APPENDIX 5:
CARBON FOOTPRINT FOR MAIZE
FINAL REPORT
Determining the Carbon Footprint of different maize farming systems within the summer rainfall crop production area in South Africa
Phase 3

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1. PROJECT BACKGROUND

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

Improved cropland management has been highlighted as an effective and practical viable carbon emission mitigation option and for that reason (and others) Conservation Agriculture (CA) is currently promoted by many role players in the agricultural industry. During Phase 1 and 2 of this project the carbon emissions and carbon sequestration potential was assessed of different CA systems.

The results from Phase 1 and 2 were integrated into Phase 3 to determine the impact of various management options on the net carbon budget and demonstrate how this can lead to improved farming efficiency, reduced emissions and alignment with future carbon market opportunities. The proposed carbon tax legislation, for example, also contains mechanisms for trading agricultural carbon credits to other South African organisations to reduce their carbon tax exposure. This project will take the first steps towards realising the potential of this farm-based carbon credit income stream.

An important outcome of Phase 3 is to communicate and raise awareness amongst farmers with regards to the benefits of CA systems to reduce carbon emissions and benefit from the potential to sequester carbon. Online videos and a web-based application were developed in this regard.

2. PROJECT GOAL AND OBJECTIVES

The aim of Phase 3 is to communicate the results and tools developed to determine the carbon footprint of selected maize cropping farming systems to key stakeholders of key agro-ecological regions of the summer rainfall crop production area of South Africa.

The project’s short-term objectives for Phase 3 (2020-2021) were:

1. To improve the demonstration and learning impact of C-footprint data, materials and tools.
2. To interact with key stakeholders in C-footprint (greenhouse gas emissions and C-sequestration) data, materials and tools during workshops and/or social media.

3. STUDY APPROACH

Phase 3 aimed to integrate the findings of Phase 1 and 2 in a user-friendly infographic format for farmers and other users through workshops and/or videos. As COVID 19 regulations restricted interaction through workshops, alternative communication methods were investigated to raise awareness of study results and products. An alternative approach to the proposed workshops was eventually selected, with the development of three online videos (by Blue North) and a web-based C-sequestration application and numerical modelling exercise (by Terrasim). Phase 3 is the final Phase of a long-term project that provided carbon footprint methodology and practical examples for the summer grain industry as an adaptive management tool (Figure 1).

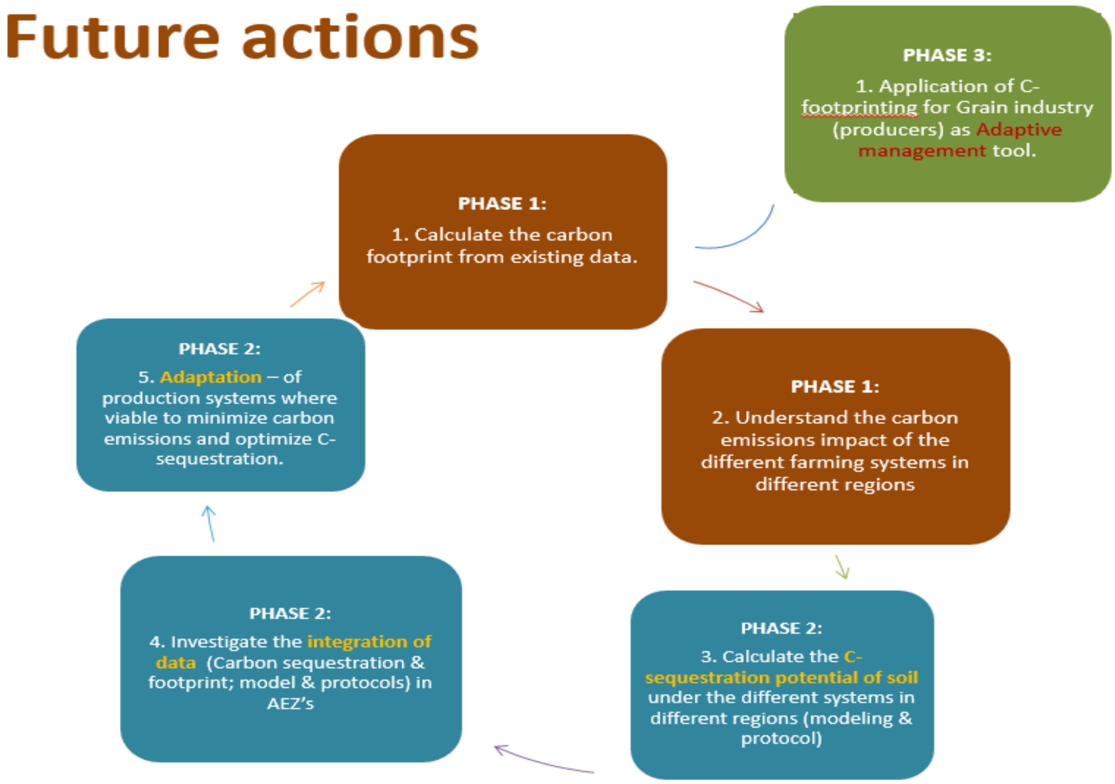


Figure 1: Carbon footprint project phases implemented over three phases.

4. STUDY SCOPE (PHASE 3)

4.1 Objective 1: To improve the demonstration and learning impact of C-footprint data, materials and tools.

This objective was achieved by applying the IPCC carbon sequestration tool (Blue North), which includes:

- Model carbon emissions data in the Phase 1 tool.
- Model carbon sequestration data in the Phase 2 tool.

The study scope to communicate study deliverables through workshops had to be revised due to Covid 19 regulations. This includes the following alternative deliverables to that of the workshops:

- Develop and prepare the carbon emission modelling (Phase 1) as an online video (Video 1).
- Prepare carbon sequestration data and results (Phase 2) as an online video (Video 2).
- Prepare e carbon emission modelling and carbon sequestration data and results as an online video (Video 3).
- Provide results from the detailed SOC sequestration modelling in a website.

Develop a soil carbon sequestration application (TerraSim)

A website for the summer grain production regions was developed to provide improved understanding and demonstrate the effects and potential of CA farming systems to sequester soil organic carbon (SOC). This involved a two-phased approach (Figure 2), which includes:

- *Detailed numerical modelling* to predict the effects of crop rotation, tillage, agronomic and grazing practices on the potential to sequester SOC based on readily available data for the regions. The numerical modelling was conducted in Phase 2 of the project.
- *Develop a user-friendly application (app)* to demonstrate the effects and potential of CA farming systems on the potential to sequester SOC, based on the results from the numerical modelling. A website was developed that was more accessible and user-friendly than an app programme that has to be downloaded and installed.

Development of the website was the focus of Phase 3 of the study.

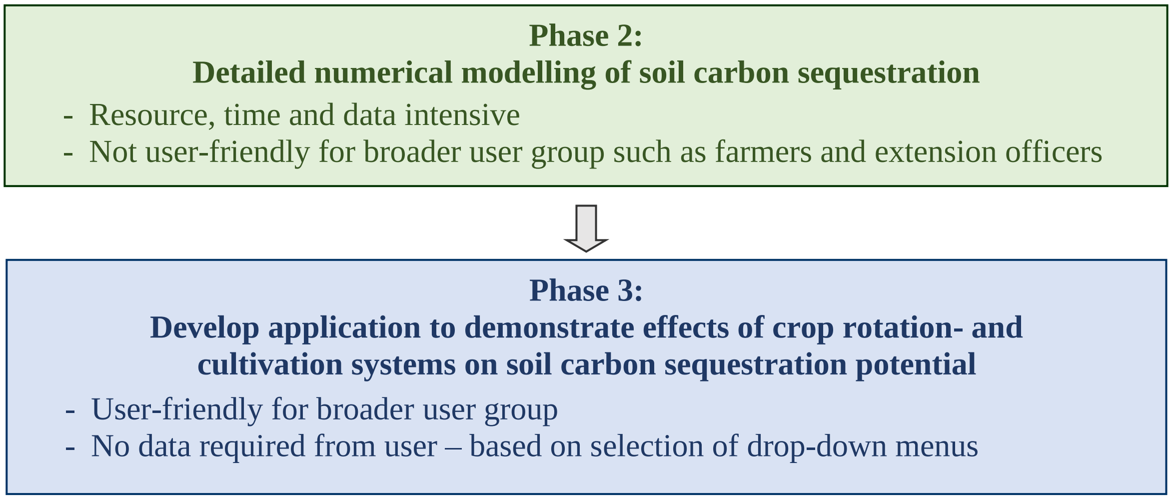


Figure 2: Approach to develop a user-friendly application on SOC sequestration potential.

4.2 Objective 2: To interact with key stakeholders in C-footprint (greenhouse gas emissions and C-sequestration) data, materials and tools during workshops.

The proposed interactive workshops to demonstrate C-footprint results, materials and tools could not be conducted due to Covid regulations that have restricted gatherings such as workshops, and videos were provided as an alternative deliverable to meet the objective to create awareness of various soil greenhouse gas emission reduction and SOC sequestration potential options and the effect of conservation agriculture for the summer grain regions. The videos will be widely shared and made available in maize production regions through the ASSET Research website and existing CA FIP project platforms, such as Ottosdal no-till club (Ottosdal, North West), Maluti study group (Clocolan, eastern Free State), Riemland study group (Reitz, eastern Free State), Ascent study group (Vrede, north-eastern Free State), Mpumalanga Highveld CA network (Ermelo) and the Mahlathini Development Foundation smallholder network.

- The advantage of the videos that were produced is that it will likely be more accessible to a wider of stakeholders group and other users of the tools and material that was developed for.

5. PROJECT IMPACTS

This Phase 3 study provided farmers and other decision makers with tools to measure and manage carbon emissions and sinks on their farms. It will create awareness in the agricultural value chain (from farmers to markets) on their C-budget, C-footprint and C-sequestration potential of farming systems (tillage and crop rotations) to minimise carbon emissions, optimise C-sequestration and reduce the impact on climate change. It will also provide farmers with a management tool to improve resource efficiency and reduce overhead costs which may improve economic sustainability of the farm. The benchmark C-footprint for the regions can enable farmers to evaluate their situations and opportunities in similar areas and/or conditions to create opportunities to learn and implement practices from their discussions, studies and knowledge gained.

Complementing the above, the numerical soil organic carbon (SOC) sequestration modelling provides the industry with the opportunity that SOC sequestration potential was predicted for typical combinations of crop rotations, tillage, agronomic and grazing practices for arable soil types and the climate of the respective summer grain production regions. The modelling results were included in a user-friendly webpage intended for use by a wider users-group to improve the understanding of and awareness making of potential options to sequester SOC.

The user-friendly SOC sequestration webpage is intended for comparison purposes of crop rotation, tillage, agronomic and grazing practice scenarios for use by a wider user group, including farmers and extension officers. The purpose of the webpage will serve to be informative and to create awareness of various SOC sequestration options. The webpage will have the advantage that data need not to be provided by the user as the user will interact through drop-down menus.

The information from the Phase 3 project and rigorous monitoring and implementation process can be used in the future if carbon market opportunities emerge. Determining the impact of various farming systems on C-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.

