soybeans	2.2	167	233	-	2,002.0	-	10%
		Wheat	1.5	167	233	-	1,370.6	-	10%
		Sunflower	2.1	167	233	-	1,901.9	-	10%
		Cover crops (Summer & Wi	18.7	167	233	-	16,830.0	-	10%
Eastern Highveld & KZN	CT	Maize	7.0	500	500	-	6,090.0	-	10%
		Soybeans	2.0	500	500	-	1,820.0	-	10%
	CA	Maize	7.0	500	500	-	6,090.0	-	10%
		Soybeans	2.0	500	500	-	1,820.0	-	10%
	Future CA	Maize	7.7	500	500	-	6,699.0	-	10%
		Maize	7.7	500	500	-	6,699.0	-	10%
		Soybean + WCC	2.2	500	500	-	2,002.0	-	10%
		Cover crops (Summer & Wi	17.0	500	500	-	15,300.0	-	10%
		Soybean + WCC	2.2	500	500	-	2,002.0	-	10%
Smallholders	CT (HEI)	Maize	4.5	500	500	-	3,915.0	-	100%
	CT (LEI)	Maize	2.0	100	100	-	1,740.0	-	100%
	CA	Maize intercropping	6.0	500	500	-	5,220.0	-	80%
	Future CA	Maize intercropping	6.6	500	500	-	5,742.0	-	50%