SECTION 1 REPORT – Understanding the Status and Dynamics

South African National Carbon Sinks Assessment

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Please note: A report focusing on 2000 and 2010 South African Land-Cover is included at the end of the document.

Introducing Section 1 the National Carbon Sink Assessment

Rationale

To better understand the nature of terrestrial carbon stocks across South Africa and associated mitigation opportunities[*], the Department of Environmental Affairs commissioned the National Carbon Sinks Assessment. The Assessment forms part of a larger suite of activities implemented under the National Climate Change Response Policy with the purpose of:

> *"…assessing the current national carbon sinks related to afforestation, forest restoration, wetlands, agricultural practice, bio-fuels, urban greening and all significant changes in land use and to quantify the potential future carbon sinks under varying climate change scenarios and land use change."*

Three themes emerged within the broad set of aims listed in the project's initial Terms of Reference:

i. The need to understand the nature of carbon stocks and fluxes at a national scale

ii. The potential for mitigation activities, including the type and extent of initiatives, potential implementing models and associated agents, monitoring and reporting aspects, the finances thereof, employment implications and the need for institutional and extension service support.

iii. The relationship between policy and terrestrial carbon stocks in terms of both the influence of existing policy on land-use, and the need to create an enabling policy environment for mitigation activities.

This Section 1 report focuses primarily on the first theme. Prior to commissioning this scope of work there was little understanding of the nature of carbon stocks and fluxes at a national scale. Substantial work on the subject had occurred in particular locations (e.g the Skukuza, Baviaanskloof and eThekwini areas) but there was very little in terms of a national map of carbon stocks and associated fluxes. Furthermore, there was little understanding of how such stocks and fluxes may vary in the future due to either changes in land-use or climate itself.

The initial proposal by the Cirrus Group, CSIR and GeoTerraImage suggested a three-step process to address the scope of work:

1. To first map terrestrial carbon stocks and fluxes across the entire country. This component was undertaken by the CSIR and the full report is located in Module 1[†].

[*] To improve readability, for the remainder of the document "land-use based climate change mitigation activity" has been abbreviated to "mitigation activity"

[†] The full written reports for Section 1.1, 1.2 and 1.4 are included within the Modules. However, there is a substantial amount of spatial data (maps) generated during the course of the analysis which can be obtain from the CSIR or GeoTerraImage independently.

2. To model the potential effect of predicted changes in climate and atmospheric carbon dioxide on terrestrial carbon stocks and sequestration rates. The Cirrus Group principally undertook the modelling exercise with support from the CSIR's Climate Studies, Modelling and Environmental Health unit on the provision of downscaled global circulation model data (Module 2).

3. To map historical land-use change within South Africa over the 2000-2010 period and to model predicted changes in land-use over the next 10-15 years - to "2020". GeoTerraImage performed this analysis (Module 3).

In terms of the value of the analysis and its application, the outcomes of these components provide much needed data for national reporting, carbon accounting and land-use planning purposes. They have formed the foundation for the analysis undertaken in Section 2 and 3 of this National Carbon Sink Assessment and provide a crucial source of data for local planning and project development. Already, during the course of the extended stakeholder engagement undertaken in Section 2, several provincial administrations and conservation authorities as well as several District Municipalities requested access to the maps and other outcomes of this analysis for urgent planning and development needs.

An additional consideration noted in the initial project description is the need to assess the potential shift in the distribution of species (and associated vegetation types) due to predicted changes in climate. However, this subject was recently given substantial consideration during the course of the Long Term Adaption Scenario (LTAS) work that is been lead by SANBI on behalf of Department of Environmental Affairs.

Next steps

This analysis provides a good foundation for national terrestrial carbon accounting and reporting as well as associated policy and mitigation activity development. In terms of next steps:

- First, each element of Section 1 can be further developed. The models developed in Module 1 and 2 can be developed substantially and the Century modelling exercise can be extended in terms of the number of sites and vegetation types modelled or even into a spatially explicit form. An initial pertinent analysis, would be to 're-run' the model develop in Section 1.1. and 1.2 with the outcomes of the land-use change modelling undertaken in Section 1.4 and the potential impact of changes in climate and atmospheric carbon dioxide. This analysis would provide a better understanding of how the nature of the national terrestrial carbon stock may change in the future.
- Second, the manner in which the outcomes are presented could be developed into a "South African Carbon Atlas" that allows practitioners to not only access the report, but the underlying data and maps in an easy and efficient manner. As stated, several stakeholders within national and local Government, research institutions and the private sector have indicated the access to the data would be an immense help to their work.
- Thirdly, the development of the set of mitigation activities and measures identified in Section 2 will require carbon mapping and accounting services during their planning, development and execution. The outcome of Section 1.1 and 1.2 (Module 1 attached), form a good foundation for planning, but there is room to develop such models further and incorporate them further into the planning and monitoring of a national land-use based climate change mitigation program.

Module 1: (Section 1.1 and 1.2) – First estimate of terrestrial stocks

National Carbon Sink Assessment for South Africa
First estimate of terrestrial
stocks and fluxes

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our future through science

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Executive summary

The report summarized here is the first deliverable of the South African National Carbon Sink Assessment, in its second version. The report contains a description of the approach and datasets used, and the results for tasks 1.1 (mapping the geographical distribution of terrestrial carbon stocks) and 1.2 (calculating the principal greenhouse gas fluxes associated with agriculture, forestry and other land-use). The models, input datasets and outputs are undergoing peer-review, following which they will be further developed and updated prior to submission of the final version, in the last quarter of 2013. All feedback on the models, calculations and data results are sincerely appreciated. Full detail is available in the underlying report.

Approach

A continuous-variable, 'wall-to-wall' approach to mapping the stocks and fluxes in South Africa has been adopted for this study, rather than a more conventional stratified-random sampling approach. A stratified-random approach would proceed by first classifying the land area of South Africa into different vegetation- or land-use types (stratification), and then estimating of the average carbon stock in each, based on a large number of randomly-located field samples. Our approach uses geostatistical methods, models and remote sensing to extrapolate a large set (several thousand) of unevenly-distributed set field measurements to the whole country. From those continuous coverages, the mean stocks and fluxes for any area can be calculated, along with an uncertainty estimate. The reasons for this choice of approach were:

South Africa is so large and ecologically diverse that using a stratified sampling approach would require a minimum of 20 strata. Based on the observed variability within strata, the number of samples needed to constrain the uncertainty to reasonable levels would be about 100. The cost and time required to undertake new, random sampling of about 2000 sites would be excessive.

Existing data is too sparse and non-randomly distributed to adequately fulfil the needs of a stratification method. For instance, some land types have no existing data.

Recent advances in remote sensing and geostatistics make it possible to estimate aboveground woody biomass stocks (i.e., trees and shrubs) for many thousands of locations, systematically distributed over large areas, at required levels of accuracy but at low cost. Similarly, new extrapolation approaches to soil profile data, and models of herbaceous and litter biomass, allow robust but inexpensive estimates over large areas.

The emergence of these new approaches means that a continuous variable approach is both more feasible and more accurate, for a given cost, than a stratified approach.

Technical procedure

All units in this report are in gC/m^2 for stocks and gC/m^2/y for fluxes. Use of these fundamental units helps prevent errors when adding up the various components, but they are hard for most people to imagine. To convert gC/m^2 to metric tonnes per hectare, divide by 100. Dry biomass is approximately half made up of carbon, thus to convert carbon (C) to dry matter (DM) divide by 0.45. To convert C fluxes to CO_2 terms (used, for instance, in the national greenhouse gas inventory) multiply by 44/12.

The national carbon stock 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. The carbon flows between the pools, and between the land and the atmosphere, land an ocean, and land and human systems are called fluxes (Figure 1).

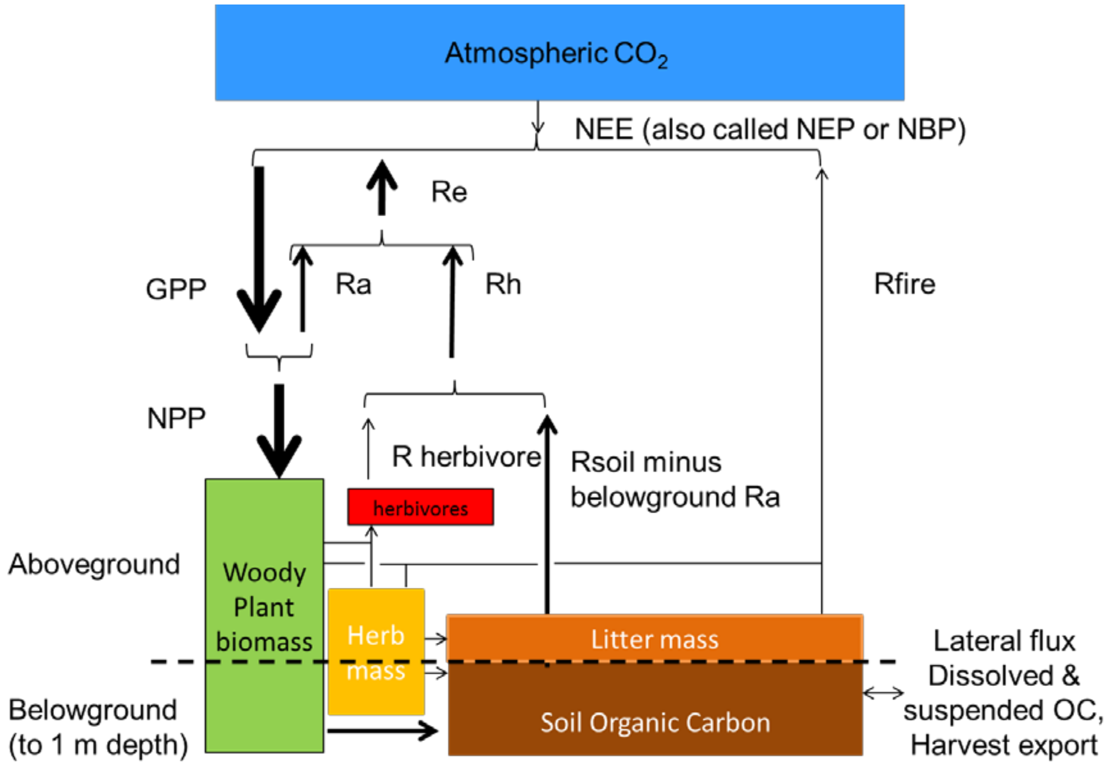
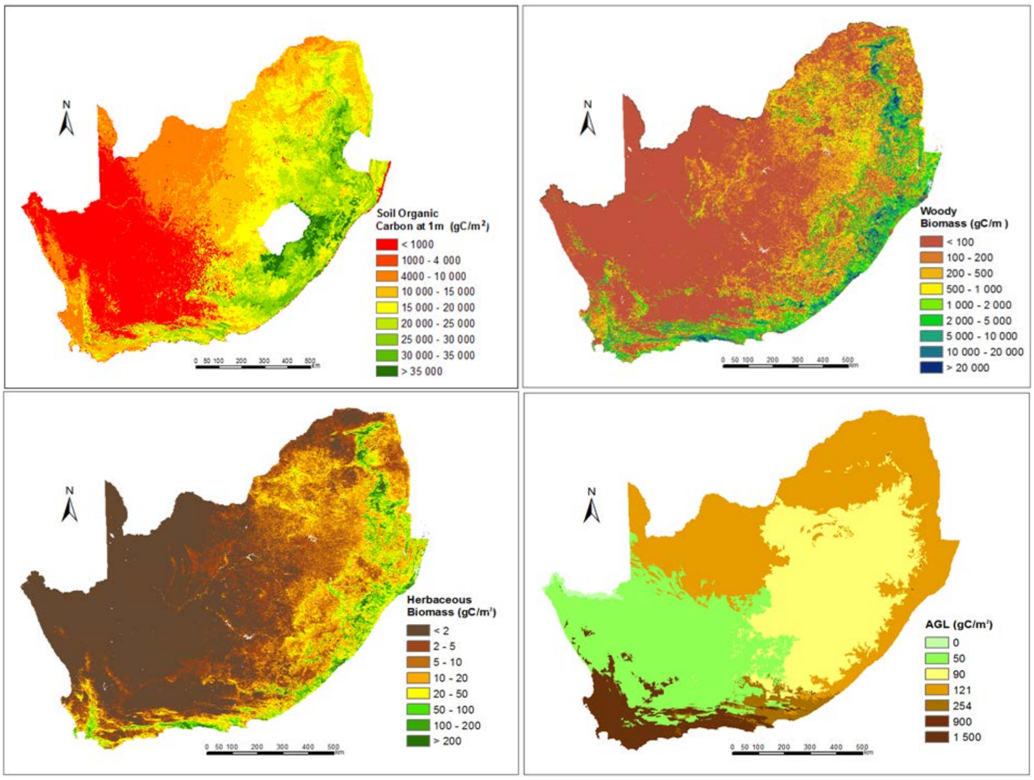


Figure ES1. Components of a generalized terrestrial carbon cycle: The size of the boxes and the arrows, which represent stocks and fluxes respectively, is only roughly indicative of their relative size. The herbivore stock is relatively small (<10^{12}gC nationally), and neither it nor the corresponding herbivory flux is directly evaluated in this study. *Terminology: NEE – Net Ecosystem Exchange, NEP – Net Ecosystem Productivity, NBP – Net Biome Productivity, GPP – Gross Primary Production, NPP – Net Primary Production, Ra – autotrophic respiration (respiration by plants) , Rh – heterotophic respiration (herbivores, carnivores and microbes), Re – ecosystem respiration (the combined respiration from all sources), Rfire – fire emissions.*

The size of each major carbon pool was estimated for every 1000 x 1000 m pixel across the range of different land-use and vegetation types in South Africa, and then summed to estimate the total carbon stock in the country (TEOC – total ecosystem organic carbon, Figure 2). The above-ground woody plant biomass was estimated using remotely-sensed tree height (from ICESAT-GLAS) and canopy cover (MODIS). The corresponding belowground biomass was estimated using published root:shoot ratios, scaled by environment. Above-ground herbaceous and litter biomass was calculated using published relationships between rainfall and annual grass and litter production and expanded to belowground herbaceous biomass using published root:shoot ratios. Soil organic carbon to 1 m depth, corrected for soil bulk density variation, was from the recently-released AfSIS Africa Soil Property map, based on over 3000 soil profiles in South Africa and a further 6000 elsewhere in Africa and a Bayesian statistical extrapolation technique taking into consideration the many factors relevant to soil carbon formation. The location and area of converted land-use types (cultivated lands, plantation forests and urban areas) were obtained from 30 m resolution land cover maps more recent than 2005. Soil and biomass stocks within the converted classes were calculated from forestry and agriculture sector databases, usually at municipal scale resolution.

The magnitude of the main fluxes from unconverted (‘natural’) systems, which dominate the South African landscape, were estimated using ecosystem-specific carbon cycle models, driven by 10-daily satellite observations of surface greenness (MERIS FAPAR) over the period 2001 to 2010 and constrained by monthly climate data. The fluxes in cultivated and plantation areas are estimated from crop and forest production data respectively, and the lateral fluxes in and out of the national territory from trade statistics and measurement-based models.



Map ES1. The components of the terrestrial carbon stock of South Africa. Top left: soil organic carbon to 1m in depth. Top right: the above- and below-ground woody-plant biomass pool Lower left: above- and below-ground herbaceous biomass pool. Lower right: above-ground litter

Terrestrial Carbon Stocks In South Africa

The main determinants of terrestrial carbon stocks are plant-available moisture, temperature, soil conditions and vegetation cover. Soil, woody-plant and herbaceous biomass carbon stocks increase from the arid areas in the western part of the country, to the moister eastern seaboard of South Africa. Carbon stocks in the Karoo and desert biomes are very low, while the highest carbon stocks per hectare are found in the coastal and montane forests. The spatial extent of these forests (and plantation forests) is small compared to the extensive grassland and savanna biomes, which have intermediate per-hectare carbon stocks, and thus dominate the national stock accounts (Tables 1 and 2). The grassland biome contain many planted trees, which add to their carbon stocks. Carbon stocks in the fynbos are quite low, due to frequent fires. Stocks in intact thickets are quite high given the dry environments in which they occur in the southern and eastern Cape, but their spatial extent is small.

The biomass estimates have been validated against a database of over three hundred plots nationally, collected completely independently of this study. Overall they are in fair agreement. It is not possible to say which is ‘right’, since both contain uncertainty. The soil carbon estimates have been independently validated against a database of nearly 200 very detailed soil carbon studies in three biomes: savannas, grasslands and thicket, and found to be in fair agreement. Croplands are mostly in former grasslands. Their soil carbon in the top 30 cm is approximately halved as a result, while the crop biomass is similar to the original grass biomass.

Table ES1. Terrestrial total ecosystem carbon stocks in South Africa by land cover class. SD stands for standard deviation, which is a measure of the spatial variability of the stock, which would need to be dealt with by collecting a large number of samples using a stratified-random approach. A continuous, total coverage approach as applied in this project has no sampling error, only an estimation error due to uncertainties in the models used. This estimation error is reflected as a lower (10%) and upper (90%) confidence limit in the totals for the entire class, on the right hand side of the table. These limits have been calculated using a rigorous error accumulation approach. Note that stratified sampling approaches *also* contain estimation errors of the same magnitude (in addition to sampling errors), but these are almost never accounted for.

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		km^2		Tg C	
Savanna	5834	3513	358473	2091	1961	5214
Grassland	10660	4725	224377	2392	2213	5736
Nama and succulent karoo	1769	1799	334812	593	587	862
Fynbos	6773	4100	61490	416	372	1140
Thicket	10101	5347	27402	277	236	785
Indigenous forest	18198	6172	857	16	12	42
Desert	799	113	7017	6	6	6
Cultivated	5980	1731	143948	860	840	1788
Plantation forestry	17559	4320	16952	298	252	769
Settlement, mines, industry	6793	2448	23119	157	152	276
Other, waterbodies etc	3167	1536	19967	64	62	97
Total South Africa			1218414	7170	6693	16715

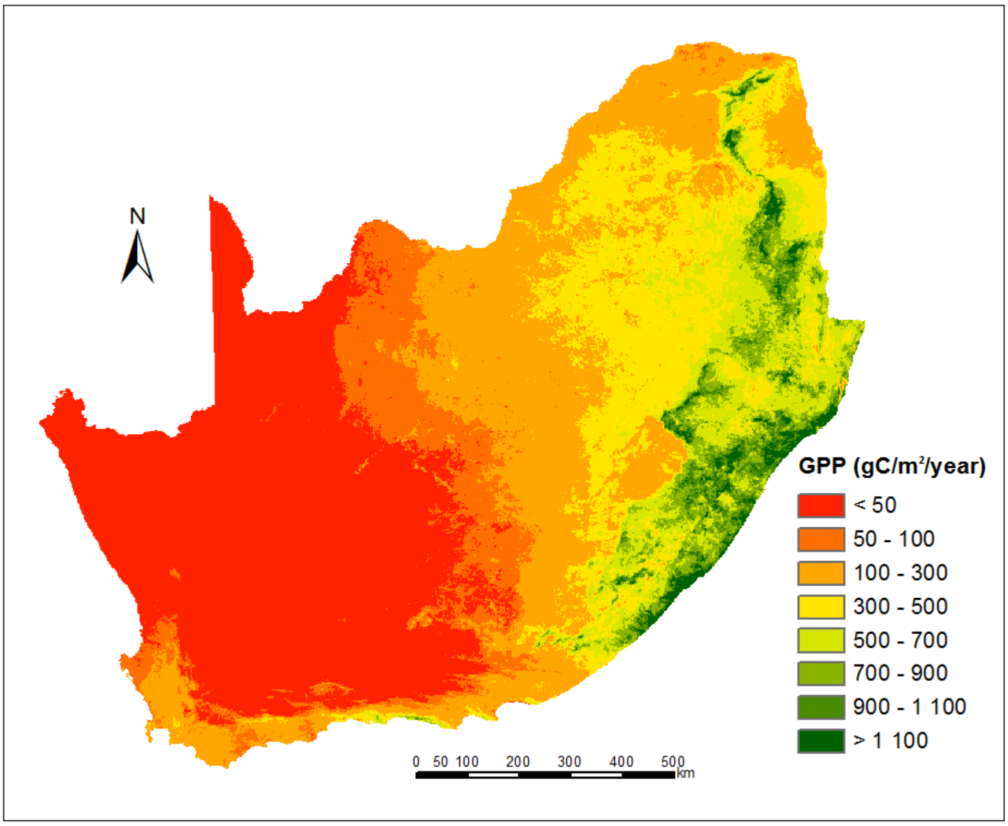
Table ES2. Soil organic carbon stocks in South Africa to a depth of 1 m, by land cover class. Soil organic carbon is the largest part of the ecosystem stock in all South African ecosystems, and the most stable. The AfSIS data extrapolation procedure did not extend into the driest, hottest third of the country, which have relatively low carbon stocks. We assumed a total soil carbon content to 1 m of 700 g/m^2 for these areas. The notes regarding the measures of spatial variability (standard deviation, SD) and estimation uncertainty (lower and higher confidence limits) apply to this table as well.