It is important to recognise that the assessment will not be representative of all farms in a specific region but rather to provide a "snapshot" view of a particular farming system in a particular region. From 9 years of experience in the agricultural carbon foot-printing, Blue North can confirm that farmers who measure their carbon footprint improve their farm management systems. This process often challenges current farm management systems and highlights areas where farm management systems can be improved. Combined with data on soil health and sequestration under different practices in the regions identified, the net C footprint or C budget can further stimulate thinking and awareness on more sustainable and climate-smart agricultural options.

6. PROJECT COLLABORATION

ASSET Research will collaborate with the following institutions:

Blue North Sustainability (Pty) Ltd manages the Confronting Climate Cahnge (CCC) Initiative on behalf of the South African Fruit and Wine Industry Bodies. CCC was established in 2008. The initiative focuses on the Life Cycle Assessment (LCA) of greenhouse gas emissions at farm-level and across agricultural value chains, as well as a climate change knowledge resources for the industry. The initiative currently focusses on perennial tree orchards, but CCC has already developed a carbon footprint protocol, the data collection tools, database and reporting tools for grain farming in South Africa.

The CCC initiative is project managed by Blue North Sustainability, a Stellenbosch-based sustainability practice that is focused on the development and implementation of robust and credible sustainability programs in agricultural businesses and value chains. Blue North was founded in 2011. Blue North Sustainability completed the C-sequestration assessment of the WCT funded C-footprint project in the Western Cape.

Terrasim CC is an environmental consulting company specialising in the earth science component of sustainable land use, rehabilitation of mine- and degraded land, and remediation of contaminated land. Terrasim was founded in 2011and has a registered professional soil scientist with 24 years of experience in soil science and environmental field. Terrasim specialises in the application of numerical modelling of the climate, plant, soil and -water aspects.

7. PROGRESS AND RESULTS USING THE IPCC CARBON SEQUESTRATION TOOL (BLUE NORTH)

To understand the terms used in the following paragraphs a brief overview and definitions are provided.

- CA: Conservation Agriculture
- CCA: Current Conservation Agriculture
- FCA: Future Conservation Agriculture
- *Carbon Footprint*: The total greenhouse gas emissions caused by an individual, event, organization, service, or product, expressed as carbon dioxide equivalent.
- *Carbon Stock*: The quantity of carbon contained in a “pool”, meaning a reservoir or system which has the capacity to accumulate or release carbon.
- *Carbon Sequestration*: Long-term storage (>100 years) of carbon dioxide or other forms of carbon to either mitigate or defer global warming and avoid dangerous climate change.

- *Intercropping*: A multiple cropping practise that involves growing two or more crops in the same field.
- *Relay intercropping*: Two or more crops are grown at the same time as part of the life cycle of each i.e. a second crop is sown after the first crop has been well established but before it reaches its harvesting stage.

7.1 Carbon emission, stocks and relationships using the IPCC carbon sequestration tool

The following maize production regions were included in the assessment:

- North West Province
- North West Free State
- Eastern Free State
- Northern Free State
- Eastern Highveld (Mpumalanga) & KwaZulu-Natal
- Smallholders (KZN)

Three different farming systems were assessed as listed below:

1. Conventional agriculture (CT); with full tillage, low organic matter inputs
2. Current Conservation agriculture (CCA); with reduced tillage, medium organic matter inputs
3. Future CA (FCA): with no tillage, an ideal but realistic CA system (based on assumptions), High organic matter inputs without manure
4. FCA for Smallholders:
    - Future CA 1 (currently assessed): Maize Intercropping, (summer season), 80% biomass cover removed through grazing
    - Future CA 2: Maize Intercropping (summer season), **50%** biomass cover removed through grazing
    - Future CA3: Maize Intercropping (summer season), + Relay intercropping with winter cover crops; **50%** biomass cover removed through grazing

A complete project report has been compiled during Phase 1 and 2 of the project that provides a detailed description of the models. These reports are not repeated here but rather attached for reference purposes. Certain updates have been made to the carbon sequestration modelling data and therefore selected information has been included in the results section below.

7.1.1 Progress and results achieved.

Carbon stocks (tC/ha) per farming system for each region

The average tonne carbon per hectare for each farming system in each of the different regions is shown in the figure below. It is clear that the Future CA (FCA) system holds the most carbon stocks compared to the other systems with the carbon stocks being the lowest in the North Western Free State and the North Western Province.

Three different models were considered for the Small Holder farmers in Kwazulu-Natal. The first system was a Future CA systems with intercropping and 80% removal of crop residue. The second system was a Future CA system with intercropping and 50% removal of crop residue and finally the third system was a Future CA system with intercropping in summer and a relay intercrop with winter cover crops with 50% removal of crop residue. The results indicated that that the third system with the relay intercrop and winter cover crop results in the highest rate of carbon stock accumulation and is a system that should be considered by farmers.

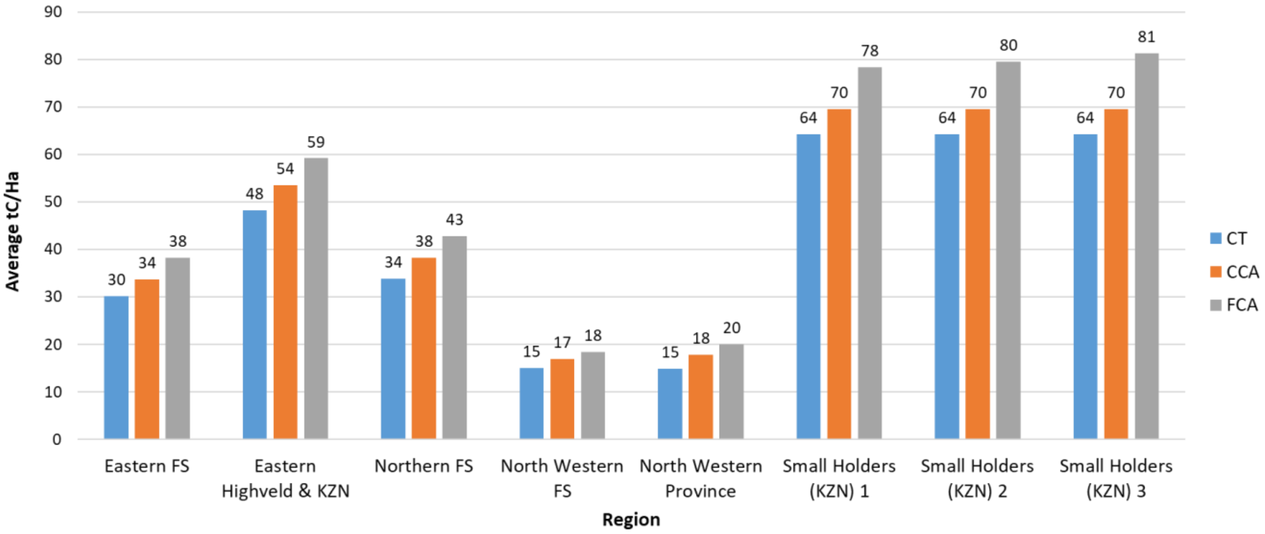


Figure 3: Carbon stocks (tC/ha) per farming system for each region.

Soil organic carbon stocks (tC/ha) per farming system for each region

The Soil Organic Carbon Stock is shown in figure 4 below. The organic carbon stock is much higher in the Natural veld than in the production areas. Once again, the soil organic carbon stock is highest for the Future CA system.

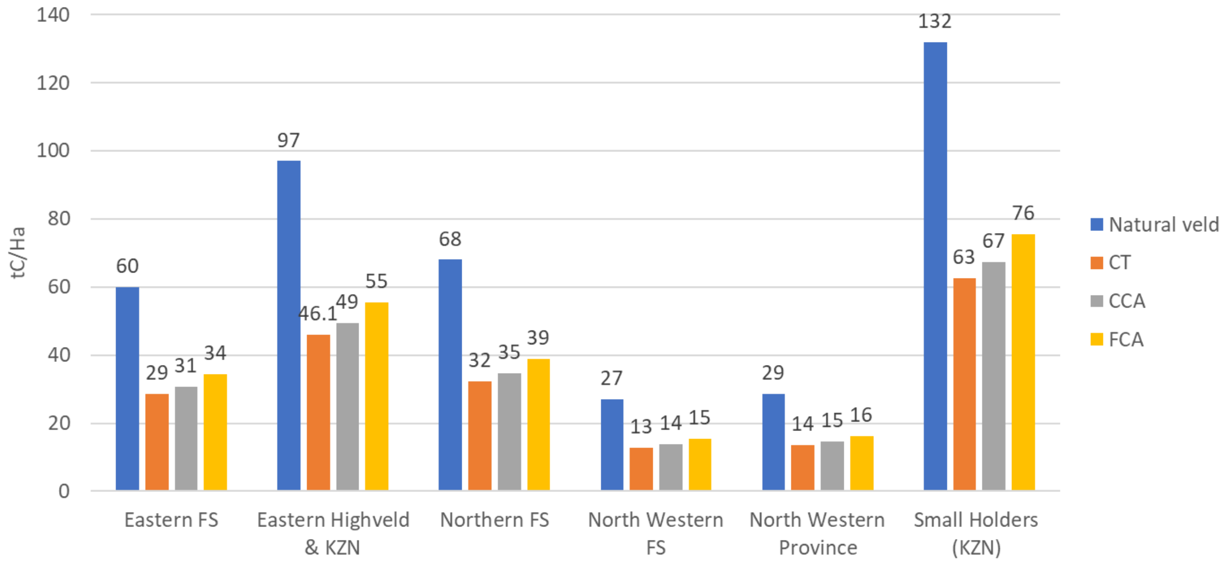


Figure 4: Soil organic carbon stocks (tC/ha) per farming system for each region.

Carbon sequestration potential of the transition to CCA and FCA systems respectively for each region

The carbon sequestration potential was modelled in a stepwise manner to show the potential increase when a farmer progresses from a Conventional system (CT) to a CA system (CCA) followed by the transition from a CCA system to a Future CA system and finally the sequestration potential from a CT system directly to the Future CA system (See Figure 5).

As expected, the biggest "wins" is to move directly from the CT system to the FCA system, however for those producers that would like to follow a step-wise transition there will be continued increases in the potential carbon sequestration.

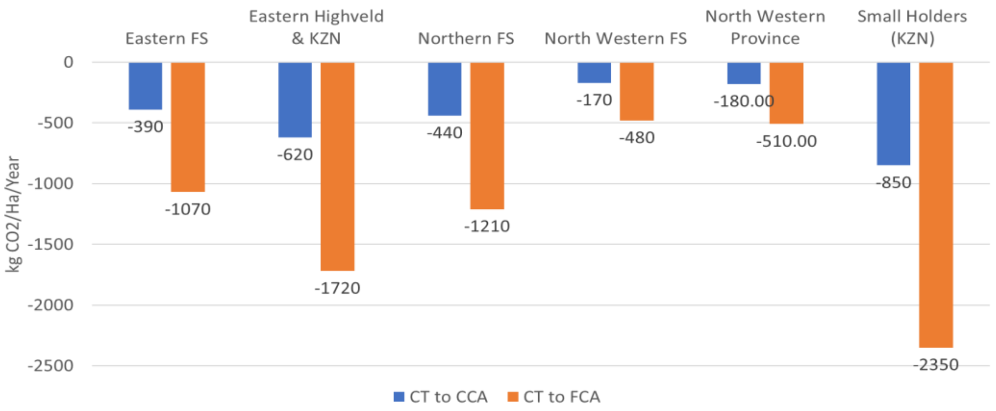


Figure 5: CO_2 sequestration potential of the transition to CCA and FCA systems respectively for each region.

Current CO_2 emissions for each system vs. the sequestration potential of transitioning to CA and FCA farming systems for Maize per region

In order to understand the relationship between the current CO_2 emissions for the production of Maize in the different provinces compared to the potential carbon sequestration when a grower transitions from the CT system to the FCA system, the values were presented in Figure 6 below.

This figure shows a particularly important element when considering the journey of a farmer to reduce carbon emissions and increase the carbon sequestration potential of their soil and that is that the very important step of understanding your emissions and the inputs that contribute most to your overall carbon emissions should not be neglected. It is here where you can significantly reduce emissions which is normally directly linked to inputs costs. Future CA systems do increase the carbon sequestration potential but only in the case of the smallholders did the sequestration exceed the emissions. In all other cases the priority should be to reduce emissions.

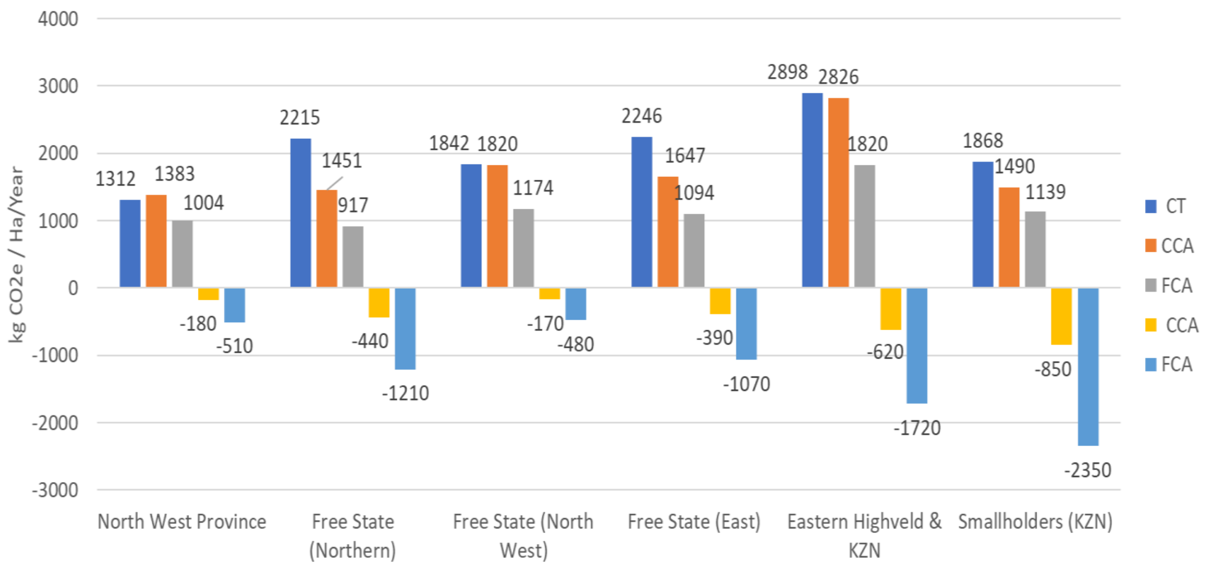


Figure 6: Current CO_2 emissions for each system vs. the sequestration potential of transitioning to CA and FCA farming systems for Maize per region.

7.1.2 Communication of results

Originally a workshop-based approach was envisaged to communicate the results of Phase 1 and 2 of the project to stakeholders. The Covid-19 pandemic posed challenges for travel and gatherings and therefore it was decided to create video material that would be loaded onto YouTube and can be shared via electronic means.

The benefit of making use of the videos is that it can be shared between multiple stakeholders. Even if workshops were held it is often difficult for stakeholders to attend and therefore the audience reached is much smaller. A further advantage is that the material can be accessed multiple times for reference purposes, even on a phone and can be forwarded via electronic messaging e.g. WhatsApp, email, etc.

Three videos were compiled in an easily understandable format with graphics. The first video serves as an introductory video to the project, the second explains the practices that could lead to reduced carbon emissions and increased carbon sequestration, whilst the third video integrates the results from Phase 1 and 2.

The videos were loaded onto YouTube and a link provided that will be available via the Asset Research website.

Links to the videos:

Video 1: Carbon footprint of Summer Maize Farming Systems in South Africa. Part 1: Introduction.
https://youtu.be/yPIwOXvrQy4

Video 2: Carbon footprint of Summer Maize Farming Systems in South Africa. Part 2: Carbon Emissions & Carbon Sequestration.
https://youtu.be/iAONeHv5V8U

Video 3: Carbon footprint of Summer Maize Farming Systems in South Africa. Part 3: Results from the work completed with The Maize Trust.
https://youtu.be/mSjpdgTSoyU

The videos and results will also be communicated at a CA Research Forum in October 2021.

8. SOIL CARBON SEQUESTRATION NUMERICAL MODELLING (Terrasim)

Numerical modelling was conducted to analyse the potential of various cropping systems to sequester soil organic carbon (SOC) for the summer rainfall grain production regions. Results of this modelling provide input to the website developed to provide a basic, user-friendly tool to demonstrate the potential of cropping systems that follow Conservation Agriculture (CA) principles to sequester SOC.

8.1 Modelling approach

The field-scale modelling approach followed was based on region-specific climate and the range of soils found in a region. The effects of crop rotations, tillage, agronomic and forage practices could be simulated in detail for region-specific biophysical properties that include climate, soil, water and vegetation.

A GIS-modelling approach was not followed for this study. GIS models need large spatially distributed data sets, which are not readily available for input to this modelling. A GIS based model that is not coupled with numerical modelling is unlikely to simulate the effects of crop rotations, tillage and agronomic practices to a level of detail that can predict how the SOC contents (and stock) will change over time. The compilation of spatially distributed databases that accurately represent the biophysical conditions, farming systems and practices found in each field in a region would considerably exceed the budget allocated for this project. The GIS model version of the EPIC model will depend on future data availability and funding. An upscaled model could transition from demonstrating potential to detailed analysis of how SOC content could change both spatially and over time in a grain production region

8.2 Model review and selection

Fourteen (14) numerical models that can predict the effects of crop rotations, tillage, agronomic and forage practices, and biophysical properties on SOC were evaluated. The Windows interface of the EPIC (Environmental Policy Integrated Climate) model (WinEPIC) was selected as a suitable model for this study for the following reasons:

- WinEPIC is freeware, and model code is downloadable from https://epicapex.tamu.edu/epic/winepic/ or from the dedicated home page https://epicapex.tamu.edu/model-executables/winepic-6-0/
- The model is well documented (how processes are simulated and the equations used, and how the model was constructed), which can be downloaded from http://agrilife.org/epicapex/files/2015/05/EpicModelDocumentation.pdf
- WinEPIC has user manuals, which can be downloaded from the home page listed above or http://agrilife.org/epicapex/files/2013/02/WinEPIC.0810.Manual.pdf
- WinEPIC can predict the effects of crop rotation, tillage, agronomic and forage practices for various crop system scenarios for the summer grain regions.

- WinEPIC is user friendly and allows relatively easy set-up of model input files to simulate a range of farming systems.
- An extensive database on crop growth and development, tillage implements, agronomic, tillage and forage practices provide appropriate default values to guide the set-up of model input files for the summer grain regions.
- For potential future studies the model can up-scale from field-scale to regions with the GIS based version.

8.3 Model description

The soil organic matter (SOM) module of WinEPIC is based on the CENTURY soil organic matter model of Parton et al. (1992). The CENTURY model simulates the SOM processes and dynamics to predict the extent of SOC loss or sequestration. According to Smith et al., (1997), the CENTURY model produced consistently low errors for all datasets in a comprehensive study that compared the performance of soil organic matter models against results of long-term experiments. Important processes and components simulated in the CENTURY model, which the WinEPIC SOM module is based on, are shown in Figure 7.

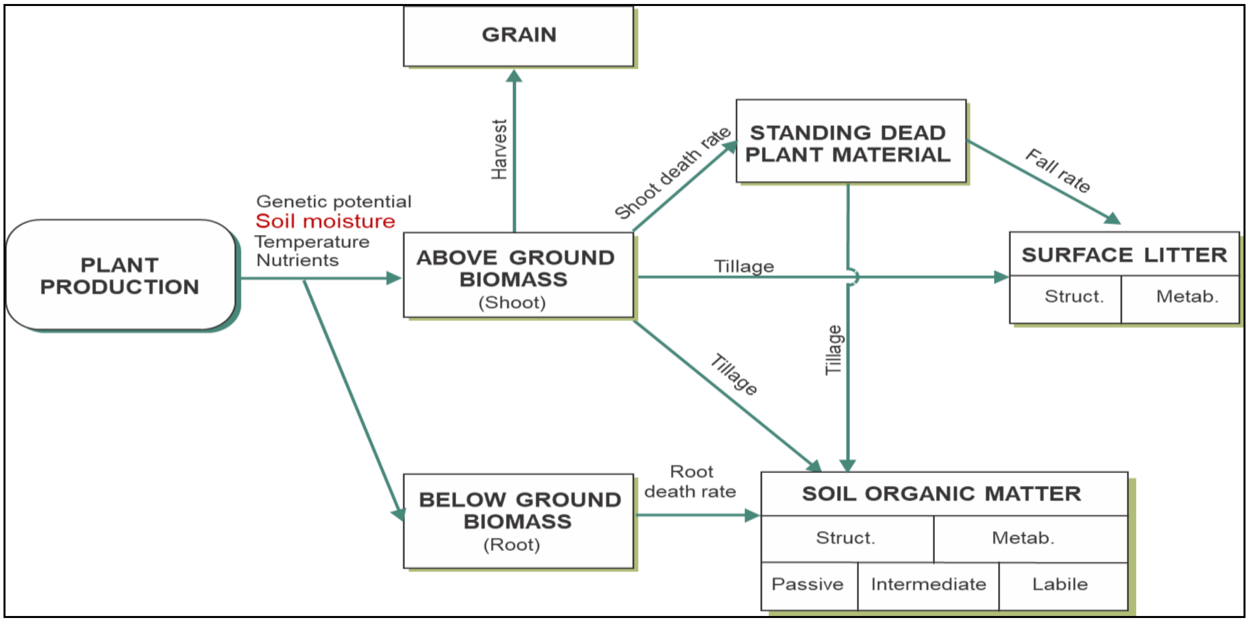


Figure 7: Summary of WinEPIC C-sequestration modelling components.