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		**km^2**		**Tg C**	
Savanna	5422	3078	358473	1943	1779	7138
Grassland	10149	4427	224377	2277	2008	7671
Nama and succulent karoo	1700	1744	334812	569	339	1872
Fynbos	5658	3854	61490	348	305	1301
Thicket	7737	3298	27402	212	189	772
Indigenous forest	11057	3497	857	9	8	30
Desert	833	112	7017	6	1	12
Cultivated	5785	1704	143948	835	774	2547

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		km^2		Tg C	
Plantation forestry	12961	3553	16952	220	193	663
Settlement, mines, industry	6375	2379	23119	148	136	414
Other, waterbodies etc	2819	1375	19967	57	50	135
Total South Africa			1218414	6624	5781	22555

Terrestrial Ecosystem Carbon Fluxes in South Africa

In the undisturbed 'equilibrium' state, Gross Primary Production approximately equals ecosystem respiration (Reco + Fire) over the long-term and at large scales. Simply put - for all the additional carbon that is accumulated in biomass through plant growth each year, an equal amount is released back into the atmosphere through respiration and fire. Although South Africa is not 'undisturbed' and the global carbon cycle is currently not at equilibrium, the balance between production and respiration remains quite close to zero. For instance, regional atmospheric CO_2 inversion analyses, completely independent of this study, suggest that the net southern African flux is small to zero. With rising atmospheric CO_2 and a changing climate, the *global* terrestrial land surface is currently a sink of about 1 PgC/y (Pg = Petagram or 10^{15} grams). A small part of this sink is probably in South Africa, due to processes such as bush encroachment. It would be somewhat less than the South Africa fraction of the global land area (1%) because South Africa is both more arid and hotter than the global average. A rough estimate would be 1-10 TgC/y (Tg – Teragrams or 10^{12} grams), which translates to around 1-10 gC/m^2/y. This would be very hard to detect over a short accumulation period, but should be detectable of a period of decades.



Map ES2 Distribution of Gross Primary Productivity (GPP) in terrestrial ecosystems in South Africa. GPP is the carbon which is taken out of the atmosphere into plant biomass through the process of photosynthesis. About half of this returns to the atmosphere within hours to months through respiration by the plant. What remains is Net Primary Production (NPP), which is the basis of production-based ecosystem services such as timber and crop yield, firewood and grazing. NPP is not equivalent to carbon storage, since most of the NPP is also ultimately respired, burned or exported. NPP does establish an upper limit to the short-term carbon sequestration rate in carbon storage projects. It is clear from this map that the potential for such projects is greatest in the wetter parts of the country, where they also come into conflict with land needs for agriculture, settlement and water provision.

Implications of this study for policy and implementation

This assessment is the first to generate a map of terrestrial carbon stocks and fluxes at national scale, with fine resolution. It results in a better understanding of how carbon stocks and fluxes vary across the country, and thus which particular biomes or areas are most and least important in terms of developing land-use based Greenhouse Gas (GHG) emission reduction activities. For example, whereas the forest biome has significant carbon stocks per hectare, due to its limited spatial extent, the total carbon stock located in forests is amongst the lowest when comparing vegetation classes (Table ES1). In comparison, the grassland and savanna biomes together contain approximately three-quarters of South Africa's terrestrial carbon stock and account for over 90% of Gross Primary Production occurring within the country (Table ES3). If land-use based climate change mitigation activities are to be created that contribute significantly to the national greenhouse gas budget, the emphasis should therefore be on developing implementation models that work within these biomes. Projects in smaller, but nevertheless high-stock potential and high-sequestration rate vegetation types, such as forests and thickets, may be viable at project scale, but can only make a limited national contribution. The potential in the arid biomes for projects which are both viable and nationally meaningful is very small.

The bulk of carbon is stored in the soil, which currently does not count towards many carbon storage projects. Woody biomass is the next largest store. The stores in herbaceous biomass and litter are too small, and too ephemeral, to matter very much. The lateral fluxes as forestry and agricultural exports, carbon in rivers and smoke from fires are small relative to the gross vertical fluxes and the national anthropogenic inventory, but are significant relative to the net natural fluxes and would need to be considered.

The annual flux in and out of natural ecosystems, at about 1100 $TgCO_2$/y, is over twice the emissions from South Africa from anthropogenic sources. Only about one hundredth of this is the 'net ecosystem production' retained in ecosystems as a carbon store. This will be very hard to measure and prove at national scale on a year-by-year basis, but may be detectable on a decadal basis.

Table ES3. Gross Primary Production (GPP) of terrestrial natural ecosystems in South Africa. GPP is the carbon taken up by the vegetated surface from the atmosphere. It is about twice the Net Primary Production, which is what is retained as biomass growth after the plant has respired part of the uptake to support its own metabolism. Estimation error calculations are in progress. Validation of these fluxes using direct measurement is only possible for a few sites in the country. They are consistent with global-scale model-based estimates.

Land cover class	Mean	SD spatial	Area	Best estimate	Lower confidence limit	Upper confidence limit
	$gC/m^2/y$		km^2		TgC/y	
Savanna	415	320	358473	149	54	351
Grassland	645	304	224377	145	72	361
Karoo	44	46	334812	15	5	34
Fynbos	142	134	61490	9	2	19

Land cover class	Mean	SD spatial	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2/y		km^2		TgC/y	
Thicket	381	264	27402	10	2	23
Desert	977	281	857	1	0	2
Forests	1	0	7017	0	0	0
Total, natural ecosystems			1014428	329	135	790

National greenhouse gas inventories are periodically required from South Africa as a party to the UN Framework Convention on Climate Change. One category of emissions (or uptakes) is from the Agriculture, Forestry and Other Land Use (AFOLU) sector. The AFOLU sector estimates thus far have had the highest uncertainty associated with them, partly because there was no reliable map of the distribution of soil or biomass carbon in the country, with the fine resolution required to calculate the impacts of land use change. This project satisfies that need.

Background and Purpose

This document represents the second version of the first deliverable of the National Carbon Sink Assessment for South Africa project. It reports the output for tasks 1.1 (mapping the geographical distribution of carbon stocks) and 1.2 (calculating the principal fluxes). The key revisions relative to the first version draft of 31 March 2013 are the inclusion of the AfSIS soil carbon data; detailed data-based calculations for transformed land; error estimates for most calculations; an estimate of lateral fluxes and a comprehensive validation section. This version is intended for peer review. After the consideration of review comments a final version will be submitted.

The report describes the scheme by which the stocks and fluxes are estimated in detail, along with the sources of data, and validation details. The models have been set up in the VisiTrails environment (an open-source software for organising complex calculations). The updating of the models as improved algorithms or datasets become available is likely to be an ongoing activity since the stocks and sinks will need to be recalculated on a periodic basis, taking into account new scientific developments and changing land use and land cover.

A continuous-variable, 'wall-to-wall' approach to mapping the stocks and fluxes in South Africa has been adopted for this study, rather than a more conventional stratified-random sampling approach. A stratified-random approach would proceed by first classifying the land area of South Africa into different vegetation- or land-use types (stratification), and then estimating of the average carbon stock in each, based on a large number of randomly-located field samples. Our approach uses geostatistical methods, models and remote sensing (satellite imagery) to extrapolate a large set (several thousand) of unevenly-distributed set field measurements to the whole country. From those continuous coverages, the mean stocks and fluxes for any area can be calculated, along with an uncertainty estimate. The reasons for this choice of approach were:

South Africa is so large and ecologically diverse that using a stratified sampling approach would require a minimum of 20 strata. Existing data is too sparse and non-randomly distributed to adequately fulfill the needs of a stratification method. For instance, some land types have no existing data. Based on the observed variability within strata, the number of samples needed to constrain the uncertainty to reasonable levels would be about 100. The cost and time required to undertake new, random sampling of about 2000 sites would be excessive.

If the strata are subdivided sufficiently finely to achieve 'near-homogeneous patches' each requiring only a modest number of samples, the number of such locations becomes very large, and a stratified approach begins to resemble a continuous field approach. Fortunately, recent advances in remote sensing make it possible to estimate aboveground woody biomass stocks (i.e., trees and shrubs) for thousands of locations that are systematically distributed over large areas, at required levels of accuracy but at low cost. Similarly, new extrapolation approaches to soil profile data, and models of herbaceous and litter biomass, allow robust but inexpensive estimates over large areas. This meant that a continuous variable approach was both more feasible and more accurate for the available resources than a stratified approach. The methods applied here are similar to those being developed for use in REDD+ projects, which have come to similar conclusions regarding sample-based versus continuous approaches.

The estimated coverages of carbon stocks and fluxes can be post-stratified in many different ways – for instance, by biome, climate class or political jurisdiction – and have a spatial resolution (1 km^2) adequate to look at quite fine-scale features, such as large regional carbon storage projects. During the course of the National Climate Change Response Stakeholder Workshop hosted by the Department of Environmental Affairs in June, several participants noted applicability of the data at a provincial and municipal scale where carbon stock maps are required to develop local-scale mitigation interventions. Adequate local maps of carbon stocks and fluxes are not currently available and can quite easily be 'cookie-cut' from this data set.

The purpose of this document is to record the procedure and to familiarise stakeholders, including the South African Department of Environment Affairs, with the approach adopted and the intended products of the project. The maps allow a general reality check on the calculations. The results and the associated error calculations allow realistic planning of future steps. The post-review, final version of this report can be used as an input to the national communications to the United Nations Framework Convention on Climate Change. It remains highly unlikely that the difference between successive stock assessments, at national scale and a few years apart, will ever be precise enough to determine absolute changes in stock in a scientifically rigorous way. The trend in the national terrestrial C stock is likely to be less than 1% per year - but even with the best technology (regardless of whether a continuous variable or stratified approach is adopted) the stock cannot be estimated with an absolute precision of less than about 10%. Furthermore, the natural inter-annual variation in the fluxes may be as high as 30%. It may be feasible to observe changes in the stocks, through measurement, over a period of a decade or more. Shorter-interval changes can be inferred from land cover changes, with a reduced level of certainty.

The scientifically valid use of this information is to understand the magnitude and distribution of the various stocks and fluxes, in order that their potential contribution to a South African climate change mitigation effort can be evaluated. These results will help to evaluate the realism of project-level claims and will improve the estimates of emissions and uptakes from the Agriculture, Forestry and Other Land Use (AFOLU) sectors in the national greenhouse gas assessment. In addition, it provides a foundation for the development of national- or provincial-scale carbon sequestration and avoided deforestation (REDD) activities.

Technical procedure

The stocks and fluxes as defined in this project are schematically represented in Figure 1.

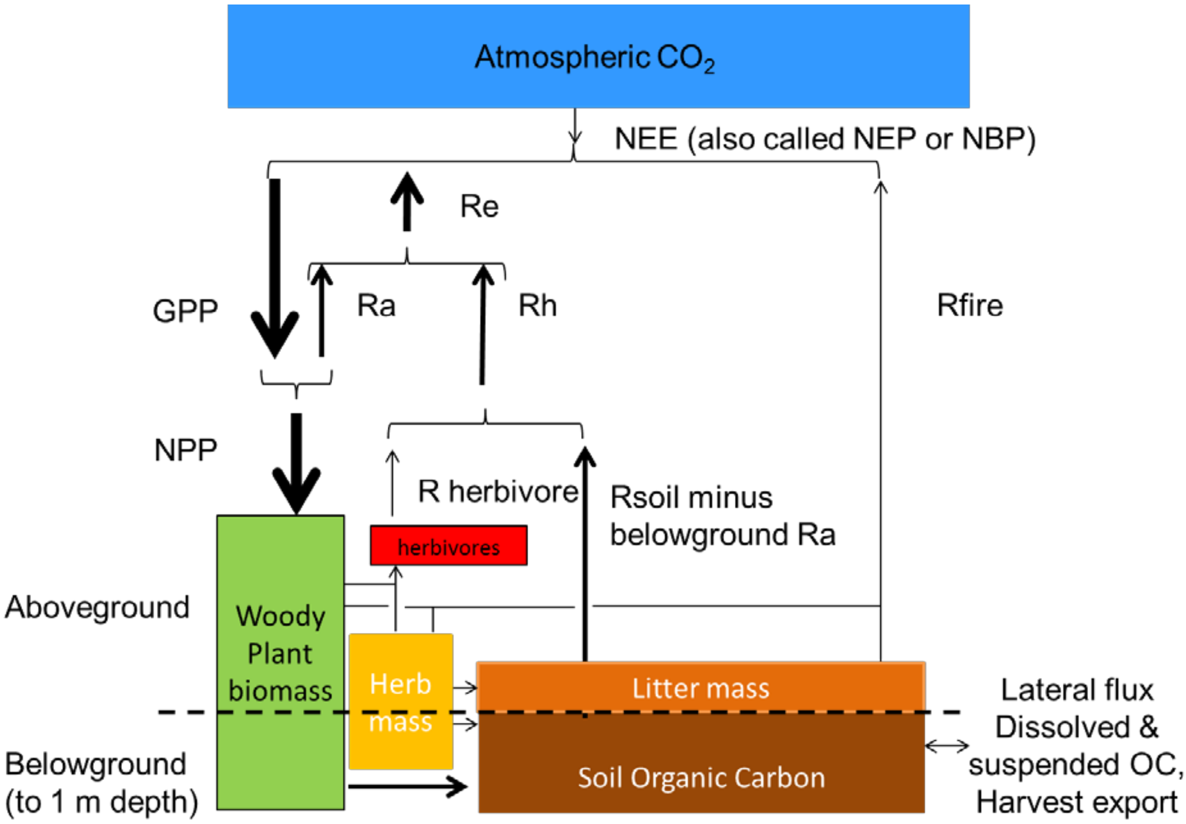


Figure 1. *Components of a generalised terrestrial carbon cycle. The size of the boxes and the arrows, which represent stocks and fluxes respectively, is roughly indicative of their relative size. The herbivore stock is relatively small (<10^{12}gC nationally) , and neither it nor the corresponding herbivory flux is directly evaluated. Terminology: NEE – Net Ecosystem Exchange, NEP – Net Ecosystem Productivity, NBP – Net Biome Productivity, GPP – Gross Primary Production, NPP – Net Primary Production, Ra – autotrophic respiration (respiration by plants) , Rh – heterotophic respiration (herbivores, carnivores and microbes), Re – ecosystem respiration (the combined respiration from all sources), Rfire – fire emissions.*

Error propagation

The top-level products of this study are accompanied by error estimates, defined as the likely range for a given level of confidence (such as 80%). They take into account the error of estimation associated with uncertainty in the measurements and models. Since the whole country is measured there is no statistical sampling error. The inherent spatial and temporal variability of carbon stocks and fluxes is reflected separately in the tables, as the spatial standard deviation (SD). This should not be confused with sampling error that is usually reported in carbon stock assessments that have taken a stratification approach.

In order to estimate the top-level error, the underlying errors in each of the variables that went into the calculation must be known or estimated. Where possible, and especially for values that make a large contribution to the overall error, these are statistically-rigorous, data-based derivatives of the variance. For factors where the data are sparse (n<5) or where the factor makes a small contributions to the overall error (<5%), an expert-based assessment of the variance (σ^2) has been made.

The propagation of error in the equations used in this study are mostly covered by the two rules outlined below, used alone or in combination.

For the sum (or subtraction) of statistically-independent, normally distributed variables with a variance denoted σ^2, the overall error is given by:

Error = sqrt ($\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \ldots + \sigma_n^2$)

For the product of n statistically-independent, normally-distributed variables each with a variance denoted σ^2 and an expected value of q, where the overall expected value is Q, the overall error is given by

Error/|Q| = sqrt ($(\sigma_1/q_1)^2 + (\sigma_2/q_2)^2 + (\sigma_3/q_3)^2 + \ldots + (\sigma_4/q_4)^2$)

Basis for calculating stocks

The working units for stock estimates are gC/m^2 ($1\ g/m^2 = 0.01$ t/ha, where t is a metric tonne = 10^6g, which is properly denoted Mg). For national sums we use TgC (10^{12}g), which is a million tonnes (teragrams).

Natural and semi-natural vegetation covers

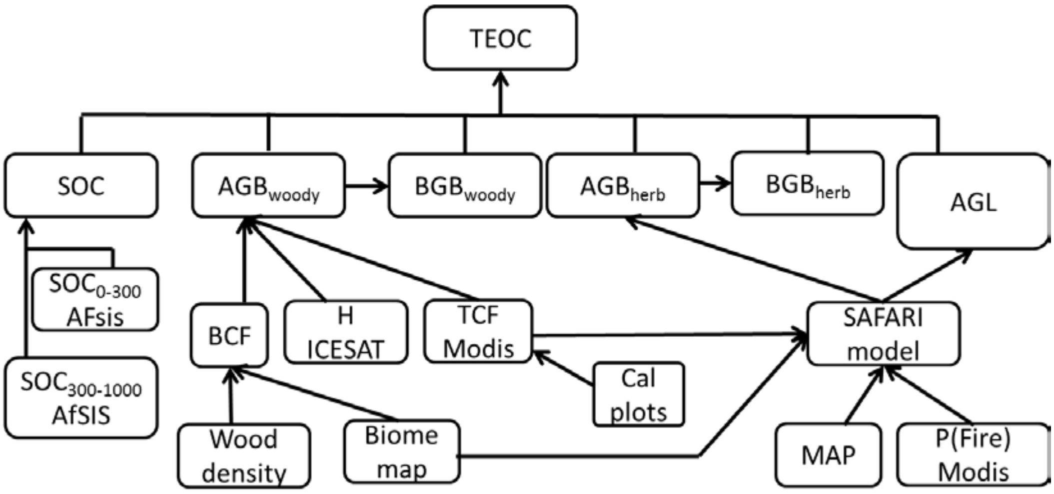


Figure 2 The workflow for calculating terrestrial carbon stocks

- TEOC = SOC + (AGB_{woody} + BGB_{woody} + AGB_{herb} + BGB_{herb} + AGL)*CF
- TEOC= total ecosystem organic carbon
- SOC=Soil Organic carbon to a depth of 1 m
- AGB_{woody}=Aboveground biomass in woody plants (leaf+stem biomass of perennial, lignified plants, regardless of height – trees, bushes and shrubs)
- BGB_{woody}=Belowground biomass in woody plants (fine+coarse roots of perennial, lignified plants)
- AGB_{herb}=mean annual maximum aboveground biomass of herbaceous plants (predominantly grasses, but also forbs, restios, sedges etc)
- BGB_{herb}=mean annual maximum belowground biomass of herbaceous plants.
- AGL = Aboveground litter
- CF = carbon fraction ie C=CF*DM ; = 0.42 (references: Safari 2000, Parton et al)

The error in TEOC is determined from the error in its parts, using a combination of additive and multiplicative rules. Note that BGB is in both cases derived from AGB, they are not independent.

Soil organic carbon (SOC) is derived from the AfSIS system (http://www.africasoils.net/data/digital-soil-mapping Markus Walsh). AfSIS uses a Bayesian prediction model, based on 12000 African pedons (about 3600 of which are from South Africa) driven by many covariates (among others, climate, soil texture, and topographic position) to estimate the SOC to any given depth (0-0.3 m is the standard for 'topsoil', while 0.3-0.7 m is used for subsoil) at a given location. These are integrated spatially at a ground resolution of 1 km to provide a national surface. The SOC surfaces are accompanied by a surface representing the estimation error, defined as the 10 to 90 percentile confidence limits at each point. The lower and upper confidence ranges are assymetric – there is a long 'tail' of possible SOC values much higher than the best estimate. Since SOC dominates the TEOC, this uncertainty and its assymetry propagates through, and has forced us to adopt the 10-90 range for the uncertainty estimates of other components as well. The confidence range cannot be easily reduced by increased sampling effort, since it depends rather on the measurement and extrapolation technology. Note that the lower (more conservative) limit is much closer to the 'best estimate', and it is the one which matters more.

The SOC data comes in the form of %SOC, which is converted to absolute gC/m^2 using the following formulae for the topsoil and subsoil respectively.

$SOC_{0\text{-}300mm} = \rho_{0\text{-}300mm} *0.3*\%SOC/100*1\ 000\ 000$
$SOC_{300\text{-}1000mm} = \rho_{300\text{-}1000mm} *0.7*\%SOC/100*1\ 000\ 000$
$SOC_{to\ 1\ m} = SOC_{0\text{-}300}+SOC_{300\text{-}1000}$

ρ is the soil bulk density (Mg/m^3). The AfSIS data does not currently include a correction for stone content, which will lead to overestimation of the profile SOC in stony soils.

AGB_{woody} is estimated using the product of tree cover and height as a proxy for the volume of the tree or shrub, which is in turn linearly related (using the constant BCF_{biome}) to aboveground biomass:

$AGB_{woody} = (H_{veg} * TCF) * BCF_{biome}$

H_{veg} is the mean maximum height of the vegetation at a location (m) interpolated from ICESAT-GLAS point records, obtained from the NASA Jet Propulsion Lab (Simard et al 2011, Sassan Saatchi pers com) and from the Woods Hole Institute (Buccini et al 2008). The ICESAT-GLAS data, which represents a laser 'spot' about 80 m in diameter, is unlikely to be reliable for small vegetation patches, or in steep topography. It may also be unreliable for closed canopy. The high-slope areas were masked out and then patched-in from the national vegetation map, with an estimate of their AGB based on adjacent level areas, or published studies. For fynbos a completely different approach was used, based on modelling the biomass accumulation since the last fire, given the rainfall.

TCF = tree cover fraction (dimensionless 0 to 1: the values are given as a percentage and are divided by 100 before use) from the MODIS satellite based sensor.

BCF is the Biomass Calibration Factor, which in principle varies by biome or sub-biome. For the savanna biome, where it varies between different savanna types from 1100 to 1900 gC/m^3 (erroneously given as 29.6 to 44.4 MgDM/ha in original Colgan et al (2012) reference). Much of this variation can be accounted for by wood density and form factor which can be related to the VegMap savanna classes. We use 1100 gC/m^3 since it corresponds to the combined savanna dataset, and has an error of about $\pm$20%. For the thicket biome the BCF is calibrated against a reserved set of intact thicket data from (Powell 2009), and came to 2029 gC/m^3. For karoo, the savanna relation was used, since the height multiplied by cover numbers are small, so any error will also be small. Grasslands also used the savanna number for BCF (1100 gC/m^3), in the absence of any calibration data.

BGB_{woody} = root:shoot$_{woody}$ * AGB_{woody}

Root:shoot$_{woody}$ is a function of mean annual rainfall (MAP).
For MAP>800 root:shoot$_{woody}$=0.25
300< MAP<800 root:shoot = -0.0035MAP+3.05
MAP<300 root:shoot=2.0

AGB_{herb} is a relatively small number, but is included for completeness. It is based on published relationships between rainfall and yearly grass production (Scholes 2003, whose units are in gDM/m^2/y), reduced proportionately to take into account competition by trees. AGB_{herb} varies greatly through the year – reaching a peak near the end of the growing and declining to near zero by the beginning of spring, especially in the presence of fire and/or herbivory. An 'annual average' is about half the peak value. It also varies greatly from year to year, which we ignore by using the mean annual precipitation (MAP) as the driver.