Model documentation that discusses how processes are simulated, the equations that are used and how the model was constructed can be downloaded from the webpage by following the link http://agrilife.org/epicapex/files/2015/05/EpicModelDocumentation.pdf.

8.4 Model input

8.4.1 Summer grain production regions

Production regions include Northwest Province, North Western-, Northern- and Eastern Free State, Eastern Highveld (Mpumalanga Province), KwaZulu Natal and smallholder farmers in the Bergville district of KwaZulu Natal (Figure 8). The North West Province region was split in eastern- and western subregions for the purposes of the SOC sequestration modelling to better represent the range in precipitation, climate and cropping systems across the region.

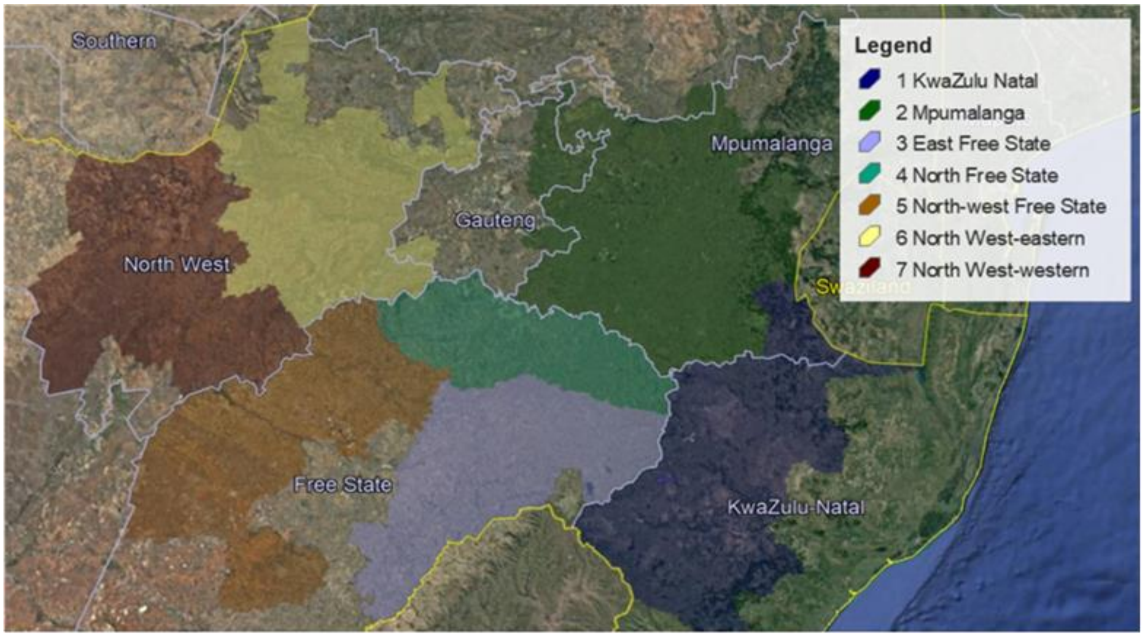


Figure 8: Summer grain production regions.

These regions reflect the range of climate, soils, crop rotation systems, tillage and agronomic practices for grain production in summer rainfall areas of South Africa.

8.4.2 Climate

A climate dataset with daily data on climate variables was prepared for each region. The climate data conforms to regional monthly mean distribution maps of the South African Atlas of Agrohydrology and Climatology by Schulze *et al.* (1997). Climate input for a region is discussed in the region's page.

8.4.3 Soil

Information on selected soil properties was obtained from the ARC-ISCW Digital National Soil Profile Database (Soil Survey Staff, 1972-2010). The database includes descriptions and analyses of a number of soil profiles for each production region.

Suitable soil forms for crop production were identified, and information on these soils was used to determine three representative soils for each region. Representative soils were selected based on particle size distribution. The median (50th percentile), lower quartile (25th percentile) and upper quartile (75th percentile) of clay content in the range of suitable soils was used to describe average texture, sandy and clayey soils. Soil texture was used as the basis to identify representative soils, which also needed to meet the following required modelling criteria:

- Texture does not vary significantly over time.
- Particle size distribution is not significantly affected by tillage, agronomic and grazing practices.
- Texture is a primary soil property that affects the range of soil, physical and chemical properties that are important to soil carbon sequestration.
- Data is readily available.

The field capacity, wilting point and dry density of representative soils were predicted using the sand-, silt- and SOC contents of soils and the Soil Water Characteristics utility developed by United States Department of Agriculture Agricultural Research Service and Department of Biological Systems Engineering of the Washington State University. The utility includes over 3000 soils for which hydraulic properties have been determined. Properties of the representative soils are discussed in the website.

8.4.4 Cropping systems

WinEPIC needs crop rotation and crop sequence as model inputs. Regional simulations include conventional tillage (CT), current CA practices (current CA) and ideal future (future CA) crop system scenarios. Forage sorghum and rye as summer- and winter cover crops are included in future CA scenarios that provide high forage and root mass to increase the potential to sequester SOC.

8.4.5 Crop characteristics

The crop database of WinEPIC includes an extensive list of parameter values on crop growth, crop and root development, biomass production, plant nutrient uptake, harvest index and organic carbon and nitrogen ratios of leaves, roots and grain. The parameter values represent the maximum potential leaf and root growth rate, leaf area and soil mass, 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. Database crop parameter values were primarily used for modelling. Parameter values that were available for the study, such as for the harvest index, forage- and biomass were used to refine parameter values contained in the database

8.4.6 Tillage, agronomic and grazing practices

WinEPIC requires information on the following farming activities and their schedule (timing):

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

The application of *pesticides* is not included in the numerical models for the respective regions, since little soil disturbance occurs during applications and the frequency and specific pesticide used can vary between growth seasons. This limits unnecessarily model detail that has no significant effect on SOC balances.

Tillage practices were used to select *implements* from WinEPIC model database, which includes detailed description of properties of an implement that affects soil carbon balances; such as tillage depth and crop residue incorporation (mixing into soil) during tillage.

Data on suggested *nitrogen, phosphorus, potassium and lime applicatio*n rates were provided by Grain SA for the respective crop system scenario. Soil phosphorus levels of 20 mg P/kg soil and potassium levels of 100 mg K/kg soil were used for modelling, which limited phosphorus and potassium deficiencies. This is a fair assumption since soil phosphorus and potassium levels in cultivated soils were increased to and maintained at these levels for crop production. *Nitrogen, and to limited extent phosphorus, fertiliser application rates were increased if the modelling indicated that a crop experience a nutrient deficit that limits the potential to sequester SOC. Modelling indicated significant sensitivity of high biomass- and grain production, and SOC sequestration towards phosphorus deficiencies. This is especially the case when cover crops were simulated.*

Modelling also indicated that *forage sorghum (as a surrogate for summer cover crops) and rye (surrogate for winter cover crops) went into a nitrogen deficit to achieve the high biomass production* indicated by ASSET Research, resulting in that *SOC contents stabilised at reduced levels determined by the extent of nitrogen deficit*. Three levels of nitrogen application rate scenarios were therefore simulated to provide an understanding of the effect of nitrogen deficiencies on SOC sequestration (Table 1). The scenarios on nitrogen application rates were based on a guideline by a Grain SA (2021) of 15 kg N/ha at planting, and subsequent top dressings of 35 kg N/ha once or twice throughout the growth season for forage sorghum. The nitrogen rates for rye are based on the lower biomass production indicated for rye (6.5 t/ha) compared to forage sorghum (18,7 t/ha).

Table 1: Nitrogen application rate scenarios for cover crops.

Scenario	Nitrogen application rate (kgN/ha)							
	At planting		**First top dressing**		**Second top dressing**		**Total**	
	Forage sorghum	Rye	Forage sorghum	Rye	Forage sorghum	Rye	Forage sorghum	Rye
Proposed rates[1]	Based on rates provided or 15 kg/ha		Difference between provided rates and 15 kg/ha				Provided rates	
Single top dressing[2]	15		35	15			50	30
Two top dressings[2]					35	15	85	45

Notes: [1] Rates indicated by Grain SA and ASSET Research for model input

[2] Guideline rates by Grain SA (2021) for integrated crops and pasture based production systems

ASSET Research proposed stocking rates of 220- and 145 cattle/ha/day for ultra-high stock density grazing practices during a single grazing for the forage sorghum and rye respectively. Maize residue left after harvesting was also grazed to 50% of the dry mass being removed, as indicated by ASSET Research. WinEPIC also accounts for the loss of maize residues and cover crop forage mass due to trampling of residue and forage into the soil and the benefits of livestock urine and manure deposited during grazing. The default ratio of WinEPIC that 80% of grazed biomass is converted to liveweight was used.

The tillage, agronomic practices and grazing activities, and the scheduling thereof, for the various cropping system scenarios are based on recommendations of Grain-SA and ASSET Research, and are discussed in the respective website pages for each region on SOC sequestration potential.

8.5 Model calibration

Model calibration is required to confirm that model simulations realistically represent the system processes that are modelled, to refine model input data or parameters, and to reduce model uncertainties. Where model simulations form part of a study, it has become accepted practice to expand model calibration to include a good modelling practice audit, which includes comment on processes used to select a model and to ensure that model input (and output) data is valid and accurate. Key aspects of good modelling practice include:

- *Selection of appropriate model(s) for the purpose of the study:* Fourteen (14) numerical soil organic matter models were evaluated to select an appropriate model for this study; which is discussed in Section 8.2 and Section 8.3.
- *Model data represent the biophysical conditions and management practices of study:*
    - Model input of this study on *precipitation and climate* is based on weather data and the mean monthly distribution of the variables of a region (Section 8.4.2).
    - Model input of this study on *soil properties* are representative of an average-, sandy and clayey textured soils for a region and the analytical data of the considerable amount of soil profiles included in the National Soil Profile Database (Soil Survey Staff, 1972-2010); which is discussed in Section 8.4.3
    - Input data on a range of model parameters on *crop rotation, tillage, agronomic and forage practices*, and the scheduling (date of activity) thereof, are based on data collated by GrainSA, ASSET Research and Blue North from farmers, specialist and workshops during Phase 1 and Phase 2 of the study.
- Collation of *experimental datasets from field monitoring trials* for model calibration, which is discussed in subsequent sections.
- *Model verification, calibration and validation:* The following model components were addressed in this study:
    - *Crop growth and development* module (Section 8.5.1).
    - *Soil organic matter* module (Section 8.5.2).

Climate Action Reserve published a guideline in 2020 on model calibration, validation of models and verification of model inputs and results, where changes in soil organic carbon stock are predicted. The guideline discusses key aspects of model calibration requirements, model validation of the accuracy of the calibrated model, and the use of experimental datasets to compare modelled predictions to monitored data published from field monitoring trials.

The guideline discusses requirements for (field) monitoring trials that should be planned and operated to provide the following information for projects that predict changes in SOC stock:

- *Experimental treatments:* It should include comparisons of different fertiliser (and lime) application rates, different tillage systems (e.g conventional tillage with and without mouldboard ploughing and CA tillage systems), and comparisons of a mono-crop rotation, multi-crop rotations and crop rotations that include cover crop(s).