AGB_{herb} = 0.5*0.42*a*(MAP-c)*(1-TCF/0.65) for TCF<0.65; AGB_{herb}=0 if TCF>0.65

Constant a is often referred to as the 'Rain Use Efficiency', and c is the amount of rain needed to have production. Constants a and c are both related to the topsoil sand content.

a=-0.0376*sand%+3.442; a=0.1 if Sand%>92; a=1.1 if Sand%<64

c=328-142/a

In the absence of topsoil texture data, we assume a sandy loam (75% sand), with a=0.622 and b=99.7.

We assumed BGB_{herb}=AGB_{herb} in all biomes, ie a root:shoot for herbaceous plants of 1.

AGL consists of downed wood, leaves and dung on the soil surface. It is generally a relatively small number, included for completeness. AGL is calculated per biome (or sub-biome, where the biome covers a wide climate range) based on a simple model including litterfall and decay rates as a function of rainfall, and validated against fuel load datasets (Shea et al 1996, and Powell 2009).

AGL = 90 $\pm$ 22 gC/m2 for grasslands (from Powell (2009), old lands)
AGL = 121 $\pm$ 49 gC/m2 for savannas (from Shea et al 1996)
AGL= 900 $\pm$ 50 gC/m2 for forests (Weider and Wright 1995)
AGL= 254 $\pm$52 gC/m2 for thickets (Powell 2009, assuming the thicket landscape is 50% degraded)
AGL = 50 $\pm$ 10 gC/m2 for karoo (no data source, expert judgement)
AGL= 1500 $\pm$ 150 gC/m2 for fynbos (van Wilgen et al 1990)
AGL= 0 for desert (expert judgement)

Transformed land

Annually-cropped cultivated lands

For calculating soil organic carbon in croplands a simplified version of the EU recommended methodology is used (Box 1). In essence the management and input factors have been assumed to be one. This is appropriate since no data on these factors is available. However, including these factors in the future would enable calculations of the contributions that could occur by moving to different management techniques such as no-till agriculture, return of residuals to the soil, adding of manure or adding biochar. A value is assigned per crop type, regardless of where it occurs in the country, consisting of

$SOC_{cultivated} = F_{lu} * SOC_{0-30} + SOC_{30-100}$

Where F_{lu} is a Land use factor reflecting the proportion of soil carbon retained in a given land use.

F_{lu} = 0.5 for dryland crops
F_{lu} = 0.8 for irrigated crops
F_{lu} = 0.8 for Horticulture tree crops
F_{lu} = 0.6 for sugar cane
F_{lu} = 0.5 for dryland crops

Box 1 EU methodology (EU 2010) for calculating soil organic carbon in agriculture

SOC = SOC ST × F LU × F MG × F I
where:

SOC = soil organic carbon (measured as mass of carbon per hectare);
SOC ST = standard soil organic carbon in the 0-30 centimetre topsoil layer (measured as mass of carbon per hectare);
F LU = land use factor reflecting the difference in soil organic carbon associated with the type of land use compared to the standard soil organic carbon;
F MG = management factor reflecting the difference in soil organic carbon associated with the principle management practice compared to the standard soil organic carbon;
F I = input factor reflecting the difference in soil organic carbon associated with different levels of carbon input to soil compared to the standard soil organic carbon.

AGB_{crop} was computed as a function of the at-harvest aboveground biomass ($AGB_{harvest}$) and the year-round residue mass left in stalks ($AGB_{residue}$). Crop duration is the average period between planting and harvest for that crop, in days.
$AGB_{crop} = AGB_{harvest} * 0.5 *$ crop duration/365+ $AGB_{residue}$

The Harvest index (HI) was used to determine $AGB_{harvest}$ per hectare
$AGB_{harvest}$ = Y (t/ha) / HI

Where:
Y = yield * (1 – fraction moisture)

Yield (in gC/m^2) was quantified at municipal level for each crop group and used the 2002 agricultural census data (STATS SA 2002) to determine the proportional distribution of crop types and local yields. The carbon fraction was assumed the be 0.47 (EU 2010) for all agricultural vegetation. We had no error information on this term so we had to assume no error. Fraction moisture was estimated for each crop type from the literature.
$AGB_{residual} = (AGB_{harvest} - Y) * R_{AGB}$

Where R_{AGB} is the residual aboveground biomass expressed as a proportion of the non-yield biomass

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

except for root crops, where BGB_{crop} is the root dry matter (DM) yield.

Crop group	HI[1]	Moisture	Below ground fraction[2]	Carbon fraction	Residual fraction AGB R_{AGB}	Residual fraction BGB R_{BGB}	Crop duration[3]
Summer cereals [4]	0.5	0.13	0.2	0.47	0.2 (dry) 0.1 (irr)	0.8 (dry) 0.6 (irr)	0.66
Winter cereals[5]	0.4	0.11	0.2	0.47	0.2 (dry) 0.1 (irr)	0.8 (dry) 0.6 (irr)	0.5
Oil seeds	0.39	0.15	0.2	0.47	0.2 (dry) 0.1 (irr)	0.8 (dry) 0.6 (irr)	0.66
Legumes	0.85	0.15	0.2	0.47	0.2 (dry) 0.1 (irr)	0.8 (dry) 0.6 (irr)	0.5
Fodder crops	1	0.5	0.2	0.47	0.2 (dry) 0.0 (irr)	0.2 (dry) 0.0 (irr)	1
Sugar cane	1	0.2	0.2	0.47	0.1 (dry) 0.1 (irr)	1 (dry) 1 (irr)	1
Other crops	1	0.5	0.2	0.47	0.2 (dry) 0.0 (irr)	0.2 (dry) 0.0 (irr)	1
Vegetables	1	0.5	0.2	0.47	0.0 (irr)	0.6 (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 1 Calibration factors used for agricultural crops

For tree crops two categories of trees where used. Grape vines and all other trees (see table 2). An area and tree category weighted average was derived per municipality. It was assumed that tree biomass is the same in all locations. Below ground biomass was assumed as a proportion of above ground biomass. A non-tree biomass of 1 t/ha was assumed for other (non-tree) biomass in the orchard.

	t/ha above ground (dry)	Belowground fraction	Residual biomass (non tree) t/ha
Vines	14	0.4	1
Other trees	38	0.4	1

Table 2 Calibration factor for tree crops

An area and crop weighted average of carbon density of agriculture was calculated per municipality for the following categories of agricultural land use:

- Dryland agriculture (this includes fallow land)
- Horticulture (agricultural tree crops)
- Sugar cane

Plantation forests and tree crops

Estimates are provided per plantation type, based on biomass measures from the forestry industry (http://www.forestry.co.za/statistical-data). SOC is derived unchanged `from the AFSIS product.

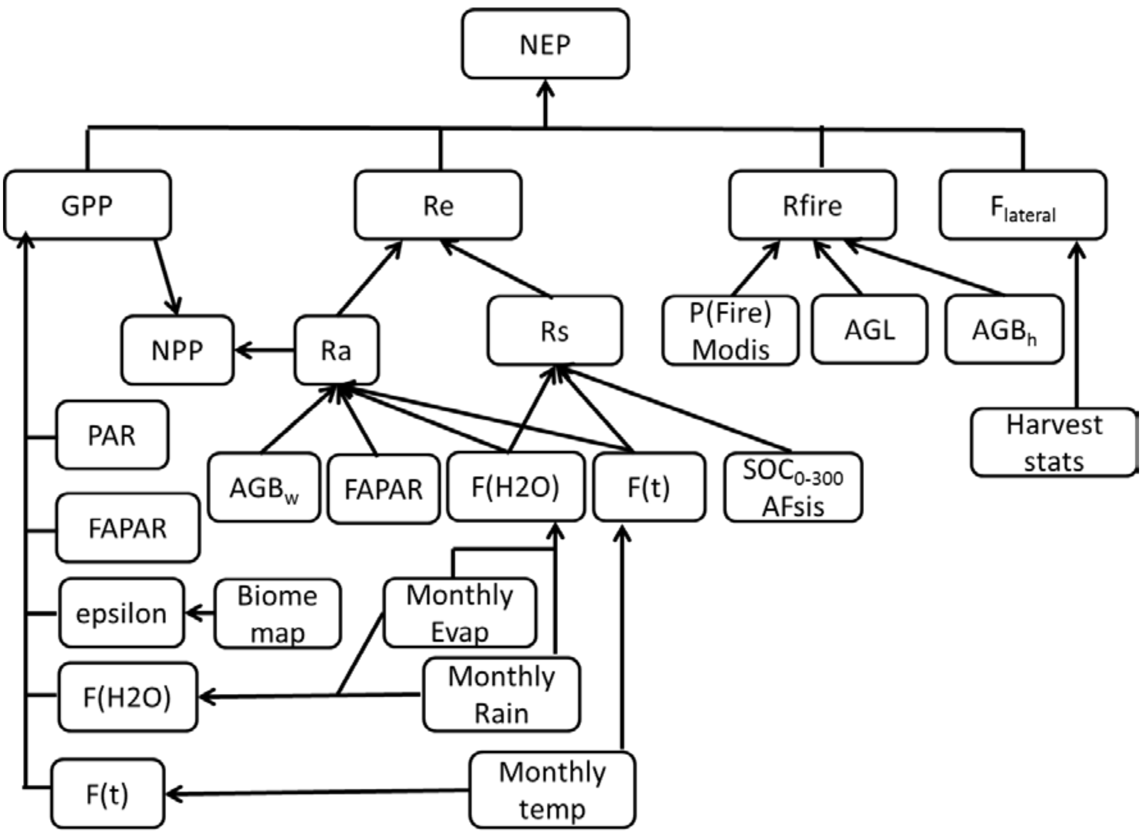
Urban areas

- AGB_{urban} = $FAPAR_{annual\ mean}$ * 5000 [gC/m^2] (Based on an IPCC 2006 value for closed urban forests. The multiplier can be adjusted to match estimates for the urban areas which have been surveyed, eg Johannesburg and eThikweni.)
- BGB_{urban} = 0.5 AGB_{urban} (assumes a mix of trees and herbaceous)
- SOC_{urban} = 0.8 $SOC_{0\text{-}1000}$ (from AFSIS)
- AGL_{urban} = 0. This could be used to reflect an estimate of carbon as timber in buildings and their furniture, plus the carbon in landfills from the National Communication.

Basis for calculating fluxes

Note that in the following the micrometeorology convention of downward fluxes (eg GPP) having negative signs and upward fluxes (eg R_{eco}) having positive signs has not been used. The equations are more intuitive when all values are expressed as positive numbers, which are then added or subtracted according to their direction. The units are $gC/m^2/y$. To get to $gCO_2/m^2/y$, used for instance in the National Communications, multiply by 44/12. To express the flux in dry matter terms per hectare (tDM/ha/y), divide $gC/m^2/y$ by 0.0045. National flux sums are expressed in TgC/y (1 Tg=10^{12}g, or a million tonnes)

Figure 3 The workflow for calculating terrestrial carbon fluxes



NEP = GPP – Re – Rf – Flateral

- NEP = net ecosystem production (also called NEE, net ecosystem exchange, or if measured at large scale and over long times, as Net Biome Production)
- GPP = Gross Primary Production

- Re = Ecosystem respiration
- Rf = fire flux
- Flateral = export and import fluxes at the scale of the whole country. Particularly harvest and trade-related fluxes, but also water and wind transport. In principle these could be import fluxes (-ve) or export fluxes (+ve), but in practice are all export fluxes (except locally, in the case of accumulation of carbon in cities, which we do not calculate).

The gross primary production (GPP) is solved for periods of time corresponding to the input data, and summed to the year. In the absence of interpolated surfaces of daily weather, or month-by-month weather, we used a climatology of monthly weather for the period 1960 to 1990, and therefore match it to a climatology of mean monthly fraction of absorbed photosynthetically active radiation (FAPAR) and mean monthly photosynthetically active radiation (PAR). There are thus 12 input files for each term, corresponding to the twelve months. The climatology averaging periods for climate and satellite data are different. For FAPAR, the MERIS dataset covers the period 2000 to 2012, and the PAR dataset is also for this period. In the future it may be possible to do these calculations in near-real time, on a monthly or 8-daily basis. The current constraint is the availability of climate data, interpolated nationally, at this time resolution.

$GPP = \epsilon_{biome}\ PAR*FAPAR * ʃ(H_2O)*ʃ(t)*ʃ(CO_2)$

ϵ_{biome} is also known as the Light Use Efficiency (epsilon). It is taken as a constant per biome, and is calculated as the weighted sum of the ϵ for each of the main plant functional types in the biome, in proportion to their contribution to the time-integrated leaf area of the biome. Note that almost all of the literature reports ϵ in its constrained form – ie, as effective ϵ *after* the effects of temperature and water have been taken into account. We are using the potential ϵ, *before* it is constrained, since the constraints are then explicitly applied.

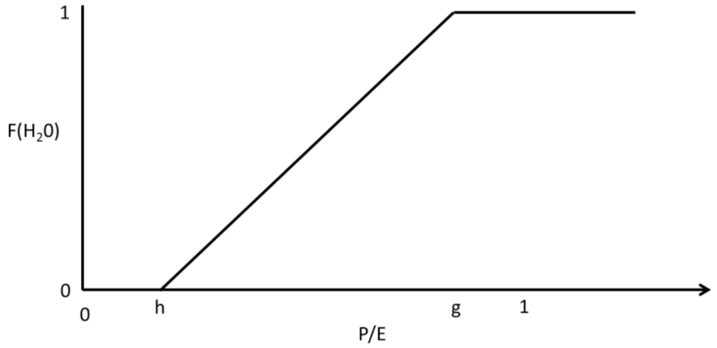
Table 1 The unconstrained light use efficiency, per plant functional type and per biome. Data sourced from Abel et al 1996, Gower et al 1999, Hunt et al 1994, Landsberg 1986, Landsberg and Waring 1997, Neilson et al 1992, Potter et al 1993, Turner et al 2003, Prince 1995, Running et al 1999, Raich et al 1991, Ruimy et al 1999, Verostaete et al 2002.

Plant functional type	ϵ unconstrained (± SD) gC/MJ
C3 (Trees, shrubs, temperate grasses)	1.8 (±0.5)
C4 (Tropical grasses)	2.34 (±0.6)
CAM	1.08 (±0.4)

Biome	Fraction C3	Fraction C4	Fraction CAM	Weighted ϵ gC/MJ
Savanna	0.5	0.5	0.0	2.07
Grassland	0.1	0.9	0.0	2.29
Karoo	0.3	0.4	0.3	1.80
Desert	0.3	0.4	0.3	1.80
Fynbos	1.0	0.0	0.0	1.80
Forest	1.0	0.0	0.0	1.80
Thicket	0.4	0.1	0.5	1.49

ʄ(H_2O) is the fractional constraint applied due to the closure of stomata. At the monthly mean temporal scale we apply here, where P=mean monthly rainfall in millimeters and E is the monthly open-water potential evaporation (units?)

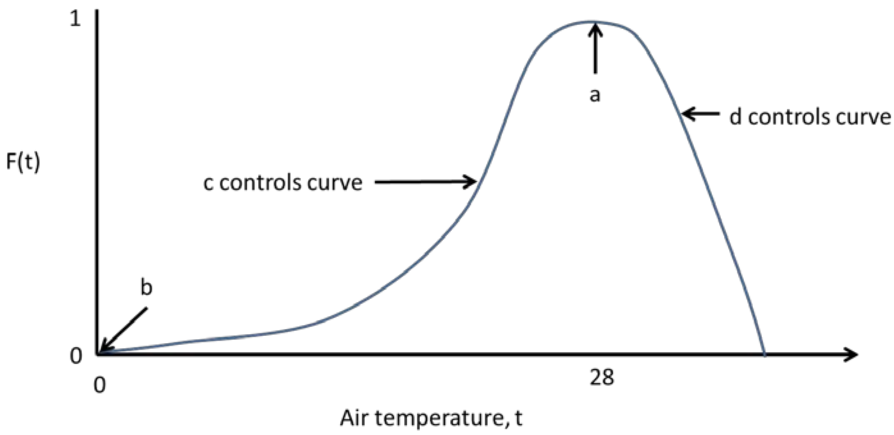
ʄ(H_2O) = 1.0 if P/E >g
ʄ(H_2O) = (P/E-h)/(g-h) if h<P/E <g
ʄ(H_2O) = 0.0 if P/E<h



The point on the P/E axis where f(H_2O) reaches 1 (no water constraint) is given by g, which is in principle a biome-specific constant (based on the mix of functional types in the biome). Initially, g has been set to 1.0 for all biomes, and can be tuned to match known data. The point on the P/E axis at which f(H_2O) reaches 0 is given by h. Initially it has been set to 0.

ʄ (t) is a hump-shaped function of temperature. The following empirical function has a temperature optimum (a) ~28 , no-growth temperature (b)=0.0; curvature below the optimum (c) =3 and curvature above the optimum (d)= 4.

$ʄ(t)_{photosynthesis}$ = exp(c*(1.0-f^d)/d)*f^c where f:= (b-t)/(b-a)



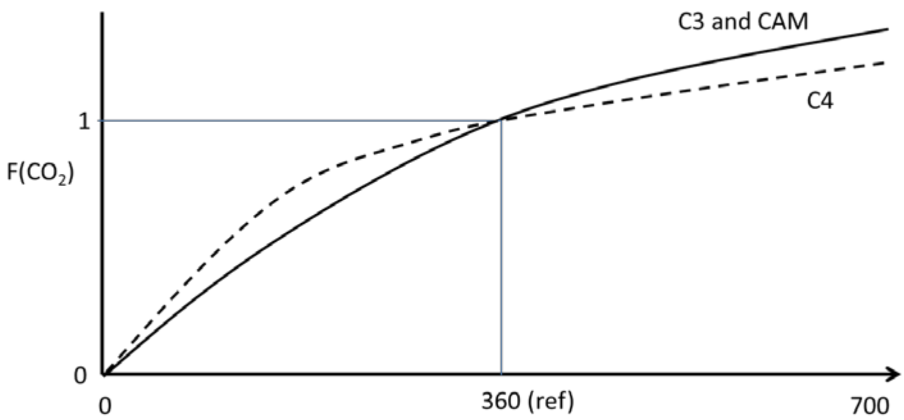
The temperature (t) used in the case of the temperature sensitivity of photosynthesis is the mean daytime temperature, approximated by

$t_{daytime} = 0.75*(t_{max}-t_{min})+t_{min}$

ʄ (CO2) is a saturating function of increasing atmospheric CO2 concentration. It is included to allow future production to be calculated – the present effect of elevated CO2 relative to the 1990's is very small and can be ignored. We use a Michaelis-Menten enzyme kinetics equation, normalised to equal 1.0 for a reference [CO_2] of 360 ppm, which corresponds to the ~1990 era when the concern over rising CO_2 began, and adjusted to reflect the observed

11% increase in productivity for C4 plants and 15% increase for C3 plants from 'double CO_2' experiments (ie ~700 ppm).

ʆ (CO2) = ($[CO_2]/([CO_2]+125)$) /(360/(360+125)) for C3 plants and CAM
ʆ (CO2) = ($[CO_2]/([CO_2]+87)$) /(360/(360+87)) for C4 plants



The same proportions of C3 to C4 can be used per biome as described for the light use efficiency (epsilon) above.

The NPP is required by the project terms of reference, and is more intuitive for most users than the somewhat theoretical GPP. This requires disaggregating Re into its autotropic (Ra, by plants) and heterotrophic (Rh) parts (Rh = Re-Ra). NPP will be solved on a grid-cell by grid-cell basis

NPP = GPP – Ra

A widely-used assumption is that Ra~0.5 GPP. We calculate Ra as a function of temperature, AGB, BGB and FAPAR. The assumption is that the woody parts of the plant have one respiration rate and the more active tissues, indexed by FAPAR, have another.

Ra = ʆ $(t)_{resp}$ * (k_1*(AGB_{tree}+BGB_{tree}) + k_2*(FAPAR))

ʆ $(t)_{resp}$ follows the same empirical form as given above, with a=28 (Archibald et al 2009). The value for k1 is about 0.01 and k2 is about 8. The temperature used in the function is the mean daily temperature $t_{mean} = (t_{max}+t_{min})/2$

In order to calculate Re,
Re = Ra + Rh

Where Rh is the soil respiration by microbes. The total soil respiration Rs, which includes Ra_{roots}, is given by Makhado and Scholes (2011) for Skukuza as

Rs = k_3*($SOC_{0\text{-}300}$ + AGL)* ʆ(H_2O)* ʆ $(t)_{resp}$

where k_3 is a constant, tuned to reflect the measured Rs. From Makhado and Scholes (2011), for the Skukuza upland soils with 1.9% SOC to 300mm and a bulk density of 1.71 Mg/m^3, apparent k_3 (including roots) is about 0.0005 day^{-1}. About half of this is due to roots, so for Rh rather than Rs, the real k_3 is about 0.00025 day^{-1} The below-seepline soils have SOC ~4% and bulk density 1.68 Mg/m^3, apparent k_3 is 0.0025 day^{-1}, a difference probably due to the smectitic nature of the clay in the latter. The k_3 for the part due to the soil microbes is about 0.000125 day^{-1}

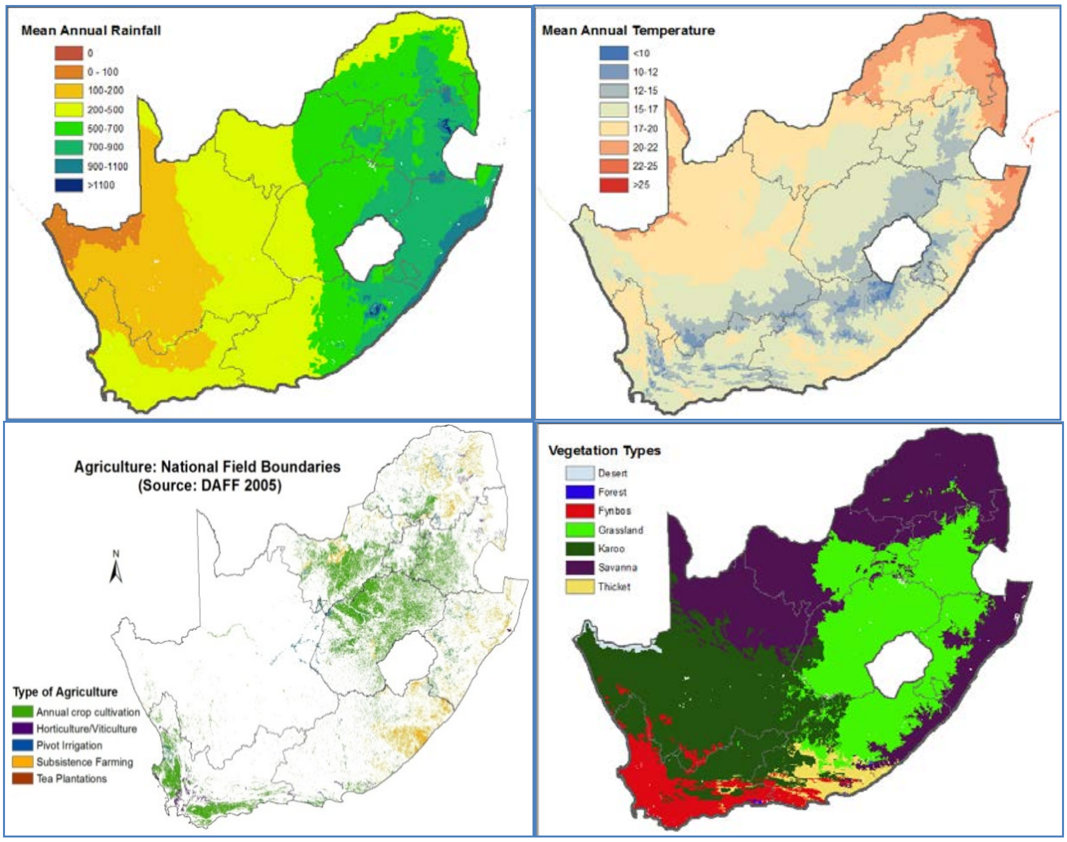
The fire flux F is given by

$$F = p(fire) * AGB_{herb} + AGL * \text{ combustion completeness}$$

Where p(fire) is the annual probability of a give point burning in a year, derived from the burned area fraction maps from MODIS. For areas of low burned area fraction (where there are many locations recording no fires in the 10-year observation period, but an expectation that fires could occur), an averaging window should be used. The size of this window should adjust to be larger when the fire probability is low, and smaller where it is high. Combustion completeness is taken as 0.8 (Safari 2000 data). Only a small part of this fire-emitted carbon is exported as a lateral flux from the territory of South Africa.

Input datasets

The four main determinants of terrestrial carbon stocks in South Africa (and elsewhere in similar environments) are moisture, temperature, soil conditions and vegetation cover. The geographical distribution of these factors is shown in Map 1. There is a general increase in plant productivity with increasing moisture (west to east), and with it, increasing soil carbon stocks and biomass. Note that even the 'wet' parts of South Africa are comparatively arid by global standards. The highest soil carbon stacks are in flooded soils (wetlands), which are small in extent in South Africa, but will be explicitly considered in future iterations of this study. There is a decrease in soil carbon with increasing temperature (south to north). Most of South Africa is warm-to-hot by global standards. There is an increase in soil carbon as the silt+clay content of the soil increases, and the carbon content of soils where the clay is of the smectitic type is higher than that of soils with kaolinitic clays. Overall the soils of South Africa tend to be sandy, but there are some important areas of clayey smectitic soils where the parent materials are basalts or dolerites. The biomass carbon varies greatly between vegetation types, in the order desert<karoo<grassland<fynbos < thicket<savanna<forest, and is largely controlled by the proportion of woody plants in the vegetation.



***Map 1**: a) climatic moisture, indexed by mean annual rainfall; b) the mean annual temperature c) National Field Boundaries d) the vegetation cover, as biomes.*

Input dataset	Source	Resolution	Error	Comments	Reference/ Custodian/ URL
Monthly mean of tmax,tmin	WRC Report 1489/1/06	1.7km	Assumed none	1950-1999	Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06
Monthly mean rainfall	WRC Report 1489/1/06	1.7km	Assumed none	2004	Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06
Monthly mean reference evaporation	WRC Report 1489/1/06	1.7km	Assumed none	1997	Schulze, R.E. (Ed). 2007. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06
Soil Organic Carbon (SOC)	Africa Soil Information Service (AFSIS)	1km	10th and 90th percentiles	2013	ISRIC – World Soil Information, 2013. Soil property maps of Africa at 1 km http://www.isric.org/data/soil-property-maps-africa-1-km
Canopy Height	NASA (JPL)	1 km	Error map provided	2011	Simard, M., N. Pinto, J. B. Fisher, and A. Baccini (2011), Mapping forest canopy height globally with spaceborne lidar, J. Geophys. Res., 116, G04021, doi:10.1029/2011JG001708 http://lidarradar.jpl.nasa.gov/

Input dataset	Source	Resolution	Error	Comments	Reference/ Custodian/ URL
Percentage Tree cover	MODIS MOD44B	250m	Standard error by cover class provided	2010	USGS LPDAAC Vegetation Continuous Fields Yearly L3 Global 250m https://lpdaac.usgs.gov/products/modis_products_table/mod44b
SANBI 2009 Land Cover	SANBI	30m	Assumed none	2009	South African National Biodiversity Institute (SANBI), Pretoria, Report 13/10/2009 http://bgis.sanbi.org/mapsearch.asp
National Field Boundaries database	SPOT 5	2.5m	Assumed none	2007,2011,2012	Department of Agriculture, Forestry and Fisheries (DAFF)
Agriculture statistics	Census of commercial agriculture	N/A	Assumed none	2002	Statistics South Africa (StatsSA)
PAR	MODIS and SeaWiffs JAXA	3km	Validated against flux tower	2000-2010	Earth Observation Research and application Center, Japan Aerospace Exploration Agency
FAPAR	MERIS (JRC-GEM)	1km	Estimated at 10%	10-daily composites 2000-2012	Gobron (2011)
Fire return period	MODIS MCD45A1	500m	5th and 95th quantiles provided		USGS LPDAAC Burn area product

Table 4 Input datasets and their provenance

Total ecosystem organic carbon

Table 5 *Terrestrial total ecosystem carbon stocks in South Africa by land cover class. SD stands for standard deviation, which is a measure of the spatial variability of the stock, which would need to be dealt with by collecting a large number of samples using a stratified-random approach. A continuous, total coverage approach as applied in this project has no sampling error, only an estimation error due to uncertainties in the models used. This estimation error is reflected on the right hand side of the table as a lower (10%) and upper (90%) confidence limit in the totals for the entire class. These limits have been calculated using a rigorous error accumulation approach. Note that stratified sampling approaches also contain estimation errors of the same magnitude (in addition to sampling errors), but these are almost never accounted for.*

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		km^2	Tg C		
Savanna	5834	3513	358473	2091	1961	5214
Grassland	10660	4725	224377	2392	2213	5736
Nama and succulent karoo	1769	1799	334812	593	587	862
Fynbos	6773	4100	61490	416	372	1140
Thicket	10101	5347	27402	277	236	785
Indigenous forest	18198	6172	857	16	12	42
Desert	799	113	7017	6	6	6
Cultivated	5980	1731	143948	860	840	1788
Plantation forestry	17559	4320	16952	298	252	769
Settlement, mines, industry	6793	2448	23119	157	152	276
Other, waterbodies etc	3167	1536	19967	64	62	97
Total South Africa			1218414	7170	6693	16715

Soil organic carbon

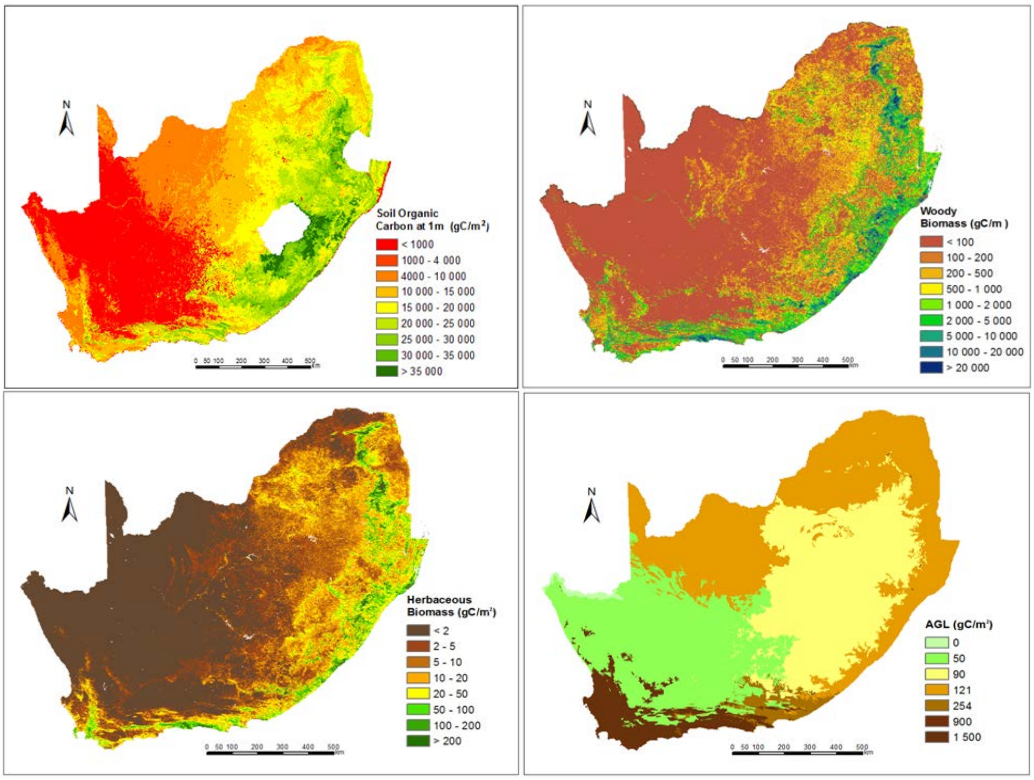
Table 6 *Soil organic carbon stocks in South Africa to a depth of 1 m, by land cover class. Soil organic carbon is the largest part of the ecosystem stock in all South African ecosystems, and the most stable. The AfSIS data extrapolation procedure did not extend into the driest, hottest third of the country, which have relatively low carbon stocks. We assumed a total soil carbon content to 1 m of 700 g/m^2 for these areas. The notes regarding the measures of spatial variability (standard deviation, SD) and estimation uncertainty (lower and higher confidence limits) apply to this table as well.*

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		km^2	Tg C		
Savanna	5422	3078	358473	1943	1779	7138
Grassland	10149	4427	224377	2277	2008	7671
Nama and succulent karoo	1700	1744	334812	569	339	1872
Fynbos	5658	3854	61490	348	305	1301
Thicket	7737	3298	27402	212	189	772
Indigenous forest	11057	3497	857	9	8	30
Desert	833	112	7017	6	1	12
Cultivated	5785	1704	143948	835	774	2547
Plantation forestry	12961	3553	16952	220	193	663
Settlement, mines, industry	6375	2379	23119	148	136	414
Other, waterbodies etc	2819	1375	19967	57	50	135
Total South Africa			1218414	6624	5781	22555

Biomass carbon: woody, herbaceous and litter

Table 7 *Terrestrial biomass carbon stocks in South Africa, by land cover class. This category includes both above and belowground parts of both woody and herbaceous plants, as well as standing dead material and organic litter. In forests, savannas, fynbos and thickets the value is dominated by the woody plant biomass, whereas herbaceous biomass dominates in grasslands, karoo and deserts.*

Land cover class	Mean	SD (spatial)	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m^2		km^2	Tg C		
Savanna	418	756	358473	150	123	342
Grassland	532	748	224377	119	109	279
Nama and succulent karoo	70	159	334812	24	30	54
Fynbos	1119	626	61490	69	51	140
Thicket	2370	3159	27402	65	41	152
Indigenous forest	7186	3423	857	6	3	13
Desert	1	17	7017	0	0	0
Cultivated	186	50	138269	26	41	56
Plantation forestry	4603	969	16952	78	56	148
Settlement, mines, industry	421	345	28798	12	12	19
Total South Africa			1169649	548	466	1203



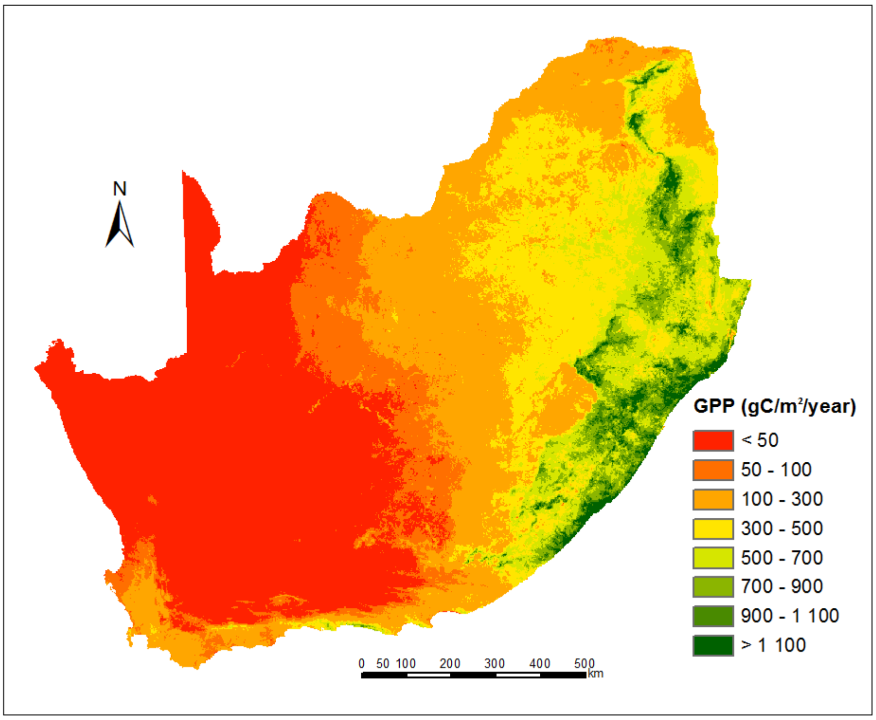
Map 2 *The components of the terrestrial carbon stock of South Africa. Top left: soil organic carbon to 1m in depth. Top right: the above- and below-ground woody-plant biomass pool Lower left: above- and below-ground herbaceous biomass pool. Lower right: above-ground litter*

Terrestrial ecosystem carbon fluxes in South Africa

Gross primary production

At a large scale, and over the long term, Gross Primary Production must equal ecosystem respiration (Reco + Fire); thus Net Ecosystem Exchange (NEE) is zero. This is probably close to true for South Africa, since the regional inversion analyses suggest that the net southern African flux is small to zero (eg Valentini 2013, under review). However, the global carbon cycle is currently not at equilibrium – with rising atmospheric CO_2 and a changing climate, the global terrestrial land surface is currently a sink of about 1 PgC/y. A small part of this sink is probably in South Africa – less than the South Africa fraction of the global land area (1%) because South Africa is both more arid and hotter than the global average – perhaps 1-10 TgC/y is a likely order of magnitude (ie ~1-10 gC/m^2/y, which would be very hard to detect over a short accumulation period). Given the uncertainty in all the parameters, our approach at this stage is to force GPP= 1.01*(Re+fire) at the climatological (>10 year) time scale and national spatial scale, by adjusting the respiration parameter values until this is true. The value of 1.01 is derived from the observation that the current global terrestrial net sink of carbon is around 2 PgC, and the current GPP is around 200 PgC; ie 1%.

This assumption prevents an evaluation of the national NEE initially, but means that the parameter values are forced to be approximately right; and the sub-annual and spatial patterns will be realistic. Going forward, this will allow relative changes in NEE to be assessed. Absolute changes in national scale NEE will require the implementation of a national inverse modelling and measurement capability, such is currently under experimental development at the CSIR.



Map 3 *Distribution of Gross Primary Productivity (GPP) in terrestrial ecosystems in South Africa. GPP is the carbon which is taken out of the atmosphere into plant biomass through the process of*

photosynthesis. About half of this returns to the atmosphere within hours to months through respiration by the plant. What remains is Net Primary Production (NPP), which is the basis of production-based ecosystem services such as timber and crop yield, firewood and grazing. NPP is not equivalent to carbon storage, since most of the NPP is also ultimately respired, burned or exported. NPP does establish an upper limit to the short-term carbon sequestration rate in carbon storage projects. It is clear from this map that the potential for such projects is greatest in the wetter parts of the country, where they also come into conflict with land needs for agriculture, settlement and water provision.

Table 8 *Gross Primary Production (GPP) of terrestrial ecosystems in South Africa. GPP is the carbon taken up by the vegetated surface from the atmosphere. It is about twice the Net Primary Production, which is what is retained as biomass growth after the plant has respired part of the uptake to support its own metabolism. Estimation error calculations are in progress. Validation of these fluxes using direct measurement is only possible for a few sites in the country. They are bradly consistent with global-scale model-based estimates, but probably an underestimate due to incertainties in selecting a value for epsilon, the light use efficiency.*

Land cover class	Mean	SD spatial	Area	Best estimate	Lower confidence limit	Upper confidence limit
	gC/m²/y		km²		TgC/y	
Savanna	415	320	358473	149	54	351
Grassland	645	304	224377	145	72	361
Karoo	44	46	334812	15	5	34
Fynbos	142	134	61490	9	2	19
Thicket	381	264	27402	10	2	23
Desert	977	281	857	1	0	2
Forests	1	0	7017	0	0	0
Total, natural ecosystems			1014428	329	135	790

Lateral Fluxes

The analysis of lateral fluxes is included for completeness, rather than because they are significant in South Africa relative to the vertical fluxes between the land surface and the atmosphere. The lateral flux analysis does not include 'virtual carbon', ie the 'embodied' carbon (as opposed to actual carbon) in exports of goods with a high energy cost of manufacture, such as metallurgical products like aluminium, steel, gold and platinum. Nor does it include the lateral flux of carbon in the form of coal exports or oil and gas imports – these are reported in the national greenhouse gas inventories.

Export flux in rivers

Carbon is exported from South Africa's land mass into the adjacent ocean in the form of Dissolved Organic Carbon and Particulate Organic Carbon. Most of this flux is believed to be trapped on the coastal shelf (the exact fraction is unknown) and therefore remains within the extended South African economic zone. The annual flux is estimated as 2.29 TgC/y, equally split between DOC and POC – ie about 1% of GPP. This value was estimated by downscaling the estimate for Africa (48 TgC/y) in Seitsinger et al (2001) by the fraction of the land area of Africa contributed by South Africa.

Export flux in trade items

Agriculture has both a large export flux and a large import flux. The result is a small net flux, which is inward in most years but outward is some: the average is about -1 TgC/y. Paper, pulp and wood is a net export of 0.4 TgC/y

Export flux as organic compound in smoke

It is estimated that about a third of the particulate carbon flux in smoke resulting from fires in South Africa leaves the subcontinent. This comes to about 10.5 TgC/y; which compares well with the van der Werf et al (2010) estimate of 10TgC/y.

Biomass validation

The aboveground biomass mapped by the study has been validated against an exhaustive search of published biomass values from South Africa (Table 9). The criteria for inclusion in this database are that the studies (although variable in their approach) are methodologically sound in terms of the area of the sample relative to the spatial heterogeneity of the vegetation, method of estimation biomass and representation of the most important biomass categories for the biome. In almost all cases, some biomass categories are *not* reported (eg roots or litter are not estimated, or herbaceous biomass is not separated from woody biomass). Some assumptions have therefore to be made to get total biomass for all studies. These assumptions match those in the modelling study. The principle ones are:

- for herbaceous biomass the root:shoot = 1 (ie root biomass is equal to herbaceous aboveground biomass);
- for woody plants, the root:shoot is a function is dependent on rainfall, ranging from 0.25 in mesic ecosystems (> 800 mm) to 2 in arid ecosystems (<300 mm).

The biomass studies were conducted up to 50 years ago, and their exact geographical location is often not known. A point-by-point validation is therefore not possible. Even if it were, there is a problem of spatial mismatch between the scale of the measurements (often only a few tens of square meters) and the spatial resolution of the estimate made in this study (1 km^2, or 1 million m^2). Therefore the studies have been classified into biomes, and the comparison is done at the whole biome scale, or in some cases (where the validation sample is only from a part of the biome) for a portion of the biome. Each biome 'measured' value contains many studies, and this is reflected in the standard deviation bar in Figure 4. The 'measured' values cannot automatically be considered to be the truth: they contain measurement and plot-scale sampling errors, are not a random sample, and contain spatial variation. They cannot therefore be assumed to be an unbiased and precise representation of the biome, despite containing all known suitable estimates. They are just the best available reality check.