- *Data:* The monitoring must, at least, provide data on:
    - Agronomic practices, such as the crop rotation sequence, use of cover crops, tillage practices, planting densities and dates, and effective root depth.
    - Tillage practices, implements used and date of tillage, extent of soil disturbance caused by an implement and the amount of residue mixed into the soil.
    - Fertiliser and lime application rates should include the type of application, together with data on the method, frequency, and timing of each application.
    - Harvesting methods and the amount of residue left after harvesting.
    - Residue management after harvesting.
    - Stocking density, forage type and quality, grazing time, and rest/recovery periods of grazing practices.
    - Soil textural class and associated clay contents of the soil(s) of the trial site(s).
    - Rainfall and climate data during the monitoring trial.
    - Soil compaction (e.g. extent and depth of limiting layer).
- *Peer-review and published experimental datasets* that, at least, includes the following:
    - Measurements of SOC stock change over time (time series data) using control plots to test the practice farming system.
    - Statistically robust repeated measurements of SOC stock change to capture multi-year changes, as farming system(s) effects on SOC may combine short and long-term changes in soil biogeochemical processes.
    - Statistically robust measurements from paired monitoring sites leveraging space-for-time analysis methods that approximate multi-year changes that may also be used to validate for SOC stock changes.
    - Soil depth(s) at which SOC stock changes were determined for the model to predict SOC stock changes at the corresponding depths.
    - Validation dataset for SOC stock change at the depths of measurements to determine the uncertainty of a model's predictions (model prediction error) and evaluate model fit.

An example of a field monitoring trial setup in South Africa that does meet above-mentioned requirements is the trials conducted at the Langgewens Experimental Farm near Malmesbury, Western Cape (Strauss *et al.,* 2021). *Time series data on SOC sequestration over time and related minimum datasets and information, as listed above, from (benchmark) monitoring field trials were not available to the study to calibrate the SOC model component for the various summer grain production regions*. Ideally, field monitoring trials should have been set up and operated in parallel at locations for the drier regions (e.g. western North West Province and North Western Free State), central (moist) regions (e.g. eastern North West Province, Northern- and Eastern Free State), and wetter regions (e.g. Eastern Highveld and KwaZulu Natal) to account for the range in climate, soil and farming systems in the model calibration and validation for the summer grain production regions. Additional monitoring trials can also include those that represent the clayey (black turf) soils found in the Northern Free State, Brits and Rustenburg areas, and for the smallholder farmers.

8.5.1 Crop growth and development model component

Parameter values in the WinEPIC plant production module were refined until the predicted above ground dry matter and grain yield corresponded with the data provided by ASSET Research. Parameters include the biomass-energy ratio (potential unstressed above ground- and root growth rate per unit of intercepted photosynthetically active radiation) and harvest index (ratio of harvestable yield to the total biomass of a crop). The results of model calibration and resulting refinement of crop parameter input values are summarised in the respective website pages of each production region.

8.5.2 Soil organic matter (sequestration) model component

The SOM model component was evaluated against available time series data on the loss of SOC (inverse of sequestration) since time series data on SOC sequestration and related minimum datasets and information for model calibration were not (readily) available for the various regions, as discussed above. The study conducted by du Toit (1992) on the effect of cultivation on SOC was used to evaluate the soil organic matter (SOM) model component for the purposes of this study. Data from this study was used for model verification for the following reasons:

- It includes study sites at 50 locations that were distributed in all the summer grain production regions, except for KwaZulu Natal. Each location includes 6 sites of cultivated soil and 6 sites of uncultivated soil where composite soil samples were collected, thus a total 600 soil samples were analysed.
- It provides *time series data on how SOC content (stock) changed over time* for periods of over 50 years.
- The time series data could provide information on the *non-linear change in SOC loss that occurred over time* for the following stages:
  - Initial stage with high rates of SOC loss;
  - Second stage at lower rates in SOC loss; and
  - Last stage where equilibrium conditions (no- or almost no decline) in SOC content (stock) were reached.
- It includes soil analytical data required for model input in addition to the SOC contents for the studied sites. The study also includes summary of climate data for the sites, which was used in the evaluation of model predictions.
- Study results were published in the *South African Journal of Plant and Soil* (du Toit et al., 1993; 1994), and discussed in follow-up review articles in the journal (e.g. du Preez et al., 2011; Mills and Vey, 2004).

WinEPIC could predict the time series data on how SOC contents changed over time for the various study sites of du Toit (1992), following model calibration of the crop growth component and mould board ploughing is accounted for that typically occurred before the 1990s without any significant refinement of model parameter values for the conventional tillage crop scenario. This evaluation of the model therefore confirms that model simulations with WinEPIC could realistically predict how SOC content (in summer grain production regions) changes over time provided that the crop growth component is calibrated and site-specific soil properties and climate conditions are used. This includes realistic predictions on the change in SOC contents for the initial stage with high rates of changes in SOC content, followed by a second stage with lower rates in changes in SOC contents. The results of the evaluation of the SOM model component are summarised in the respective website pages of each production region. Graphs on predicted SOC content (and stock) against measured contents are included in Appendix A on the *extent that WinEPIC could predict the change of SOC over time*, including the extent that the initial period characterised by high rates of decline in SOC content could be predicted. Variability between measured SOC contents of similar years is due to spatial variability of soil properties between the locations of the sites.

8.6 Predicted soil carbon sequestration

WinEPIC modelling assumed a baseline of natural veld conditions followed by 50 years simulation of the conventional tillage (CT) scenario of the study that includes mouldboard ploughing. Similar trends and rates of losses in soil organic carbon (SOC) contents were predicted to those used during model calibration (Appendix A).

These 50 years was followed by Conservation Agriculture (CA) farming systems modelling with baseline of the CT. Results of WinEPIC modelling report on predicted soil carbon stocks over a period of 50 years of CA farming, per farming system. The results are summarised in Figure 9 and Figure 10.

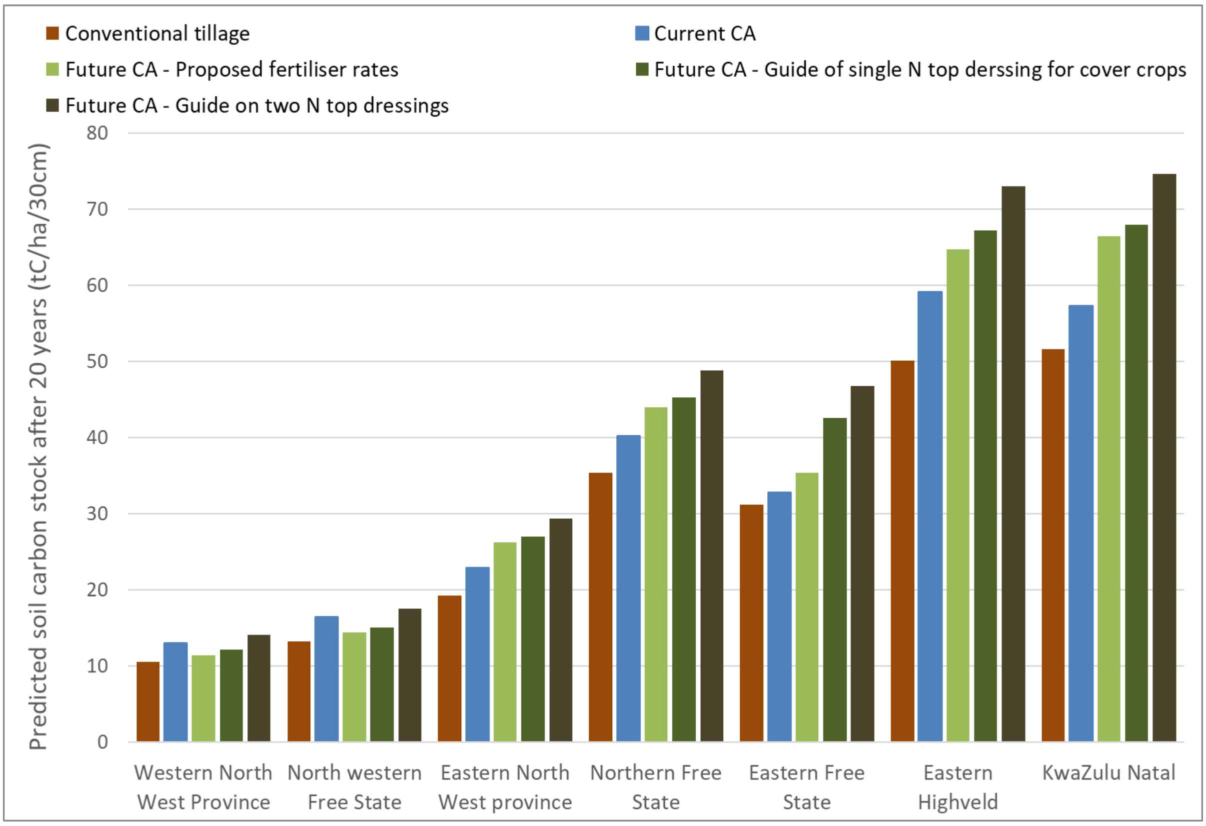


Figure 9: Predicted soil carbon stock after 20 years for different soil fertility scenarios.

The baseline carbon stocks of the numerical modelling study are in general lower compared to the stocks reported in Section 7.1 with the IPCC method. However, comparative SOC sequestration (i.e. the difference between CA and CT scenarios) were determined between the two approaches. The lower baseline of the modelling study can be ascribed to the 50 years of CT before implementation of CA systems, whereas the IPCC method is based on 20 years. 50 years of CT period was applied in the modelling study since most arable land in the summer rainfall regions is cultivated for well over 20 years. The predicted SOC at 50 years is also more representative of SOC of the considerable amounts of soils included in the National Soil Profile Database (Soil Survey Staff, 1972-2010).

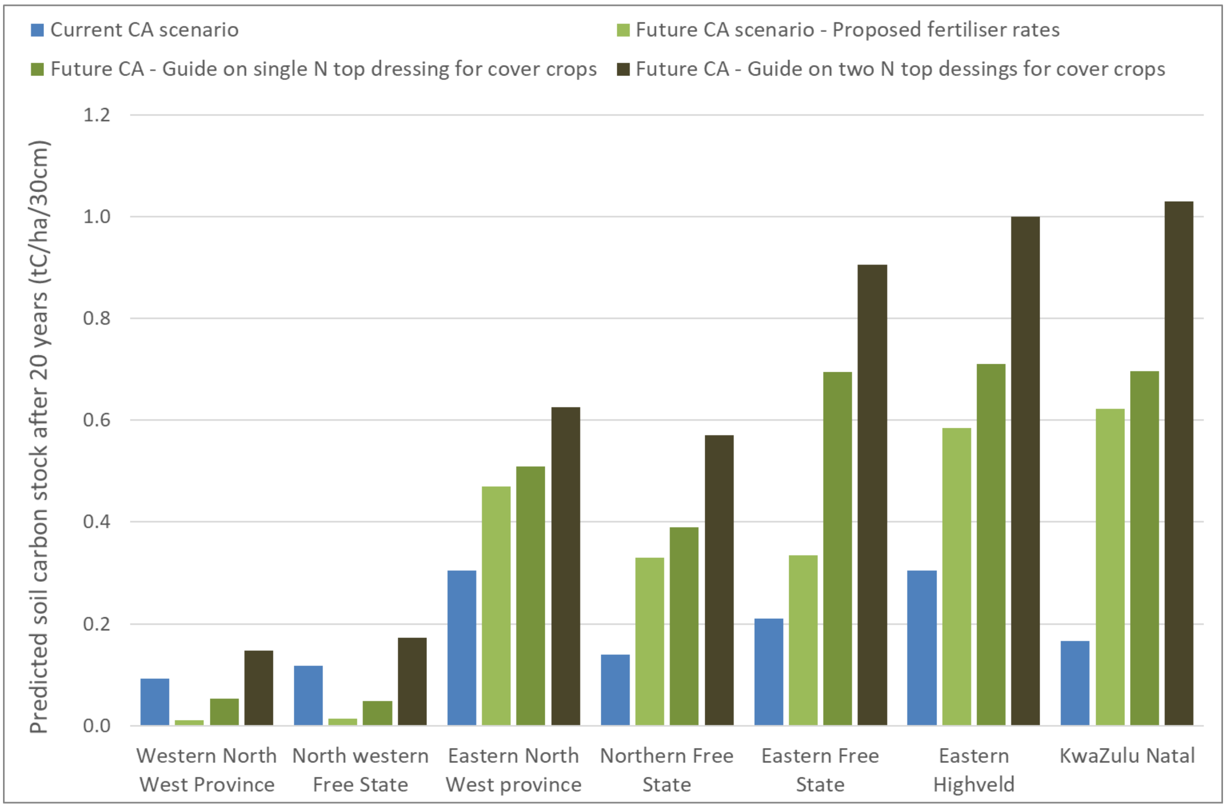


Figure 10: Predicted rate of soil carbon sequestration over 20 years.

Carbon stocks for the CA farming systems were compared with the carbon stocks of CT, with SOC stocks of natural veld as a preferred future condition. Carbon stocks are defined as the Soil Organic Carbon (SOC) contained in the upper 30 cm of soil and expressed as tonnes carbon per hectare (tC/ha).

Gains in SOC stock are markedly higher in higher rainfall areas with predominately clayey soils and visibly lower in drier areas with sandier soils. When gains are, however, expressed as a percentage of SOC levels reached with CT, the relative gains can be higher in sandier soils.

Rainfall and soil texture also determines the maximum amount of SOC that can be sequestered for a region. Predicted maximum potential SOC sequestration simulated for the CA farming system at the drier regions (western North West province and North Western Free State) is lower than the SOC stocks of natural veld. Consequently, the natural background SOC stock may not be achieved for these CA systems that include only one cover crop in the crop rotation. Predictions shows that the SOC contents of natural veld can be achieved, and even exceeded, at the other regions where the climate permits 2 or more cover crops in a rotation.

The high dry mass values (17-18.7 t/ha) that was provided for forage sorghum could not be simulated for the drier regions. A maximum dry mass of about 13 t/ha was predicted for the western North West province and North Western Free State, which corresponds to the biomass production for high yielding farming systems reported by Grain SA (2021).

Carbon stocks are the lowest in the drier North Western Free State and the western North Western Province regions, and the highest in the wetter Eastern Highveld and KwaZulu Natal regions. The drier regions are also characterised by predominantly sandier soils with a lower carbon sequestration potential than at the wetter regions that have predominantly more clayey soils.

The potential SOC sequestration achieved by changing from CT to CA systems is clearly demonstrated. As expected, CT systems showed the lowest soil carbon stocks for each region. The transition from CT to current CA and future (ideal) CA systems resulted in increased SOC stocks, with future CA systems showing higher SOC stocks. It is clear that the Future CA (FCA) system holds the most carbon stocks compared to the other systems.

Cover crops clearly emerged as the most important element in facilitating SOC sequestration in a hierarchy of which aspects of CA were more effective. The *potential benefits of cover crops are, however, limited by nutrient management,* where healthy root development is a function of both (readily available) nitrogen and carbon levels in soil. The modelling clearly demonstrated that SOC sequestration is limited by deficiencies in nitrogen and phosphorus availability in the soil and crops. This emphasises the vital importance that soil fertility is assessed regularly (preferably at same frequency than crop production) and managed accordingly to sequester SOC. Figure 11 (example from North West Province) illustrates that the initial gain in SOC (blue line) is lost after about 5-7 years for a cover crop that experiences nutrient deficiencies. The CA scenario without a cover crop, but with sufficient nutrient availability (yellow line), outperformed the cover crop scenario. However, the use of cover crops in combination of soil fertility management is the most effective manner to sequester SOC (green line). Grazing also needs to be managed. Overgrazing of cover crops can lead to some reduction in root mass and reduced nutrient storage within the soil.

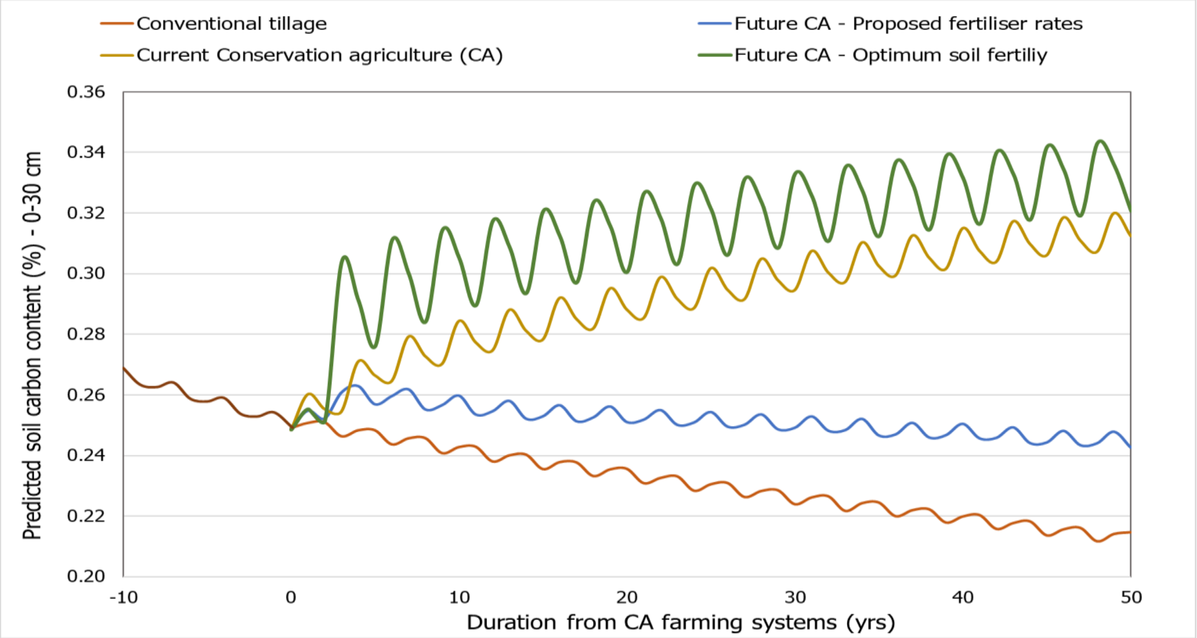


Figure 11: Importance of soil fertility to achieve desired SOC sequestration with cover crops (example from North West Province).

9. WEBSITE ON SOIL CARBON SEQUESTRATION

An important outcome of Phase 3 is to communicate and raise awareness amongst farmers with regards to the potential of CA farming systems to sequester soil organic carbon (SOC). The first objective of the study involves *inter alia* the development of an application to improve the understanding of and awareness making of potential options to sequester SOC.

The application was developed in the format of a website with the advantages to be user-friendly; a program does not have to be downloaded and installed, the website can be hosted by for instance ASSET Research and The Maize Trust to be accessible for a wide group of users, and information (such as presentations or publications) can easily be added in the future as needed.

9.1 Intent and use of website

The website intends to provide a basic, user-friendly tool to:

- Demonstrate the potential of Conservation Agriculture (CA) principles to, when applied to cropping systems, facilitate sequestration of soil organic carbon (SOC).
- Create awareness and improve understanding, among farmers and other app users, of options to improve soil carbon sequestration in summer grain production regions and resulting potential of CA farming systems to sequester SOC.

The website was developed as a tool for comparison of the effects of cropping systems, and tillage, agronomic and forage practices on SOC sequestration for use by a wide group. The website is not intended to conduct detailed analyses or modelling for the specific conditions (climate, soils, farming system and practices) of a farm, or to replace the need for professional advice related to applying CA to individual farms.

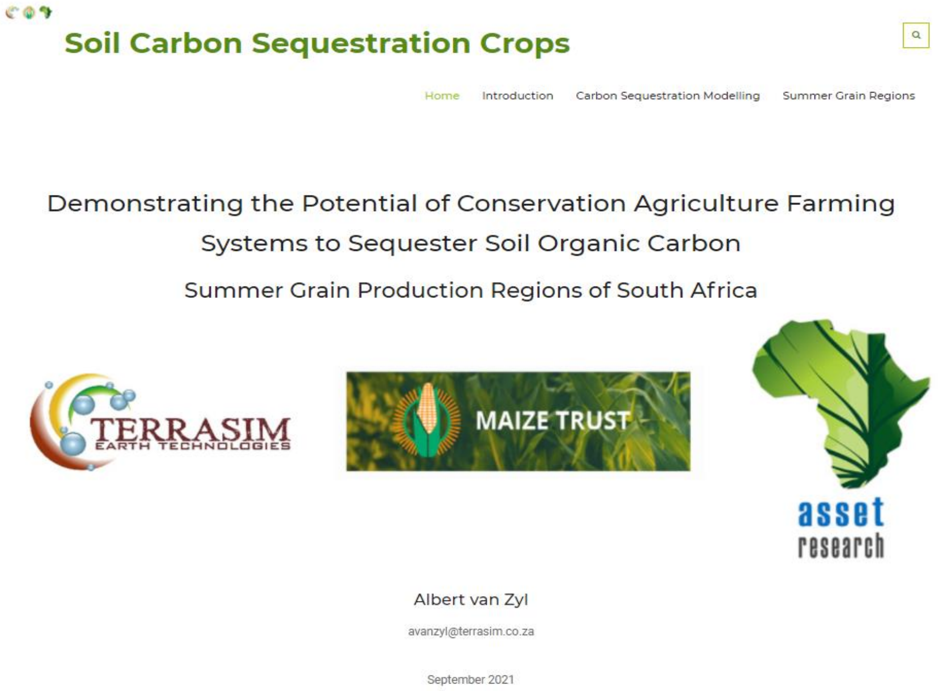
The SOC sequestration represented on the website is based on detailed numerical modelling, discussed in Section 8, which used region-specific, readily available data to create worked examples. The website allows users to select a grain production region from a drop-down menu to access a worksheet that show the effects of farming systems, crop rotation, tillage, agronomic and forage practices, and inclusion of cover crops on the potential to sequester SOC. The webpage does have the advantage that data need not to be provided by the user as the user will interact through drop-down menus.