Study reference	Samples	Comments
Savanna		
Shackleton, CM PhD thesis, University of the Witwatersrand; and Shackleton, C.M and Scholes, R.J. 2011. Above ground woody community attributes, biomass and carbon stocks along a rainfall gradient in the savannas of the central lowveld, South Africa. South African Journal of Botany. 77 (2011), 184-192	61	Primary source for woody biomass in savannas. Well distributed throughout the biome. An expansion factor of 35% was applied to the aboveground woody biomass to include leaves and roots.
Shea, RW, Shea BW and Kauffman JB 1996. Fuel biomass and combustion factors associated with fires in avannah ecosystems of South Africa and Zambia. JGR 101 (D19) 23551-23568	12	Primary source for grass aboveground and litter mass mass in savannas. Sample from southern KNP only.
Grassland		

Study reference	Samples	Comments
O'Connor, TG 2009 Influence of land use on phytomass accumulation in Highveld Sourveld grassland in the southern Drakensberg, South Africa. Af J Range and Forage Science 25, 17-27	9	Mesic grassland near Underberg. 3 sites each on commercial, communal and conservation land. High root estimate due to inclusion of dead roots, which are technically belowground litter.
O'Connor, TG, LM Haines and HA Snyman 2001 Influence of precipitation and species composition on phytomass of a semi-arid African grassland. J Ecology 89, 850-860	57	Semi-arid grassland near Bloemfontein. 19 years of data from 3 trials: good, medium and poor condition veld. No root biomass.
Gerber, L 2000 Development of a ground truthing method for determination of rangeland biomass using canopy reflectance properties. Af J Range Forage Science 17, 93-100	6	Kalahari, Karakul research station 28° 21S 24° 14 E. One experiment, six years. Mostly grass, 6-8% shrub. No root biomass.
Karoo		
Gerber, L 2000 Development of a ground truthing method for determination of rangeland biomass using canopy reflectance properties. Af J Range Forage Science 17, 93-100	6	Grootfontein research station, Middelburg. Estimated visually read off figure 1. Two grazing trials, each with 3 camps.
Mills, AJ et al 2005 Ecosystem carbon storage under different land uses in three semi-arid shrublands and a mesic grassland in South Africa. SA J plant and Soil 22, 183-190.	2	Two succulent karoo sites, near 32° 15 S 22° 50 E; 31° 20 S 19° 10 E. Estimated from fig 5. Root data included.
Fynbos		
Kruger, FJ 1977 A preliminary account of aerial plant biomass in funbos communities of the Mediterranean-type climate zone of the Cape province. Bothalia 12, 301-307	24	Jonkershoek, Zachariashoek and Jakkalsrivier catchments. No litter values or roots.
Van Wilgen BW and FJ Kruger 1985 The physiography and fynbos vegetation communities of the Zachariashoek catchments, south-western Cape province SAJBot 51, 379-399	4	Only total live biomass given.
Van Wilgen BW, KB Higgins and DU Bellstedt 1990 The role of vegetation structure and fuel chemistry in excluding fire from forest patches in the fire-prone fynbos shrublands of South Africa J Ecol 78, 210-22	1	Only used the fynbos site.
Van Wilgen BW 1982 Some effects of post-fire age on the aboveground plant biomass of fynbos (Macchia) vegetation in South Africa J Ecology 70, 217-225.	4	Jonkershoek. No roots.
Rutherford, MC 1978 Karoo-fynbos biomass along an elevational gradient in the western Cape. Bothalia 12, 555-560	3	Restionaceous, Proteaceous and Renosterbos. No root mass.
Higgins, KB, AJ Lamb and BW van Wilgen 1987 Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek Valley, south-western Cape province. SA J Botany 53, 249-257	N/A, only used for R:S	Primary source for root:shoot ratios in fynbos.
Thicket		

Study reference	Samples	Comments
Mills, AJ and RM Cowling 2010 Belowground carbon stocks in intact and transformed subtropical thicket landscapes. Journal of Arid Environments 74,93-100	123	Source for soil data. 49 intact thicket (18% of landscape), 49 degraded (35%), 25 old fields (47%). Values weighted to reflect biome as a whole.
Powell MJ 2009 restoration of degraded subtropical thickets in the Baviaanskloof Megareserve, South Africa. MSc, Rhodes University, Grahamstown.	160	Primary source for thicket biomass data. Includes the sites cited by Mills and Cowling 2010 and more. 2/3 used for validation, 1/3 held aside for calibration of $BCF_{thicket}$
Indigenous forest		
Glenday, J 2007 Carbon Storage and Sequestration Analysis for the eThekwini Environmental Services Management Plan Open Space System. eTthekwini Municipality	40	Used biomass data only. Soil data uses unrealiable bulk density approach, and is at too fine a resolution for validation.
Seydack AHW1995 An unconventional approach to forest yield regulation for multi—aged multispecies forests. For Ecol Management 77, 139-153 (pers comm G Durrheim)	1 (but large area)	Mean standing volume 150 m^3/ha for large stems, doubled for all stems. Assume wood density of 0.8, and root expansion factor of 1.28.

Table 9 Sources of data used in the biomass validation study

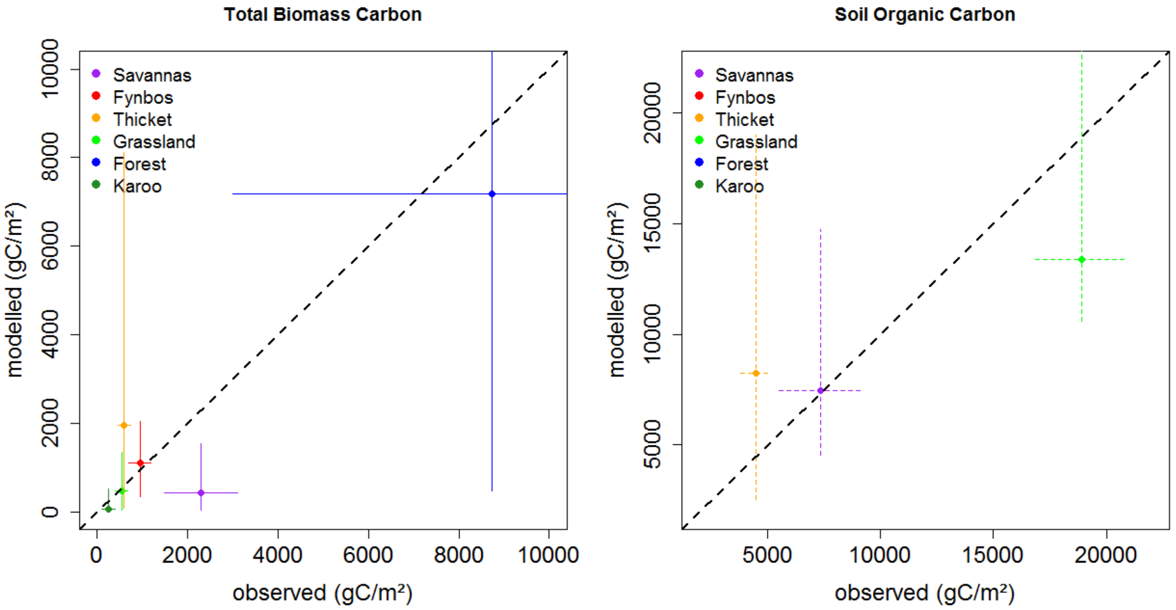


Figure 4 *Observed biomass (Left panel) and soil carbon (right panel) means and 5-95% confidence limits for South African biomes, plotted against the means and confidence limits estimated in this study.*

Validating soil carbon stocks

The overwhelming majority of samples in the South African databases on soil profiles were apparently used in the creation of the AfSIS maps used by this study, and could therefore not be used in its validation. We relied on completely independent datasets, mostly collected for the purpose of soil carbon inventory at local scale, and therefore satisfying the following onerous criteria: measured to rock or 1 m depth; bulk density and stone fraction measured and recorded; soil carbon analysed by an accurate method. The studies used are listed in table 10. Most of the data were obtained directly from the investigators, since it is generally not given in disaggregated form in papers or reports. Although most of the profiles in these studies have exact GPS locations, for similar reasons to those given above (scale missmatch) we did not attempt to do a point-by-point validation. We did restrict the domain of the validation to the area of the biome where the profiles were located.

Source	N	Comments
Savannas		
Lesogo Kgomo, University of Cape Town. lesogok@gmail.com	62	Granite landscapes of Kruger National Park
Grasslands		
Graham von Maltitz, CSIR gvmalt@csir.co.za	16	Mesic grasslands, Ukhalamba (Drakensberg)
Thickets		
Mills, AJ and RM Cowling 2010 Belowground carbon stocks in intact and transformed subtropical thicket landscapes. Journal of Arid Environments 74,93-100	120	49 intact thicket (18% of landscape), 49 degraded (35%), 25 old fields (47%). Values weighted to reflect biome as a whole.
Mike Powell, Rhodes University, Grahamstown	160	The primary source for the data reported above, and further sites. A random third of the dataset was reserved for calibration purposes if necessary.
m.powell@ru.ac.za		

Table 10 Studies used for soil carbon validation

Validating GPP

Eddy covariance flux data measures Net Ecosystem Exchange (NEE, but usually misses R_{fire}). After making a number of assumptions, GPP and Re can be calculated from NEE. Flux data is scarce in South Africa – only two sites (Skukuza and Malopeni) are available, with one in Potchefstroom (a grassland with scattered *Acacia* trees) possibly available in future. The site at Skukuza has operated for 12 years at the ecotone between a *Combretum* and *Acacia* savanna (Archibald et al 2009). Meaurements over a 5 year period, extrapolated using a 25-year climate record 1981-2005 give a NEE of 75 gC/m^2/y (with a SD of 105 and an annual range from -138 to +155 gC/m^2/y). The micrometeorological convention is followed in this instance, with positive numbers meaning fluxes from the land to atmosphere – thus this site is on average a moderately strong source of carbon, rather than a sink. In wetter-than average years it is a sink. The herbivory flux for this site is estimated at 9.5 gC/m^2/y and the fire flux at 40 gC/m^2/y (interannual SD 17.5). The site at Malopeni, in a hot, dry *Colphospermum mopane* savanna, has operated for 3 years (Nickless et al, in prep). Preliminary NEE estimates are 1.36 and 1.28 gC/m^2 in 2009 and 2011 respectively, a small source.

An inter-comparison (rather than true validation, since these products are themselves highly uncertain) can be made with other spatial models of GPP. Most of these are continental or global in scale, and have a spatial resolution of >20km. Recent models (those included in the Climate Model intercomparison Project CMIP 4 and CMIP 5) are presented by Beer et al 2010 and Jung et al 2009 and have been reviewed by Valentini et al (2013) for Africa. The GPP of South Africa ranges from near 0 gC/m^2/y in the west, in the hyperarid desert areas, to around 1500 gC/m^2/y in the wettest parts of the east. This pattern and range is the same as that estimated by the SA carbon sinks study.

Validating NPP

A validation can be made against NPP estimates made using traditional cut-and-weigh techniques, for a few locations. This technique typically underestimates NPP (by up to 50%), because it misses important components such as those belowground, those which decay rapidly (such as root exudates) or are in gaseous form (such as Volatile Organic Carbon). There is a long-term dataset for grasslands near Bloemfontein by O'Connor et al (2001), another for a fertilizer experiment in grassland at Towoomba near Bela Bela, and a grassland mowing experiment at Ukalinga. These suggest a grassland range of about 100 to 500 gC/m^2/y. There is a savanna estimate for Nylsvley by Scholes and Walker (1993) of 950 g DM/m^2/y (ie~460 gC/m^2/y. Doubling these numbers to get GPP suggests that the GPP estimates in the SA national C sinks study are somewhat too low.

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Module 2: (Section 1.3) – Modelling the effect of predicted climate change and elevated atmospheric CO_2 on terrestrial carbon stocks in important South African biomes

Introduction

This analysis aims to answer two of the principle questions requirements raised in the South African National Carbon Sink Assessment's Terms of Reference:

1. The need to understand the potential effect of projected climate change and elevated [CO2] on terrestrial carbon stocks in important South African biomes
2. The need to understand the potential effect of projected climate change and elevated [CO2] on the outcome of land-use based climate change mitigation activities located in South Africa

These elements were included in the Terms of Reference due to a growing body of evidence which predicts that changes in climate and atmospheric carbon dioxide ([CO2]) may lead to substantial changes in the rate of plant growth, litter decay rates and other ecological variables that determine observed above- and below- ground carbon stocks. In the context of the project, assessing this potential is important to first understand how the terrestrial carbon stocks and fluxes reported in Section 1.1 may change in the future, and second, to understand how the outcome of land-based climate change mitigation activities[‡] identified in Section 2 may be influenced by changes in climate and elevated [CO2].

An extensive body of published work indicates that predicted changes in climate are likely to affect terrestrial ecosystems through changes in primary productivity, litter accumulation and decay rates, fire occurrence and intensity, and several other mechanisms that influence terrestrial carbon stocks and associated fluxes (Ojima et al. 1996, Peng and Apps 1999, van der Werf et al. 2008, Rosenzweig et al. 2008, Doherty et al. 2010). Consideration of this effect of climate change is particularly pertinent in southern Africa where the climate is predicted to change substantially and to a larger extent than the global norm over the next 50 to 100 years (Boko et al. 2007, Engelbrecht et al. 2011).

In addition to the potential influence of changes in climate itself, is the related impact of predicted increases in atmospheric carbon dioxide. Principally through the "CO2 fertilization effect", several published empirical and modelling assessments have indicated that elevated [CO2] may have a substantial influence on plant growth, observed vegetation types and carbon stocks, (Bond and Midgley 2000, Doherty et al. 2010, Kgope et al. 2010).

Due to pure time and cost practicalities, a modelling approach is typically used to assess the potential influence of changes in climate and elevated [CO2] on carbon dynamics in terrestrial ecosystems. Guided by the results of Section 1 and 2 of the National Carbon Sink Assessment, the modelling exercise focused on vegetation types that are important in terms of their contribution to the national carbon stock and opportunities for mitigation activities - grassland, savanna, woodland, sub-tropical thicket and closed canopy forest ecosystems.

[‡] To improve readability, for the remainder of the document "land-use based climate change mitigation activity" has been abbreviated to "mitigation activity"

Two principle scenarios were modelled:

- The effect of climate change and elevated [CO_2] on existing carbon stocks in each vegetation type
- And, the effect of climate change and elevated [CO_2] on the rate of carbon sequestration during the restoration of degraded ecosystems.

The first scenario will allow one to understand the potential impact of climate change on the national terrestrial carbon stock and activities that reduce emissions from deforestation and forest degradation (REDD). The second will provide an estimate of the influence of climate change on afforestation, reforestation and grassland management activities as well as the rate of biomass accumulation in the context of Biomass to Energy initiatives.

The modeling process

Each of the sites in Appendix 1 was modeled using the Century Ecosystem Program[§] that has been successfully used in numerous past studies to model carbon, nitrogen and phosphorus dynamics (e.g. Parton et al. 1993, Song and Woodcock 2003, Mooney et al. 2004, Luo et al. 2008).

Figure. 1 is an example of a typical Century simulation. The model is initially run for approximately 2000 simulated years using a historical climate dataset allowing the program to reach an equilibrium state (section 'a', Fig.1). In the example below, a disturbance event ('b', Fig.1) was then introduced that reduces the carbon in the system (point 'c', Fig. 1). The disturbance event could be an ecological disturbance (e.g. fire), or a management intervention (e.g. unsustainable harvesting or browsing) that leads to a loss of carbon. The pre-2000 simulation routine is then reintroduced from point 'c' onwards and the system is allowed to regenerate.

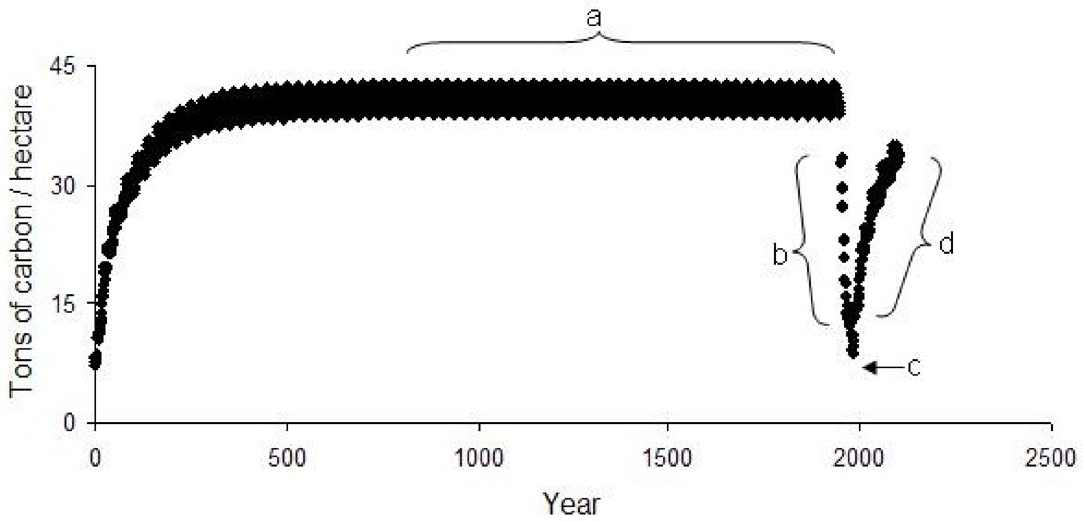

Figure 1 An example of the results of a typical Century Ecosystem Program simulation run for sub-tropical thicket. 'a' is the 'equilibrium' intact state, 'b' is the period in which the carbon stocks are reduced to a 'degraded state' through substantial increases in herbivory or the harvesting of wood. From point 'c', the additional harvesting of wood is removed and the system is allowed to recover (section 'd').

For each vegetation type, a typical degradation event was simulated followed by a potential carbon sequestration, rehabilitation initiative. For the mopane, broad-leaf and fine-leafed savanna sites that are situated in the Kruger National Park, the degradation scenarios were based on the studies of Shackleton et al. (1994), Shackleton (1997) and Scholes (1987) on degraded land in rural communal areas adjacent to the Park. In such communal areas, degradation is due to overgrazing and unsustainable fuelwood collection that reduces the standing biomass to ~ 10-15% of its intact state. The scenario for sub-tropical thicket was based on studies by Lechmere-Oertel et al. (2005) and Mills et al. (2005), that describe the rehabilitation of degraded thicket following unsustainable goat farming in the 1960's and

§ The model is freely available at www.nrel.colostate.edu/projects/century

‘70’s. The grassland scenarios were based on the observations of Snyman and Fouche (1991) in degraded grasslands.

Each of the degradation scenarios cited above were simulated in Century by introducing additional grazing, cropping or fire events during phase ‘b’ in Figure 2. These additional degrading events were then halted at point ‘c’, and the system was allowed to regenerate (phase ‘d’ in Figure. 2.).

For the REDD activity simulation, the model was allowed to reach an equilibrium state. Thereafter changes in [CO2], temperature and rainfall were ramped in over a period of 50 years depending on the particular GCM and scenario simulated.

Sources of data

Appendix A lists the sites modelled during this exercise. Whereas one would optimally seek 20-30 sites strategically positioned to adequately sample variation across each vegetation type, due to time and especially budgetary constraints, this analysis is based on available data in published papers and reports as well as in published and personal datasets.

To adequately parameterize the Century model for a particular site, a substantial set of data is required. At a minimum:

- A 20-30 year record of monthly rainfall and minimum and maximum temperature
- Soil texture - sand / silt / clay context
- Soil carbon content
- Soil nitrogen content
- Soil bulk density
- Leaf lignin content
- Biomass or phytomass

These requirements have constrained the number of potential sites to those listed in Appendix A. Whereas there are a vast number of sites in South Africa where particular metrics have been recorded e.g. aboveground biomass or soil carbon, there are few where the full set of required parameters has been recorded. This is especially true for the more arid areas of the country and the fynbos biome. The results should therefore be viewed as a good indicator of typical carbon sequestration rates expected in each biome and the effect of predicted climate change on carbon stocks and accumulation, but not a comprehensive analysis of the potential range within each biome.

Modelling the effect of predicted climate change and elevated [CO2]

Choice of climate models

The projections of six coupled global circulation models (CGCMs) were used to estimate the potential effect of future climate change on each of the modelled vegetation types (Table 1). The six CGCMs contributed to the Coupled Model Intercomparison Project (CMIP3) and Assessment Report 4 (AR4) of the Intergovernmental Panel on Climate Change (IPCC). All six simulations are for the A2 scenario as described in the Special Report on Emission Scenarios (SRES, Nakicenovic et al. 2000) over the period 1961-2100.

The data was obtained from the CSIR's Climate Studies and Modelling and Environmental Health Research Group that downscaled the CGCMs using a conformal-cubic atmospheric model (CCAM). As noted by Engelbrecht et al. (2012) and Malherbe et al. (2012), the CCAM has been shown to successfully downscale this set of CGCMs for southern Africa.

CGCM	Source
CSIRO Mark 3.5.	Ver 3.5. Commonwealth Scientific and Industrial Research Organisation
GFDL-CM2.0	Ver. 2.0 Geophysical Fluid Dynamics Laboratory, NOAA, United States
GFDL-CM2.1	Ver. 2.1 Geophysical Fluid Dynamics Laboratory, NOAA, United States
ECHAM/MPI-Ocean Model	Max Plank Institut, Germany
MIRO3.2-medres	Japanese Agency for Marine-Earth Science and Technology

Table 1 Coupled Global Change Models used to simulate the effect of projected climate change on terrestrial carbon stocks and associated sequestration rates

Adjusting climate data for each site to a global climate change model

For each CGCM, the projected monthly minimum and maximum temperatures, and precipitation for baseline (2000) and 2050 were extracted for each site location. As the CGCM baseline projection for the baseline in the year 2000 differs from true observed data, the GCM projected change in climatic variables is applied to observed data.

Calculating the change in climatic variables between the baseline and 2050 GCM projections does this. For minimum and maximum temperatures, the change is the absolute difference in temperature between the two projections. In the case of precipitation, the change is calculated as a multiplier as to avoid negative rainfall data been calculated. The change in climatic variables between the baseline and 2050, whether in the form of an absolute value or a multiplier, is then applied to the observed baseline data using a sliding linear scale.

The observed baseline (2000) data is calculated by averaging the minimum and maximum monthly temperatures, and monthly precipitation of observed data for at least the past 30 years. For the majority of study sites, this data was obtained from the South African Weather Bureau.