The website can be accessed through the following link: https://soilcarbonsequestration.co.za/ The homepage of the website is shown in Figure 9.

9.2 Website layout

The website has been organised according to the following pages:

- Introduction that includes information on:
    - Intent and use of the website.
    - Disclaimer and terms of use.
    - Acknowledgement of the Maize Trust for financial support to develop the website, and Dr Hendrik Smith as project leader for his support and motivation.
    - Where further information can be obtained.



Soil Carbon Sequestration Crops

Demonstrating the Potential of Conservation Agriculture Farming Systems to Sequester Soil Organic Carbon

Summer Grain Production Regions of South Africa

Albert van Zyl

avanzyl@terrasim.co.za

September 2021

Figure 12: Website home page.

- Carbon sequestration modelling that includes information discussed in Section 8.
- Predicted effect and potential of CA farming systems to sequester SOC for the following grain production regions:
  - North West Province – western- and eastern areas,
  - North Western Free State,
  - Northern Free State,
  - Eastern Free State,
  - Eastern Highveld (Mpumalanga Province),
  - KwaZulu Natal, and
  - Smallholder farmers (Bergville district, KwaZulu Natal).

A worksheet that shows the effects of farming systems, crop rotation, tillage, agronomic and forage practices, and inclusion of cover crops on the potential to sequester SOC can be accessed by selecting the region of interest from the drop-down menu on the summer grain regions listed above (Figure 10).

The pages on the production regions include information on model data used, model calibration , and predicted effect of conventional tillage-, current CA- and future CA farming systems to sequester SOC.

- North West Province (western area)
- North West Province (eastern area)
- North Western Free State
- Northern Free State
- Eastern Free State
- Eastern Highveld (Mpumalanga)
- KwaZulu Natal
- Smallholder farmers (Bergville)

Figure 13: Drop-down menu on summer grain production regions to select region of interest.

9.3 Information provided in website pages on regions

The pages on the production regions include information on:

- Predicted effect and potential on SOC sequestration (Figure 10):
  - Farming systems (conventional tillage vs conservation agriculture systems) and crop rotations.
  - Tillage, agronomic and grazing practices.
  - Effect of inclusion of cover crops.
- Model input used on:
  - Region specific climate conditions and soils.
  - Crop systems, rotations and sequence.
  - Tillage, agronomic and grazing practices, and dates of activities.
  - Fertiliser and lime application rates for various crops used for modelling.
- Model calibration results.

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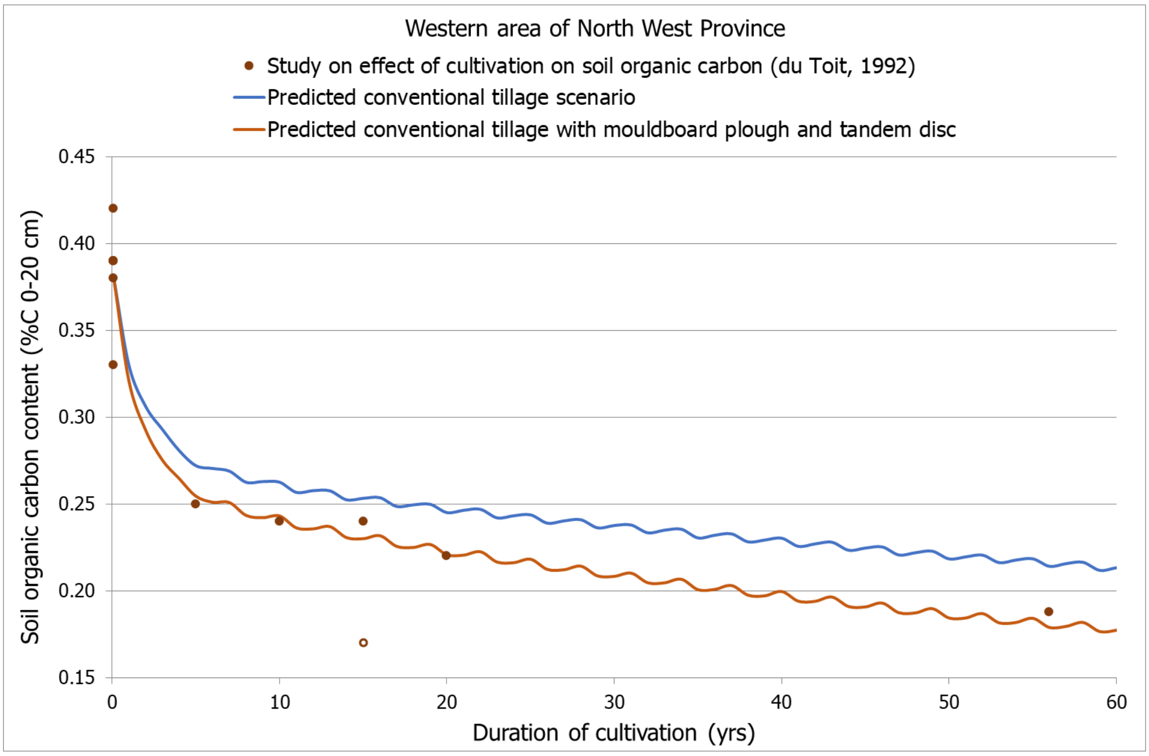
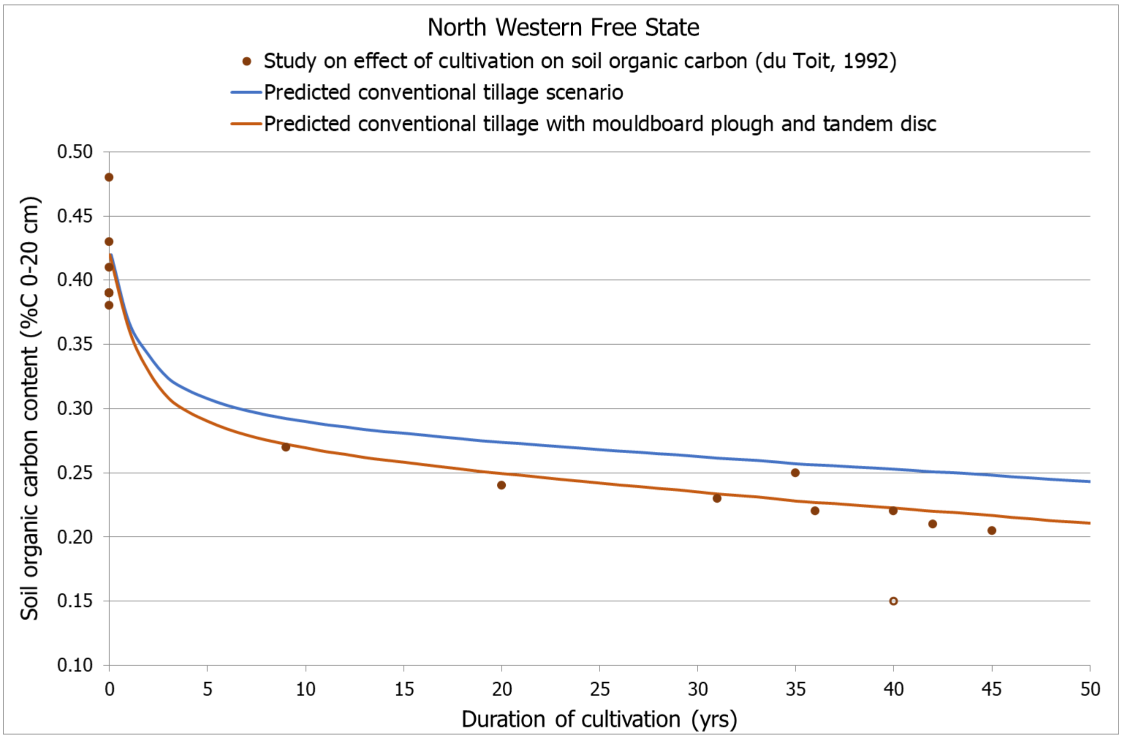
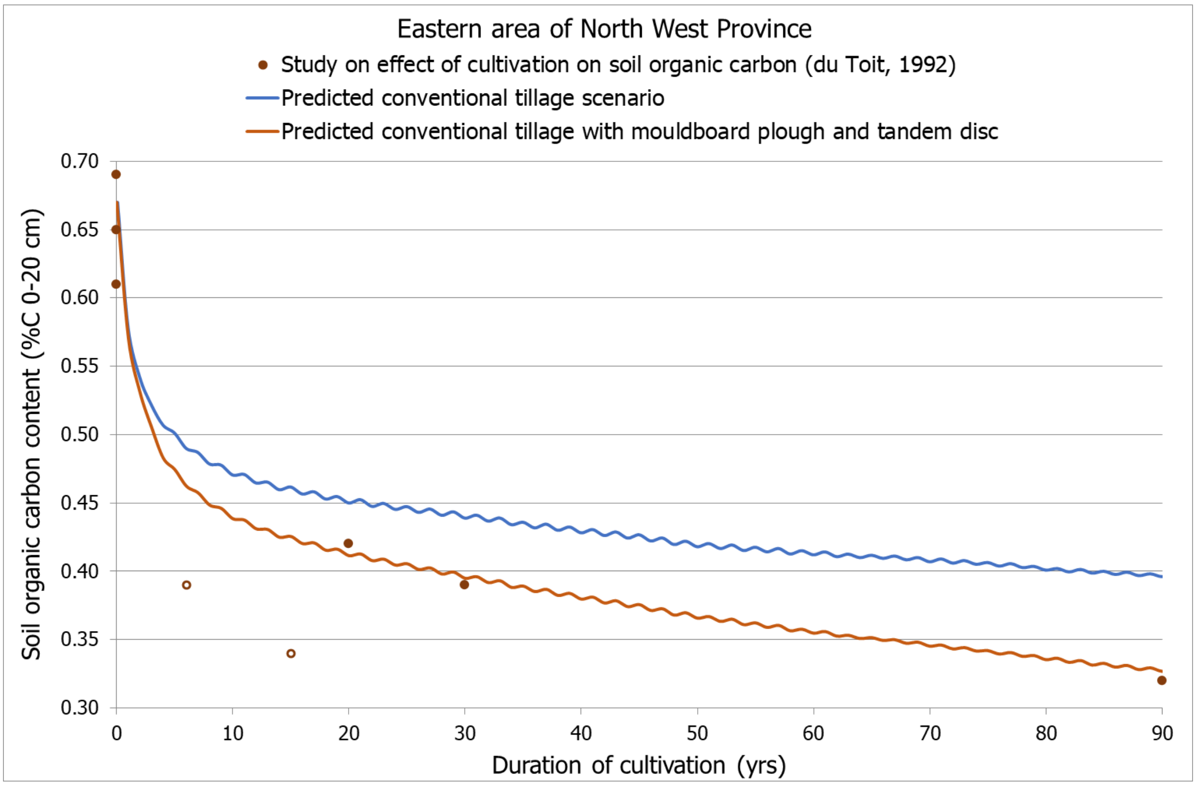
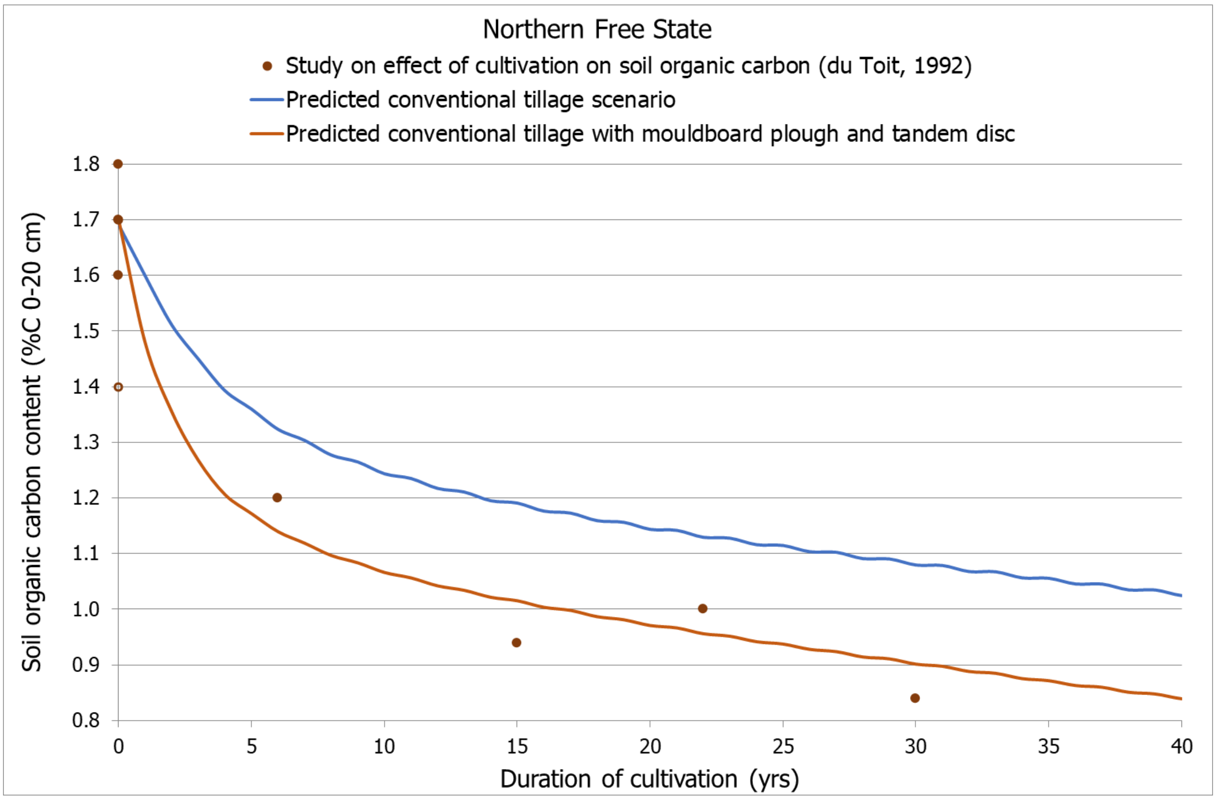
Appendix A