Calibrating to Century parameter files to model climate change

The changes to the parameters in Century have been done as per recommended for "Enriched CO2 Effects" in the Century 5 User Guide and Reference.

- An additional weather file for each site is created that includes the GCM projected climate changes for 2000 – 2050.
- The transpiration and production rate variables (CO2itr and CO2ipr), the carbon/nitrogen and carbon/potassium ratio variables (CO2ICE(*,*,*)), and the root : shoot ratio (CO2IRS(2)), in the tree and crop parameter files are adjusted to simulate the presence of additional atmospheric carbon dioxide.
- The baseline and projected atmospheric carbon dioxide concentrations are entered into the .fix file by adjusting the CO2ppm parameter and the ramp function is chosen using CO2rmp. These changes to the .fix file are 'switched on' during the simulation by adjusting the CO2 systems variable in the schedule file using event.100.

The results of the modelling exercise indicate that the impact of projected climate change and elevated [CO2] is likely to vary between vegetation types and locations, both in terms of the direction and the magnitude of the effect. Whereas both carbon stocks and sequestration rates are likely to increase in the modelled woodland, savanna and grasslands ecosystems, the change in coastal lowland and scarp forest is anticipated to be neutral to negative in direction (Fig. 2,3).

A 20 year and 30 year period were modelled as these are the project periods typically adopted for land-use based climate change mitigation activities, as well as time-frame often used by Government and commercial entities for land-use planning activities. The observed effect over 20 years is generally extended in magnitude over the 30-year period, although not in a linear manner or a consistent manner between CGCMs (Fig. 2,3). For example, over a 20-year period in Mopane Woodlands, the adoption of the GFDL-CM2.0 CGCM lead to largest change in carbon stocks of the five models used (Fig. 2). However, over a 30 year period, the adoption of the model only leads to marginal additional increase in carbon stocks, whereas the use of the GFDL-CM2.1 model has lead to a substantially larger increase in carbon stocks in the 20-30 year period.

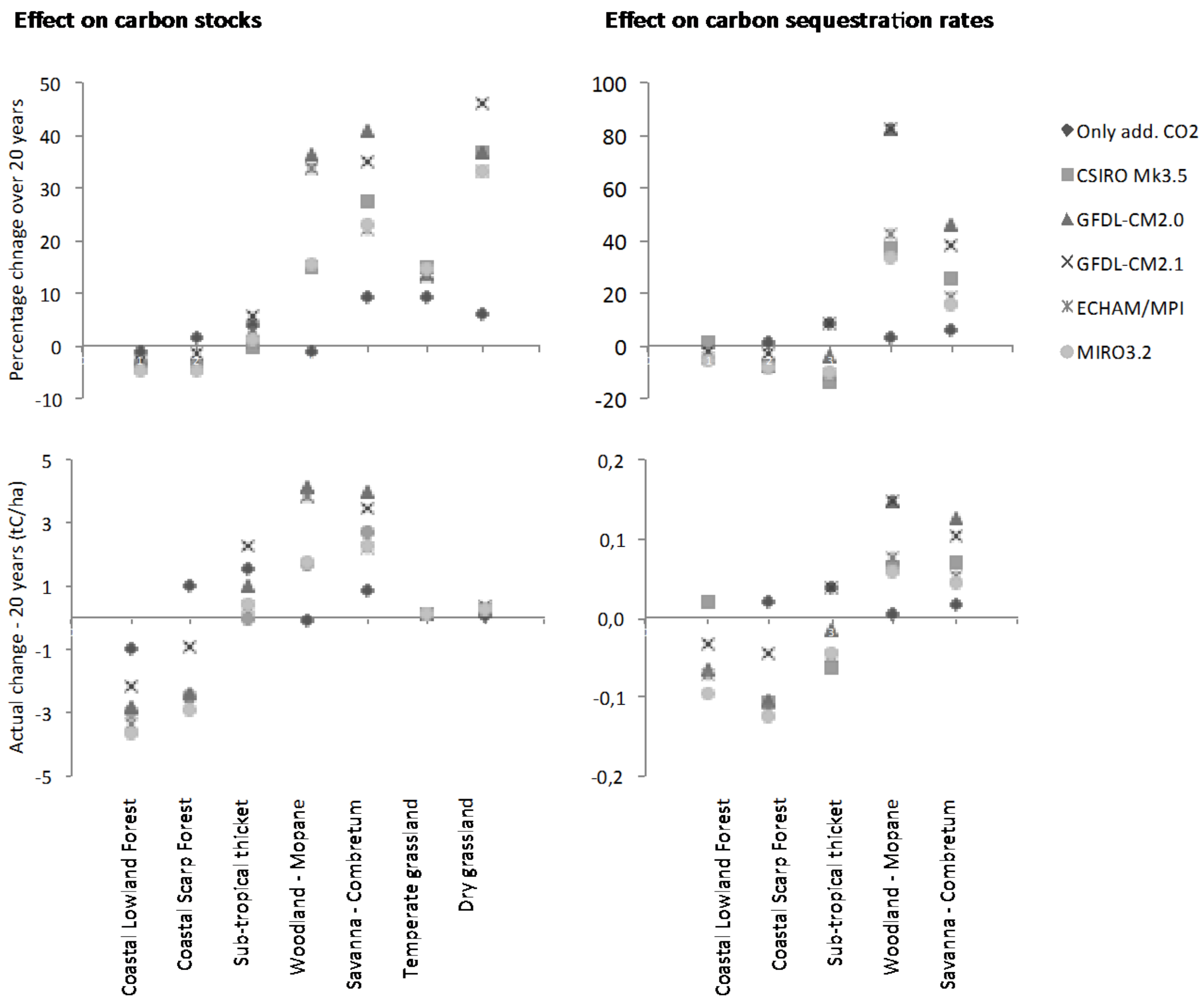

Figure 2. The modeled effect of predicted climate change and elevated [CO2] on aboveground carbon stocks and carbon sequestration rates (during restoration or reforestation activities) over the next **20 years**.

An interesting observation is the range of outcomes predicted by different CGCMs in particular locations (Fig 2,3). For example, the modelled percentage change in aboveground carbon stocks in coastal lowland forest systems ranges from -1 to -4 percent (depending on the particular CGCM used), whereas the results for Combretum savanna site range from 9 to 40 percent.

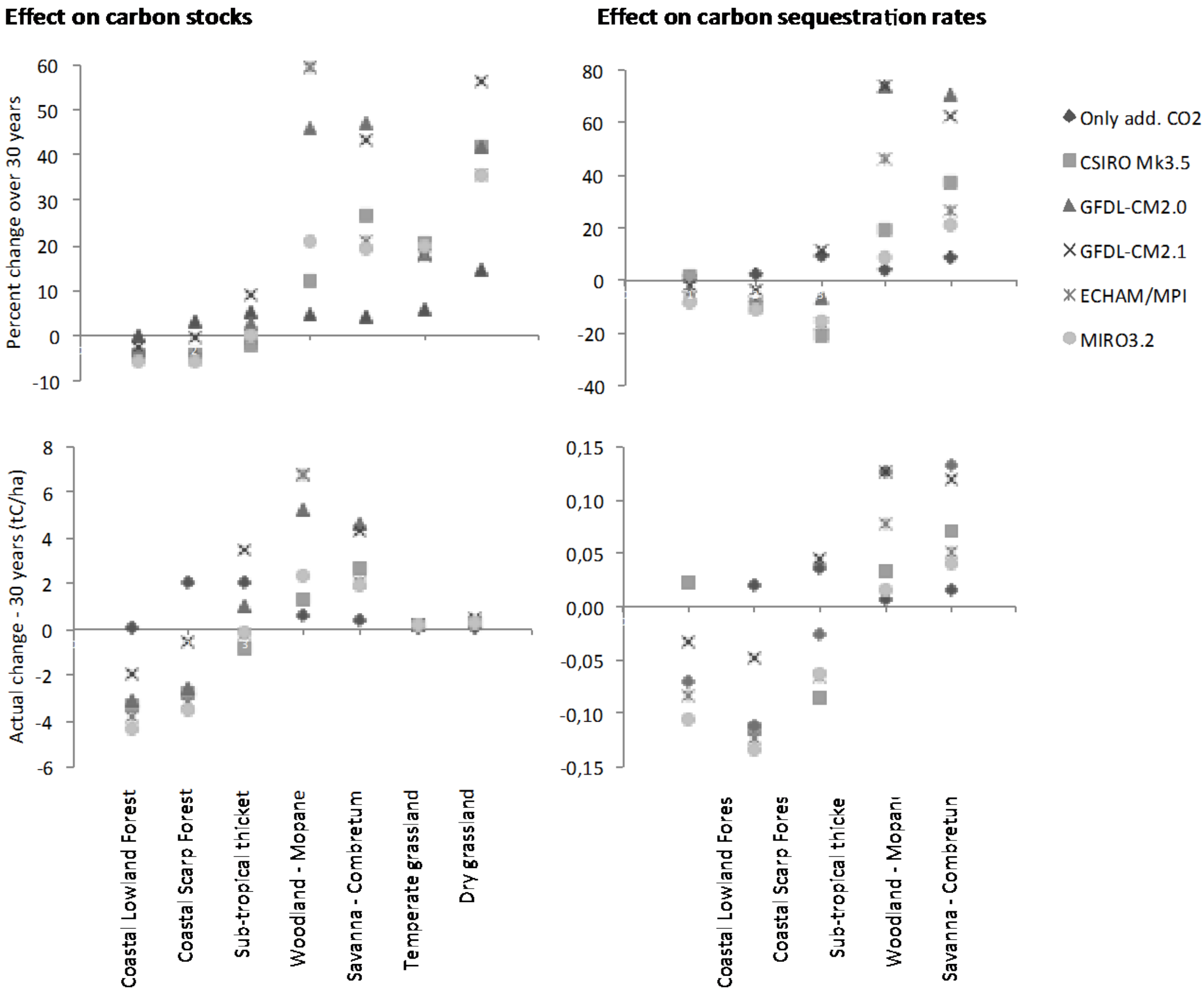

Figure 3: The modeled effect of predicted climate change and elevated [CO2] on aboveground carbon stocks and carbon sequestration rates (during restoration or reforestation activities) over the next **30 years**.

This range of responses is both due to the particular CGCM modelled as well as factors governing, and especially limiting, plant growth and litter and nutrient turnover in particular locations. The changes in carbon stocks and sequestration rates observed in Fig 2 and 3 are broadly related to the changes in minimum and maximum temperature and especially rainfall predicted by each CGCM (Fig 4). However, the response is also substantially influenced by limiting constraints to plant growth in certain systems. For example, plant available moisture may be a clear constraint to carbon sequestration in dry woodland and savanna ecosystems. In this context, an increase in rainfall leads to a clear increase in biomass accumulation. Yet in other ecosystems, for example coastal lowland and scarp forest, a similar change in rainfall leads to a negligible change in carbon stocks. In these ecosystems, plant growth may be more limited by soil nutrient availability rather than climatic factors.

Elevated atmospheric CO2 alone (modelled with a continuation of historical climate) is predicted to lead to a positive change in carbon sequestration rates ranging from 1-8 percent, depending on the particular vegetation type modelled (Fig 2, 3). The effect of [CO2] on standing carbon stocks is less consistent. In certain systems, for example, coastal lowland forest, the effect may be negligible to marginally negative (<1%). However, for most of the ecosystems modelled, elevated [CO2] is anticipated to lead to a 2-10% increase in aboveground carbon stocks over period of 20-30 years.

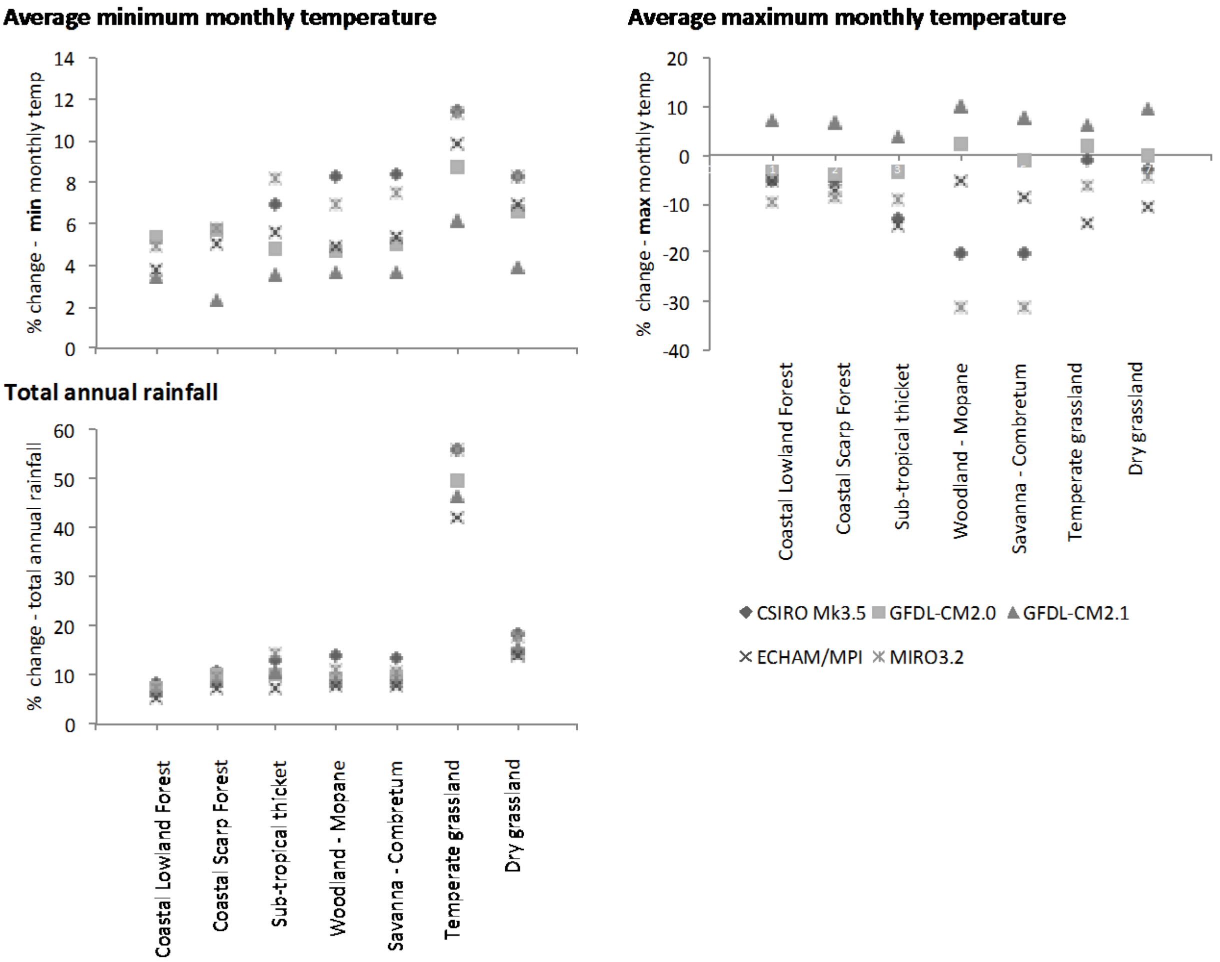

Figure 4: The change in precipitation and minimum and maximum temperature predicted by each Couple Global Circulation Model adopted for the analysis

Relative compared to actual changes

The relative changes in carbon stocks and sequestration rates reported Fig 2a,b and Figure 3a,b, should also be viewed in terms of the actual change in carbon stocks and sequestration rates (Fig. 2c,d and 3c,d). This is especially true when seeking to understand the impact of climate change on the outcome of land-use based mitigation activities and magnitude of the national terrestrial carbon stock. For example, although the relative change in carbon stocks in grassland systems is predicted to be considerable (up to 40%), the actual change equates to less than 0.2tC.ha-1 over 20 years. In comparison, a similar relative change in woodland and savanna systems results in an increase of 3-5tC/ha-1 over the same period.

This is particularly pertinent when considering predicted changes in carbon sequestration rates. Although the relative change is considerable (over 40% in woodland and savanna systems), the actual change equates to an increase of less than 0.1tC.ha-1.yr-1.

Does climate change present a considerable risk to mitigation activities in South Africa?

One of the principle reasons why this analysis was included in the scope of the South African National Carbon Sink Assessment was to understand if climate change and elevated [CO_2] will have a considerable effect on national terrestrial carbon stocks as well as the outcomes of land-use based climate change mitigation activities. Does climate change present a significant risk to the climate change mitigation projects identified in Section II of the assessment (reforestation, afforestation, grassland restoration, biomass to energy)?

The results of this modelling exercise indicate that climate change is likely to have a negligible effect on the outcome of mitigation activities in the majority of vegetation types, if not slightly increasing carbon stocks and sequestration rates in the future. An initial area of concern may be the predicted decrease in carbon stocks and sequestration rates in coastal forest (Fig 2,3), but the magnitude of the predicted change is anticipated to be less than 5 percent over 20 years. These results should be seen relative to other determining factors and in the context of mitigation activities, in the perspective of the initiative's greater risk profile.

A number of forms of risk can affect the outcome of a mitigation activity. Typical risk classes considered include operations, technological and financial risk. For land-use based mitigation activities, an additional class of risk in the form of 'biophysical' risk is considered which includes factors that may effect the permanence of carbon stocks over an activities lifetime, for example, fire, pests and climate change.

Due to these forms of risk, the majority of standards created to verify land-use based mitigation activities (for example, the Verified Carbon Standard (VCS) and Gold Standard), include a compulsory "buffer mechanism" that is a form of risk management through which a Standard provides insurance against permanence and delivery risk over a project's lifetime. At present, the VCS and emerging Gold Standard rules and regulations stipulate a 20-30 percent "buffer", where the volume of issued emission reduction units ('carbon offsets') is discounted by this amount. The withheld units from each project are essentially held in a joint account that allows a Standard to ensure a particular project in case of default.

Considering the risk that climate change presents in this context, the results of the modelling exercise indicate that changes in climate and elevated [CO_2] are generally likely to lead to an increase in carbon stocks -'upside risk'. Where a decrease in carbon stocks is predicted (in the case of coastal forests), the magnitude of the potential change is less than five percent and well within the 20-30 percent discount typically applied to land-use based mitigation projects in a near compulsory manner.

The effect of climate change relative to other drivers

The predicted effect of changes in climate and [CO_2] reported here needs be seen in perspective and especially in the context of a greater set of ecosystem drivers that may also change over time. For example, fire, grazing and utilization regimes may well change in the future as land-use priorities shift and management changes accordingly. Changes in the occurrence or intensity of these drivers may even have a larger effect on carbon stocks than predicted in the above analysis. This point is raised not to discount the need to consider climate change but to caution against viewing its predicted effect in isolation. Rather a true systems ecology approach is required.

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Appendix A:

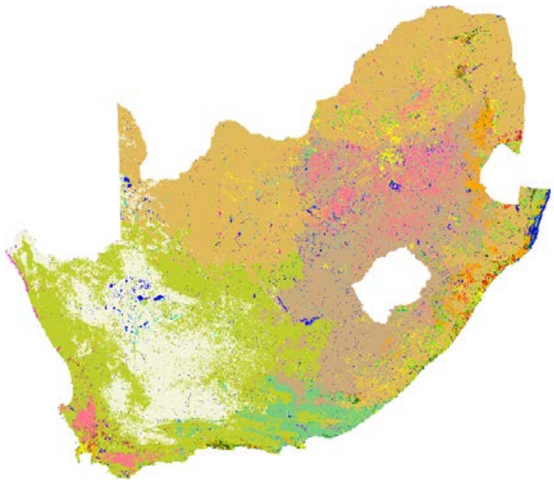
Vegetation type	Location	Geog. co-ords decimal degrees		Elevation	Mean Annual Rainfall	Above-ground carbon stock
		South	East	Meters	mm	tC.ha-1
Coastal Lowland Forest	eThekwini	29,82542	31,01564	74	800	75
Coastal Scarp Forest	eThekwini	29,80402	30,33656	380	800	65
Sub-tropical thicket	Baviaanskloof	33,63857	24,45454	450	413	41
Savanna - Combretum	Skukuza	24,99244	31,59774	264	572	9,5
Woodland - Mopane	Letaba	23,85367	31,57554	234	506	11,5
Dry grassland	Bloemfontein	29,10000	26,95000	1350	560	0,3
Moist temperate grassland	Cathedral Peak	28,92680	29,12730	2565	1324	2,3

Table A.1. The principle set of input variables used to calibrate the Century Model for each location.

Vegetation type	Soil texture (fraction 0-1)			Bulk Density	Source
	Sand	Silt	Clay	g/cm3	
Coastal Lowland Forest	0,89	0,03	0,08	1,39	Glenday, 2007
Coastal Scarp Forest	0,76	0,08	0,16	1,19	Glenday, 2007
Sub-tropical thicket	0,83	0,09	0,08	-	Mills et al. 2005, Lechmere-Oertel et al. 2005, Powell 2009
Savanna - Combretum	0,69	0,05	0,26	1,74	Shackleton 1997.
Woodland - Mopane	0,80	0,10	0,10	1,35	Scholes 1987, Shackleton 1997, Paterson and Steenkamp 2003
Dry grassland	0,87	0,03	0,1	1,48	du Preez and Snyman 1993, Snyman 2004, Snyman 2009
Moist temperate grassland	0,23	0,24	0,53	0,80	Everson 1985, Everson et al. 1998

Module 3: (Section 1.4) – Modelling of '2020' Future South African Land-Cover

Summary Report & Metadata



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Version 2

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ARC	Agricultural Research Council
CDNGI	Chief Directorate National Geospatial Information
CGS	Council for GeoScience
CSIR	Council for Scientific and Industrial Research
DAFF	Department of Agriculture, Forestry and Fisheries
DEA	Department of Environmental Affairs
DFID	Department for International Development
DRDLR	Department of Rural Development and Land Affairs
DWA	Department of Water Affairs
EIA	Environmental Impact Assessment
EWT	Endangered Wildlife Trust
FEPA	Freshwater Ecosystem Priority Areas
GHG	Greenhouse Gas emissions
GIS	Geographic Information System
GTI	GeoTerraImage
INR	Institute of Natural Resources
KZN	Kwa-Zulu Natal
MODIS	Moderate Resolution Imaging Spectroradiometer
NCCRP	National Climate Change Response Policy
NDP	National Development Plan
NFEPA	National Freshwater Ecosystem Priority Areas
NPAES	National Protected Area Expansion Policy
SA	South Africa
SANBI	South African National Biodiversity Institute
SIP	Strategic Infrastructure Plan
SKA	Square Kilometre Array
UNFCCC	United Nations Framework Convention on Climate Change
WRC	Water Research Commission

INTRODUCTION

In early 2013, the Department of Environmental Affairs (DEA) commissioned a National Carbon Sink Assessment to better understand the size and nature of terrestrial carbon stocks and fluxes in South Africa. The Assessment forms part of a larger suite of activities implemented under the National Climate Change Response Policy (NCCRP) with the purpose of: "…assessing the current national carbon sinks related to afforestation, forest restoration, wetlands, agricultural practice, bio-fuels, urban greening and all significant changes in land use and to quantify the potential future carbon sinks under varying climate change scenarios and land use change."

The national assessment consists of three principle components:

- Understanding the status and dynamics of the national carbon sink
- Understanding the potential for land-use based climate change mitigation opportunities
- Supporting policy: Current status and future needs

This report, focusing on historical and potential future changes in land-use, forms part of the first component of the analysis. Together with other elements of Section 1 - a national-scale map of terrestrial carbon stocks and fluxes and an analysis of the potential effect of predicted climate change on carbon stocks and fluxes - it forms the required template from which to develop the implementation and policy aspects of the assessment. In itself, Section 1 forms the country's first real understanding of the status and dynamics of carbon stocks at a national scale. Its results are crucial not only in terms of the NCCRP, but also for national planning purposes and South Africa's formal communications to the United Nations Framework Convention on Climate Change (UNFCCC).

In terms of listed in the Terms of Reference that this report addresses:

- *Mapping of geographic distribution of vegetation types, agricultural landscapes, forests, and natural ecosystems and making an inventory of historic trends and existing carbon-stocks, emissions and removals from these areas.*
- *Model anticipated shifts in geographical ranges and changes in the composition of species in the different ecosystems (due to climate change) and managed landscapes (due to land use change) which will have an effect on sink-source capacity of these landscapes.*
- *Mapping of the historic and current land use changes and land cover changes that have an effect in GHG emission profile of the sector.*
- *Assessing the historical and likely future effects of land use changes and land cover changes on GHG emissions of the AFOLU sector – e.g. conversion of grasslands to agricultural landscapes. This should cover a period to be recommended by the service provider based on available evidence.*

The advertised Terms of Reference initially required the service provider to assess both an analysis of historical as well as potential future changes in land-use (i.e. from 2000 through to 2020). Fortunately, GTI was already in the process of undertaking an analysis of current land-cover and historic changes in land-use at a national scale on behalf of the DEA in support of national GHG modelling and reporting information needs (a project co-ordinated by the University of the Witwatersrand and funded by the United Kingdom's Department for International Development). The analysis of current and historical land-cover was completed in April 2013. A full description of the 2001, 2005 and 2010 land-cover datasets is provided in Appendix A (2001, 2005 and 2010 MODIS generated SA Land-Cover Datasets). This analysis therefore focuses only on a potential '2020' future South African land-cover landscape.

2020 SA Land-Cover Dataset

The modelled '2020' land-cover dataset is not strictly linked to that specific year, but is rather an interpretation of a likely scenario in approximately 10 – 15 years time. The future changes are based on potential landscape changes arising from either planned or highly likely land-use changes, associated developments, and resultant land-cover changes, linked if possible to current or proposed legislation. Geographical restrictions on land-cover and land-use changes have been included within the modelling process by using current and potentially protected, conserved and environmentally sensitive areas likely to be safeguarded from change through an EIA or similar legislated processes.

The data product is based on the same ± 500 x 500m raster cell framework used in the 2010 base land-cover dataset; is presented in the same Albers Conical Equal Area (18:32:24:00), WGS84 map projection format; and contains the same 17 x land-cover classes.

As per the 2010 dataset, only the dominant (modelled) land-cover (or land-use) class is shown in each pixel, although in reality it can be expected that a significantly greater range of cover classes will occur within each pixel extent. For this reason therefore, the reported areas of each land-cover cannot be seen as exact measurements, but rather as comparative modelled areas, which approximate to real-world land-cover area statistics. The modelled results are directly dependent on the validity and accuracy of the modelling data inputs, theoretical assumptions and associated modelling rules.

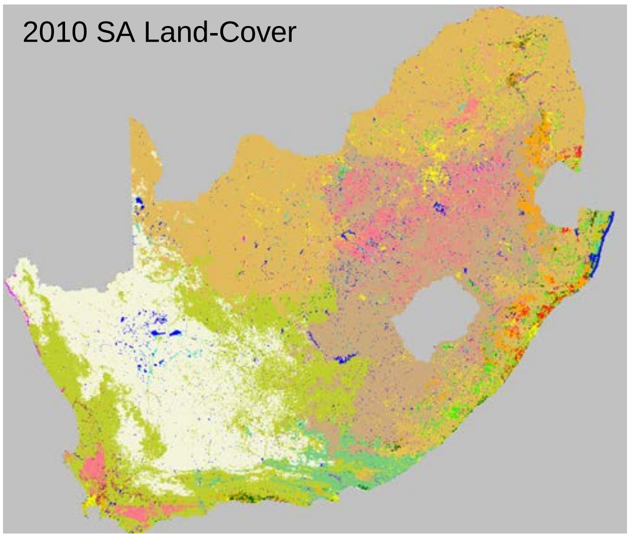
Due to the modelling processes and data inputs used it should be clearly understood and communicated to all end-users that the 2020 land-cover product, as with the 2001, 2005 and 2010 land-cover products, has been developed *specifically* in support of the DEA carbon stock reporting information needs and should *not* be considered a new national land-cover dataset for wider application without full knowledge and understanding of the manner and processes by which it has been generated. Figure 1 compares the 2010 and 2020 SA land-cover datasets.

The "2020" land-cover modelling is based on readily accessible reference information and spatial data, obtained from a wide range of sources, which in GTI's view encapsulate all major drivers and restrictors of landscape change that are generically applicable at the scale and detail contained in the land-cover dataset. Full disclosure of the data sources, data inputs, data modelling and final model outputs are provided below in order to provide transparency on the overall methodology, in support of further modifications and improvements to this initial output.

2020 Land-Cover Results

As indicated previously, the combination of a coarse spatial modelling resolution (i.e. ± 500 x 500m cells, based on the source MODIS satellite imagery format), and the limitation of only reporting the dominant (by area) land-cover class in each cell has influenced the area statistics for each of the modelled 2020 land-cover class (as it did with the modelled 2001, 2005 and 2010 land-cover datasets). It is however still possible to compare the results of each land-cover dataset to determine changes in landscape composition.

Figure 1: Comparison of modelled 2010 and 2020 SA land-cover datasets.



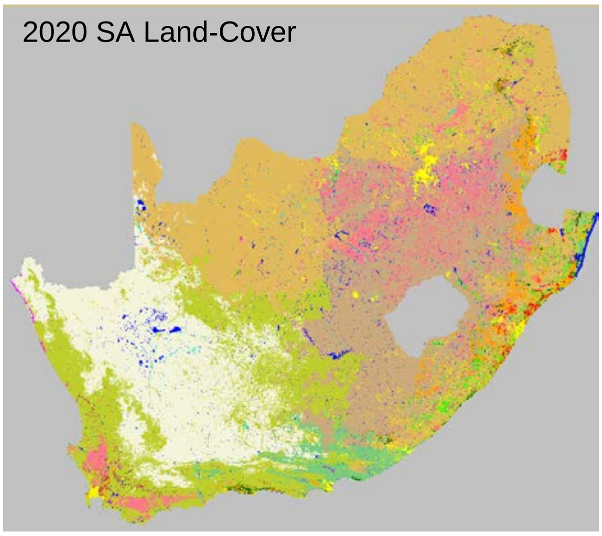


Table 1 below contains the following:

- Modelled extent of each land-cover in Ha, for 2001, 2005, 2010 and 2020,
- Modelled extent of each land-cover as %, for 2001, 2005, 2010 and 2020,
- Percentage change in land-cover extent between 2001 and 2005,
- Percentage change in land-cover extent between 2005 and 2010,
- Percentage change in land-cover extent between 2010 and 2020,
- Percentage change in land-cover extent between 2001 and 2010,
- Percentage change in land-cover extent between 2001 and 2020.

	Landcover class	2001		2005		2010		2020			% change	% change	% change	% change	% change
		HA	%	HA	%	HA	%	HA	%		2001-2005	2005-2010	2010-2020	2001-2010	2001-2020
1	Indigenous Forest	552496	0.5	534567	0.4	477456	0.4	475805	0.4		-3.2	-10.7	-0.3	-13.6	-13.9
2	Thicket	3325699	2.7	3058480	2.5	2874000	2.3	2800118	2.3		-8.0	-6.0	-2.6	-13.6	-15.8
3	Savanna	36757626	30.1	36066931	29.6	35822295	28.8	35092289	28.8		-1.9	-0.7	-2.0	-2.5	-4.5
4	Plantations	2277153	1.9	2204923	1.8	2144402	2.1	2572467	2.1		-3.2	-2.7	20.0	-5.8	13.0
5	Annual commercial crops (non-pivot)	5832155	4.8	5817400	4.8	6439682	6.0	7271900	6.0		-0.3	10.7	12.9	10.4	24.7
6	Annual commercial crops (pivot)	344147	0.3	384551	0.3	426586	0.3	425621	0.3		11.7	10.9	-0.2	24.0	23.7
7	Orchards	165693	0.1	179311	0.1	181670	0.1	180705	0.1		8.2	1.3	-0.5	9.6	9.1
8	Viticulture	231640	0.2	233892	0.2	234900	0.2	234900	0.2		1.0	0.4	0.0	1.4	1.4
9	Annual semi-commercial/subsisten	692797	0.6	626571	0.5	1019851	0.8	1002715	0.8		-9.6	62.8	-1.7	47.2	44.7
10	Sugarcane	239597	0.2	296386	0.2	313328	0.3	309511	0.3		23.7	5.7	-1.2	30.8	29.2
11	Settlements	1775742	1.5	1814517	1.5	1821101	1.9	2371088	1.9		2.2	0.4	30.2	2.6	33.5
12	Wetlands	1105764	0.9	1135381	0.9	1137290	0.9	1132293	0.9		2.7	0.2	-0.4	2.9	2.4
13	Grassland	24463078	20.1	25178865	20.6	24830129	19.7	23977880	19.7		2.9	-1.4	-3.4	1.5	-2.0
14	Mines	195889	0.2	177874	0.1	179161	0.2	245923	0.2		-9.2	0.7	37.3	-8.5	25.5
15	Water bodies	1832767	1.5	1699501	1.4	1715092	1.4	1718588	1.4		-7.3	0.9	0.2	-6.4	-6.2
16	Bare ground	15620226	12.8	22896415	18.8	22642814	18.5	22616907	18.5		46.6	-1.1	-0.1	45.0	44.8
17	Other	26539667	21.8	19646571	16.1	19692380	16.0	19523427	16.0		-26.0	0.2	-0.9	-25.8	-26.4
	totals	*121952136*	*100*	*121952136*	*100*	*121952136*	*100*	*121952136*	*100*						

Note: Ha values are calculated from a pixel size of 463.31 x 463.31m per raster cell

Table 1. Comparison of modelled 2001, 2005, 2010 and 2020 SA land-cover datasets.

Comments on Land-Cover Change Results

Overall, the comparison of all modelled land-cover results show an expected general increase in the area of transformed land-cover classes (i.e. mines, settlements, plantations, and cultivation), and a comparable loss in natural / semi-natural vegetation types between 2001 and 2020. The rate and extent of change however varies significantly with cover type (Figure 2 & 3).

During the period 2001 – 2010 the expansion of all cultivated lands, especially semi-commercial subsistence-level activity and sugarcane represent the main drivers of landscape change in terms of percent change in area (Fig. 2 & 4). Furthermore, there is a substantial increase in the area of 'bare ground' on private, communal and Government land. The increase in 'bare ground' may be both due to the degradation of indigenous vegetation classes (forests, thickets, savannas and grasslands) as well as short-term decreases in primary productivity in rangelands. One should not therefore solely interpret the increase in bare ground as due to the long-term conversion of intact indigenous ecosystems, but rather a combination of short-term decreases in vegetation cover (linked to primary productivity) as well as some longer-term changes in land-use.

During the modelled period from 2010 – 2020, this pattern changes with both sugarcane and subsistence cultivation decreasing in spatial extent, while commercial agriculture continues to expand (note that this excludes pivot irrigated cultivation since this was not a modelled class for 2020 since it was impossible to predict where an individual farmer would place new structures). Mines, settlements and plantation areas all show potential expansion with a corresponding decrease in indigenous thicket, savannas and grasslands (Fig. 2 & 5). The change in area covered by bare ground is marginal in this period compared to the previous ten years.

The variable changes indicated for water bodies across all years, representing both increases and decreases can be attributed to the wetter conditions under which the earlier 2001 MODIS imagery was acquired compared to drier subsequent years, despite the counterbalancing effect of increasing the number of major water dams included in the 2020 landscape scenario.

The greatest potential percentage area losses in natural vegetation are associated with thickets and indigenous forest, mainly as a result of the cell-based modelled agricultural expansion in the Eastern Cape and the creation of new dams. However this does not necessarily equate with the largest areas of actual physical transformation, since whilst the percentage change is high for indigenous forests (13.9%), the forest class represents less than 0.4 % of the total area of S. Africa; compared to a 2.0% loss for grasslands, which cover ± 20 % of S. Africa.

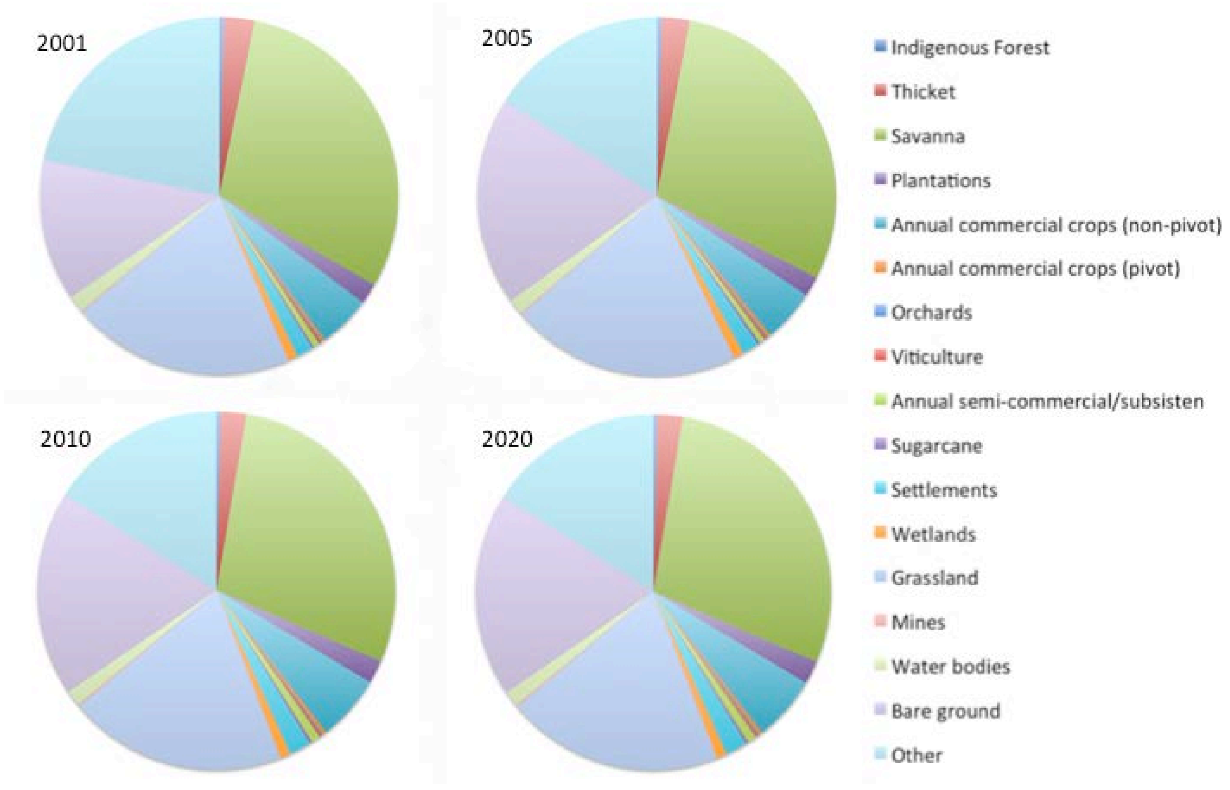


Figure 2 Comparison of modelled 2001, 2005 2010 and 2020 SA land-cover datasets.

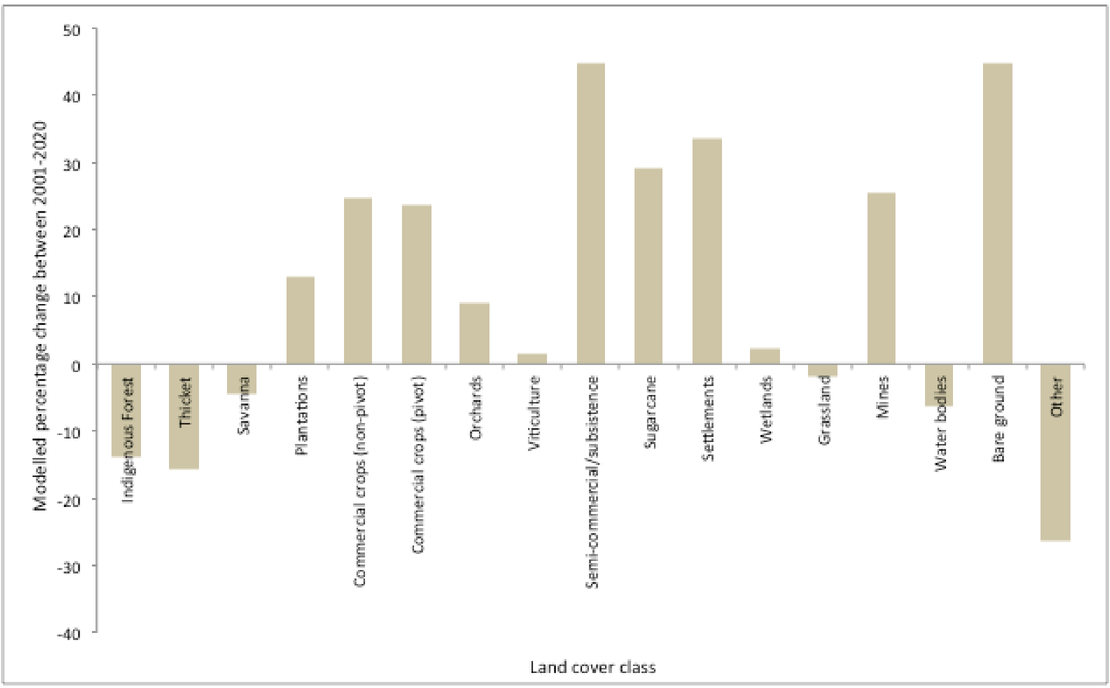


Figure 3 Modelled percentage change in each land-cover class between 2001 – 2020

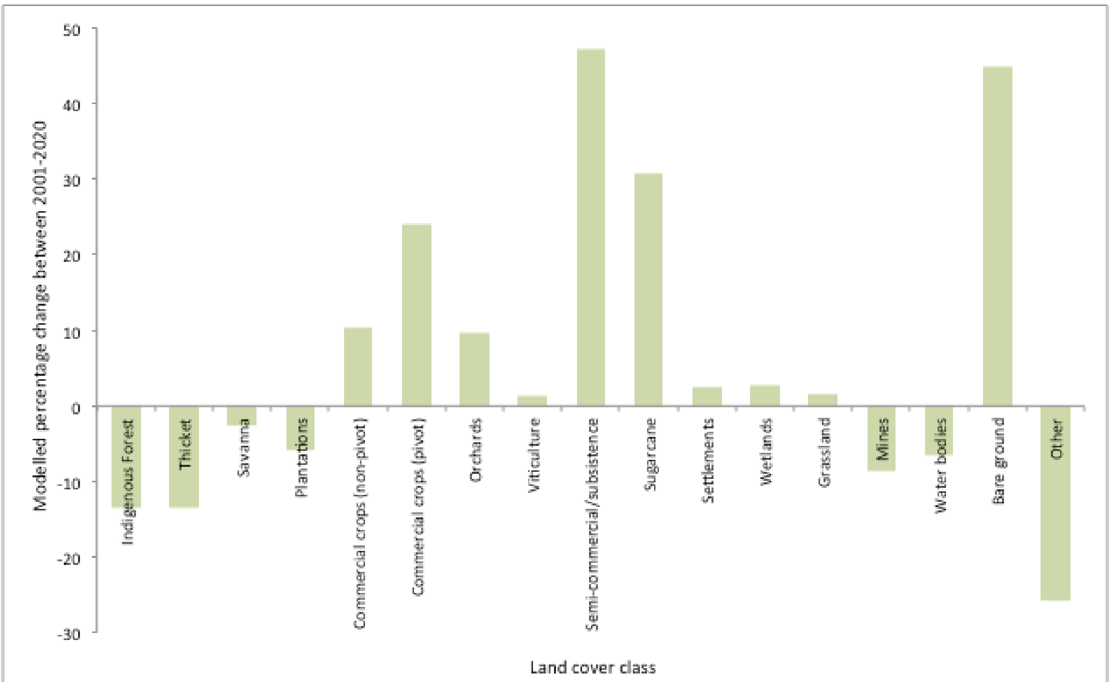


Figure 4: Modelled percentage change in each land-cover class between 2001 – 2010

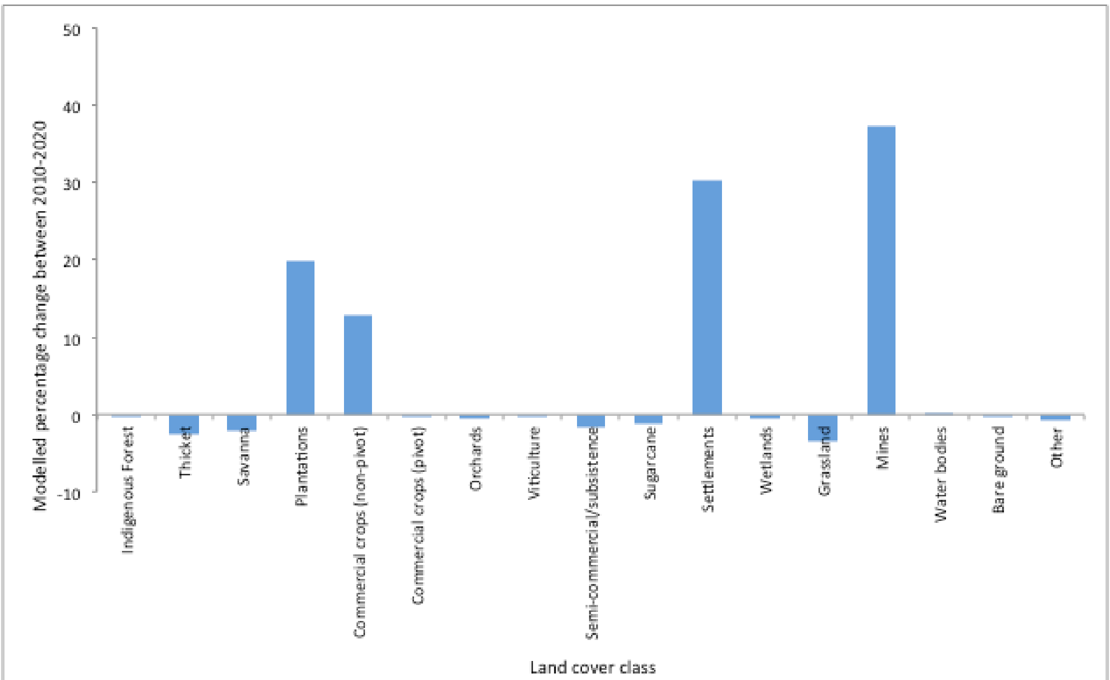


Figure 5: Modelled percentage change in each land-cover class between 2010 – 2020

Potential terrestrial carbon stock and flux implications

To fully understand the impact of historical and predicted future land-cover changes on the size of the national terrestrial carbon stock and associated fluxes, the GIS surfaces generated in this analysis need to be integrated into a spatially explicit carbon stock and flux model (for example, the model created by the CSIR in Section 1.1 and 1.2 of the National Carbon Sink Assessment). Such a model would allow the carbon stock and flux implications of changes in land-use to be assessed in detail and would provide valuable data for Government planning and UNFCCC reporting purposes.