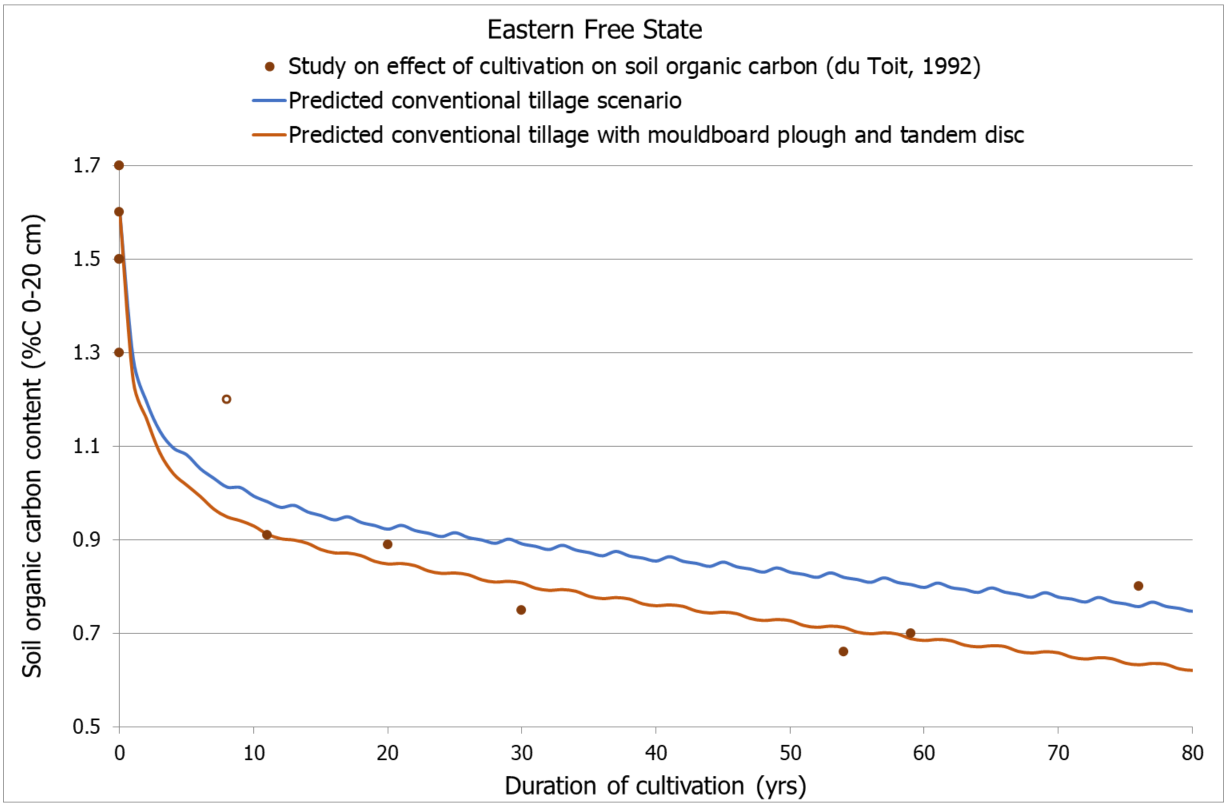
Predicted soil organic carbon contents against measured data

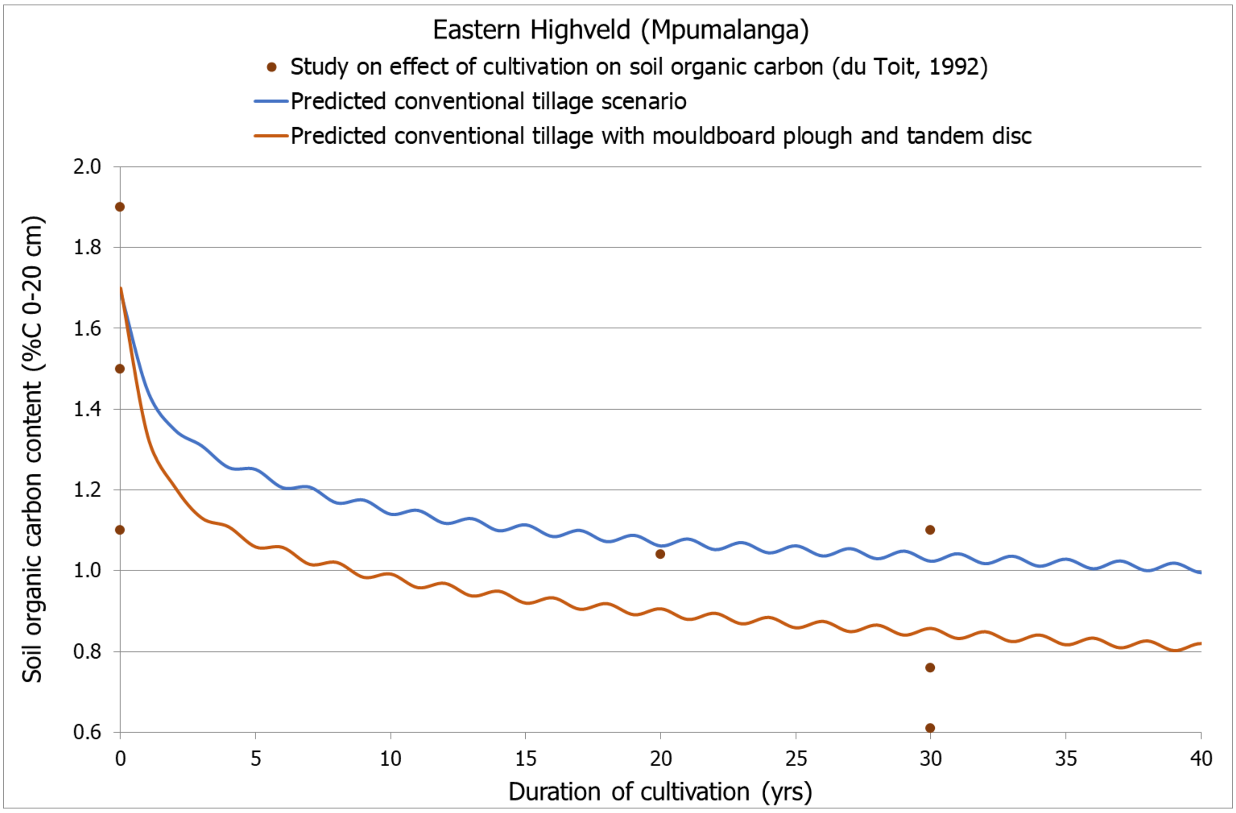





Eastern area of North West Province
Study on effect of cultivation on soil organic carbon (du Toit, 1992)
Predicted conventional tillage scenario
Predicted conventional tillage with mouldboard plough and tandem disc
Soil organic carbon content (%C 0-20 cm)
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0
10
20
30
40
50
60
70
80
90
Duration of cultivation (yrs)


Northern Free State
Study on effect of cultivation on soil organic carbon (du Toit, 1992)
Predicted conventional tillage scenario
Predicted conventional tillage with mouldboard plough and tandem disc
Soil organic carbon content (%C 0-20 cm)
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
5
10
15
20
25
30
35
40
Duration of cultivation (yrs)


Eastern Free State
Study on effect of cultivation on soil organic carbon (du Toit, 1992)
Predicted conventional tillage scenario
Predicted conventional tillage with mouldboard plough and tandem disc
Soil organic carbon content (%C 0-20 cm)
1.7
1.5
1.3
1.1
0.9
0.7
0.5
0
10
20
30
40
50
60
70
80
Duration of cultivation (yrs)


Eastern Highveld (Mpumalanga)
Study on effect of cultivation on soil organic carbon (du Toit, 1992)
Predicted conventional tillage scenario
Predicted conventional tillage with mouldboard plough and tandem disc
Soil organic carbon content (%C 0-20 cm)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0
5
10
15
20
25
30
35
40
Duration of cultivation (yrs)