In the interim, it is reasonable to assume that the observed historical change in land-use in South Africa (the general conversion of indigenous landscapes into built environments and commercial and subsistence agriculture) has led to a net decrease in the size of the national terrestrial carbon stock. As indigenous ecosystems are cleared and ploughed (in the case of cultivation), the carbon sequestered in above-ground biomass and soils is released into the atmosphere.

The predicted expansion of exotic plantations over the next 10 years may lead to an increase in woody carbon stocks in particular forestry areas, but overall, the size of the national terrestrial carbon stock is expected to decrease in size due to the anticipated expansion of settlements, mines and areas under commercial cultivation.

Modelling Data Sources

The following organisations were contacted either telephonically, by email, internet and/or physical meetings to source potential information and spatial datasets in support of the future land-cover modelling:

- Department of Rural Development and Land Affairs (DRDLR), Chief Directorate National GeoSpatial Information (CDNGI),
- Department of Rural Development and Land Affairs (DRDLR), Spatial Planning and Information (SPI)
- Endangered Wildlife Trust (EWT)
- i@consult (commercial Town and Country Planners, Pretoria)
- CSIR Built Environment (CSIR-BE), (Pretoria)
- CSIR Natural Resources and Environment (CSIR-NRE), (Stellenbosch)
- SA National Biodiversity Institute (SANBI) (via BGIS website)
- Gauteng City-Region Observatory (GCRO)
- NW Provincial Government (NWPG), Dept of Economic Development, Environment, Conservation and Tourism (DEDECT)
- Department of Water Affairs (DWA), Directorate of Planning
- Department of Environmental Affairs (DEA), Directorate of Planning
- Department of Environmental Affairs (DEA), Atmospheric Carbon Mitigation
- Department of Environmental Affairs (DEA), EIM Systems and Tools
- Department of Agriculture, Forestry and Fisheries (DAFF), Directorate Land Use and Soil Management
- Department of Agriculture, Forestry and Fisheries (DAFF), Directorate: Forestry Regulation and Oversight
- MetroGIS (commercial GIS-Environmental Planning company)
- Council for GeoScience (CGS)
- STATS SA
- ESKOM (GIS Techonology, Midrand).

Modelling Data Inputs

The following datasets were used as the inputs into the future SA land-cover modelling, based on minimising duplication of (comparable) information from different sources, suitability and relevance of data content, geographical coverage, (perceived) information reliability and age.

Land-cover change restrictor (i.e. "protectionist") data:

- ***DEA Formal Protected Areas***: Formally (i.e. legally) protected national and provincial conservation areas (vs 2013), (source: DEA)
- ***SANBI Protected Areas***: Informal (i.e. no legal protection) conservation areas, (i.e. areas defined by formal administrative boundaries such as ownership, but not formally (i.e. legally) protected in terms of natural resource content, e.g. private game reserves, conservancies etc, but which could expect a significant level of developmental protection from EIA processes, public pressure etc (souce: SANBI)
- ***SANBI "National Protected Area Expansion Policy" 2008 (NPAES):*** future national and regional areas likely to become legally protected (source: SANBI BGIS)
- ***SANBI Threatened Ecosystems*** dataset: areas not defined by biodiversity / natural resources rather than administrative boundaries, which could expect a significant level of developmental protection from EIA processes, public pressure etc (source: SANBI BGIS)
- ***Water Research Commission's (WRC) "National Freshwater Ecosystem Priority Areas for South Africa" (NFEPA)*** Atlas, sub-quaternary River FEPA dataset (source WRC Atlas of Freshwater Ecosystem Priority Areas data CD); which could expect a significant level of developmental protection from EIA processes, public pressure etc (source: WRC Atlas data CD).

Land-cover change driver (i.e. "transformer") data:

- ***Agricultural Research Council (ARC) national (agricultural) Land-Capability Dataset***, which defines 8 x agricultural potential land-capability classes, based primarily on climate (rainfall), terrain and soils. A digital (vector) version of this was sourced from DAFF.
- ***DAFF Potential Forestry Expansion Datasets***, based on climate, terrain and soil suitability. The data for the E Cape was originally supplied to DAFF as part of a Strategic Environmental Assessment (SEA) for the Zone of Afforestation Potential in the E. Cape (Coastal and Environmental Services (CES) May, 2006). The data for Kwa-Zulu Natal was sourced from a DWA commissioned report by the Institute of Natural Resources (INR): Afforestation Potential Study in KZN and Mpumalanga: Environmental Assessment Report (March 2009).
- ***DWA New Dams***: Location of planned and/or proposed new major water storage dams, as described by DWA. In the majority of cases the geographical extent of the proposed new dam (maximum water level) was manually interpreted from pdf (or equivalent) engineering map diagrams onto relevant base (satellite) imagery before inclusion in the future land-cover modelling. The following dams were included: De Hoop (Olifants, Mpumalanga), Foxwood (Adelaide, E.Cape), Springrove (Durban), Nwamita (Levhuvhu, Letaba), and Zalu (Lusikisiki, E Cape).
- ***CGS Coal Reserves & Mining Rights***: Approximate boundary of all major coal reserves, and associated exploration and current and future extraction licences,

based on farm and sub-farm units (as granted by Department of Minerals and Energy up to 2012), as sourced from the Council for GeoScience.

- ***CGS Iron / Manganese Reserves & Mining Rights***: Approximate boundary of all major iron and manganese reserves, and associated exploration and current and future extraction licences, based on farm and sub-farm units (as granted by Department of Minerals and Energy up to 2012), and sourced from Council for GeoScience.
- ***ESKOM Future Power Stations***: Point coordinate data for future planned and/or proposed ESKOM power stations (all fuel types), major regional sub-stations, wind and solar farms. These datasets were sourced independently from DEA and ESKOM. Any duplication of information (based on coinciding locations) was eliminated before modelling commenced.
- ***CDNGI CRDP's***: Geographic boundaries of administrative districts / municipalities defined as priority development regions within the DRDLR's Comprehensive Rural Development Programme. These were sourced from the CDNGI.
- ***NDP / SIP Mega Build Projects***: significant urban-build and / or construction projects as defined in the National Development Plan (NDP) / Strategic Infrastructure Plan (SIP), excluding those already defined separately (i.e. ESKOM capital expansion projects). These were sourced from CSIR Built-Environment as a (point-based approximate location only) digital GIS dataset.
- **SKA:** Approximate geographic footprint of the Square Kilometer Array (SKA) telescope project. This was sourced from information available on the internet (www.ska, www.wikipedia)

The following section describes the actual modelling rules used to create the "2020" SA future land-cover:

Protected Areas

Protected areas were defined on 5 levels, based on the level of existing legal protection, possible future legal protection, and likely protection from processes such as EIA's etc, especially if found in a pre-defined environmentally sensitive or threatened area.

Level	Protection		Dataset
0	least	All other undefined areas in S.A	n/a
1		All "Level 1" FEPA threatened sub-quaternary river catchments (defined on catchment boundaries).	SANBI / WRC
2		All "critically" threatened ecosystems (not defined on any formal administrative and/or ownership boundaries.	SANBI
3		All future Protected Areas Expansion Plan sites	SANBI
4		All existing informal conservation areas, i.e. no legal status, other than defined within formal administrative and/or ownership boundary, e.g. private game parks, conservancies etc)	SANBI
5	maximum	All existing formal conservation areas protected by legal status.	DEA

Agricultural Expansion:

According to DAFF, there is a need to develop ± 1 M ha of compensatory new agricultural land to replace cultivated land expected to be lost to mining in the near future. The regional priorities for this replacement land are likely to be E.Cape,, KZN, NW and then Limpopo. Very little expansion is expected within the Free State since this already at near maximum cultivation capacity. Note that modelled future cultivation *expansion* was limited to only the commercial cultivation class, and did not include any changes to subsistence, orchard, viticulture or sugarcane classes, since these are not considered as primary food security classes, and (b) no national-level data was identified to support future modelling of these specific crop-types. Potential new cultivated expansion areas were modelled thus:

- high agricultural potential land (as defined by ARC land capability classes 1- 4), re-weighted according to provincial location:

		DAFF land capability rating			
Provincial weights		1	2	3	4
E.Cape	1	1	1	2	3
KZN	2	1	1	2	3
NW	3	1	2	3	4
LPP	4	1	2	3	4

where 1 = most likely to be new cultivation

- that is currently classified as natural vegetation (excluding indigenous forests) in 2010, or

- classified as coal mines in 2010, and thus rehabilitation of high potential agricultural land could be possible by 2020, and
- on slopes <20° (as defined using the SRTM terrain dataset, re-scaled to the same cell resolution as the SA modelling exercise), which is the CARA (Conservation of Agricultural Resources, Act 4 / 1983) defined threshold for conventional cultivation, and
- with priority weightings applied to targeted provinces (EC = 1st, KZN = 2nd, NW = 3rd and Limpopo = 4th, or lowest weighting), and
- not identified as future 2020 mining sites, and
- not identified as future 2020 major dam / reservoir inundation sites, and
- not within protected areas (classes 4 and 5).

OR

- as above, but inclusive of forestry potential classes 2 if the potential land falls within a CRDP defined district boundary (to allow for expanded rural development).

Forestry Expansion

According to DAFF, future expansion of commercial forestry is most likely to occur in either E.Cape or KZN, since Mpumalanga is at near maximum capacity. Potential new cultivated expansion areas were modelled thus:

- high forestry potential land (classes 1 for both E.Cape and KZN data),
- that is currently classified as natural vegetation (excluding indigenous forests) in 2010, and
- that is not targeted for future cultivation expansion, and
- not within protected areas (levels 3, 4 or 5), and
- not identified as future 2020 mining sites, and
- not identified as future 2020 major dam / reservoir inundation sites, and
- on 2010 existing coal mines that could be re-habilitated

OR

- as above, but inclusive of forestry potential classes 2 if the potential land falls within a CRDP defined district boundary (to allow for expanded rural development).

Dam Expansion

All major DWA defined future dam developments were incorporated into the 2020 SA land-cover based on the best available interpretation of maximum flood level. All existing 2010 land-covers were over-written with the new dam extent, except for settlement-classified data cells, regardless of any future planned land-cover, use or protection status. Note this possibility of new dam extent overlapping existing urban codes is possible due to the single majority cover-code allocation to each pixel and the coarse resolution of the data modelling.

Future Coal Mines

Potential 2020 coal mines were defined as all land-cover pixels:

- located within a 500 km buffer (i.e. 1 km diameter) radius of the centroid point of each farm portion within which a future coal exploration and/or extraction licence has been granted, and

- which are located within defined national coal reserve areas; and
- which had not been previously identified as mining in either 2000, 2005 and/or 2010 land-cover datasets, or settlements, and
- were not within level 4 or 5 protected areas, or a 40km buffer exclusion zone around the SKA telescope development.
- Future coal mines were given priority over future cultivation and forestry expansion areas.

Future Iron / Manganese (Non-Coal) Mines

Potential 2020 iron and manganese mines (i.e. minerals with large open-cast mining footprints) mines were defined as all land-cover pixels:

- located within a 500 km buffer (i.e. 1 km diameter) radius of the centroid point of each farm portion within which a future iron / manganese exploration and/or extraction licence has been granted, and
- which are located within defined national iron and manganese reserve areas; and
- which had not been previously identified as mining in either 2000, 2005 and/or 2010 land-cover datasets, or settlements, and
- were not within level 4 or 5 protected areas, or a 40km buffer exclusion zone around the SKA telescope development.
- Future coal mines were given priority over future cultivation and forestry expansion areas.

Future Infrastructure Build

Transformation foot-prints from potential future large infrastructure build projects were all incorporated into the "settlements" class, regardless of the type of infrastructure development. The potential expansion areas were defined as a 1km buffer (i.e. 2 km radius) around the defined central location point for all ESKOM future power stations (regardless of fuel type), and the NDA/SIP defined Durban Bridge Development project. Future ESKOM power sub-stations and DEA/ESKOM defined potential wind and solar power farms were allocated a single 500x500m pixel footprint. Solar and wind farm locations were defined as were the ESKOM sourced SEA phase 1 (solar/wind) potential areas intersected with the centroid points (of each farm unit) for which there was an associated DEA sourced EIA application for a wind or solar park. The SKA telescope development footprint was defined as a 10km buffer around the core location of the SKA development. It is however acknowledged that the SKA development is a low impact development (within a large area) and this modelling approach may have created an over-emphasis of actual land-cover change.

Future Urban Expansion

Future urban expansion areas were modelled using a 3x3 moving window majority filter over all existing 2010 "settlement" pixels, and re-coding all adjacent non-urban pixels to "settlements" if the majority of surrounding pixels were classified as "settlements" in 2010, and the targeted new "settlement" cell was:

- Within 10km of any of the 2020 defined new infrastructure build cells (based on ESKOM and other mega projects), or
- Within a 2010 defined metropolitan or (selected) municipalities deemed to have development / expansion potential (i.e. Ekhurhuleni, eThekwini, City of JHB, Buffalo City, City of Cape Town, Mangaung, Emalahleni, Mbombela, The Msunduzi, uMhlathuze, Nelso Mandela Bay, City of Tshwane, Rustenberg and Mafikeng), or

But *not*:

- Within a protected area of level 4 or 5, or
- Within potential agricultural lands defined by land-capability classes 1 and 2, or
- On 2010 cells as cultivated land (except for sugar-cane, which was allowed, as a non-food security crop to be "lost"), or
- On 2020 or 2010 cells containing mines, plantations, wetlands, or water; or
- On slopes > 20°;
- Within the 40km SKA exclusion area buffer.

Note that no settlement expansion was modelled within CDRP's, unless as a result of other influencing factors as define above, since the aim of the CRDP's is to stabilise existing populations with employment opportunities rather than attract new migration.

[end].

References

- Modelling of Land-Cover Change in South Africa (2001 – 2010) in Support of Green House Gas Emissions Reporting. Summary Report & Metadata. GeoTerraImage project report for WITS Commercial Enterprise Pty Ltd, 14 Feb 2013, vs 7.1.

- Land-Capability: Other Land Categories. P94-95 of original Agricultural Research Council / Department of Agriculture, Fisheries and Forestry report. *Referenced "as-is" in terms of supplied pdf document. Original source and date unknown.*

- Conservation of Agricultural Resources, 1982 (Act 43 of 1983) (CARA)

- Afforestation Potential Study in KwaZulu-Natal and Mpumalanga. Environmental Assessment Report. March 2009. Supplied by Department of Agriculture, Fisheries and Forestry. *Original source unknown*.

- The development of a Strategic Environmental Assessment (SEA) for the Zone of Afforestation Potential in the Eastern Cape. Final Report. Department of Water Affairs and Forestry. 30 May 2006.

APPENDIX A:

The 2001, 2005 and 2010 MODIS generated SA Land-Cover Datasets

Copy of report: *Modelling of Land-Cover Change in South Africa (2001 – 2010) in Support of Green House Gas Emissions Reporting. Summary Report & Metadata. GeoTerraImage project report for WITS Commercial Enterprise Pty Ltd, 14 Feb 2013, vs 7.1.*

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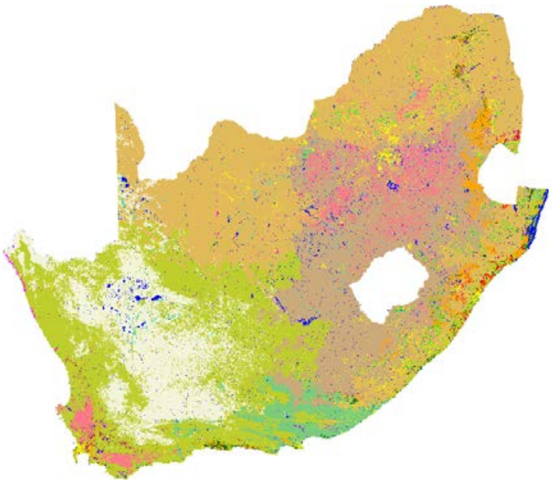
Modelling of Land-Cover Change in South Africa (2001 – 2010) in Support of Green House Gas Emissions Reporting

Summary Report & Metadata.



Produced for

Wits Commercial Enterprise (Pty) Limited
University of Witswatersrand
Wits Professional Development Hub
South Africa

by

GeoTerraImage (GTI) Pty Ltd

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1. BACKGROUND.

The Department of Environment Affairs (DEA) requires the determination of land-cover change between the years 2000, 2005 and 2010 in support of their determination of Green House Gas Emissions reporting to the international community. The datasets described below were generated in response to this need. The data modelling approaches and final product content and format were all conceived to be in-line with DEA's urgent need for such data, which imposed significant constraints in terms of overall production time. The University of Witwatersrand (WITS) coordinated the project with GeoTerraImage Pty Ltd (GTI) on behalf of the DEA.

Due to satellite data archival limitations associated with the proposed methodology, it is not possible to access suitable historical imagery for the year 2000, simply because the data does not exist. Hence the final set of land-cover data is based on the use of satellite time series data from 2001 – 2010 instead.

2. OBJECTIVE.

To create three standardised land-cover datasets for the whole of South Africa, representing conditions in 2001, 2005 and 2010; and to provide quantitative estimates of land-cover change between these three assessment dates. The methodology used was practical (i.e. time, cost, available input data), scientifically defensible (i.e. transparent and rigorous), repeatable in the future (except for loss of satellite systems etc out of our control etc), and has produced usable, standardised, wall-to-wall land-cover data for the required assessment periods.

3. DELIVERABLES.

Three (3) separate land-cover data coverages have been provided, representing landscape characteristics across the full extent of South Africa in 2001, 2005 and 2010. The datasets are based on a 500 x 500 m (25 ha) raster grid framework, within which the dominant (by area) land-cover within each cell has been defined. This is the same cell-based format and resolution as the MODIS satellite imagery used as the primary modelling dataset. All final data products have been delivered in digital (raster) format suitable for use and incorporation within GIS data modelling and analysis systems.

Table 1 lists the land-cover classes which have been modelled for each assessment year, which are in accordance with IPCC land-cover information reporting requirements:

In addition to the three digital, raster format land-cover datasets, three summary tables have been provided (in Excel spreadsheet format) that document the calculated changes in land-cover between the assessment years. These tables represent non-spatially, the changes between each cover class in both percentage and area values.

No.	IPCC Primary Class	Sub No.	DEA GHC Sub-Classes 500m
1	Forest lands	1	Indigenous Forest
		2	Thicket (remaining untransformed biome)
		3	Woodland / Savanna (remaining untransformed biome)
		4	Plantations (*incl clearfelled*)
2	Crop lands	5	Annual commercial crops (non-pivot), incl other non-pivot irrigation
		6	Annual commercial crops (pivot)
		7	Permanent crops (orchard)
		8	Permanent crops (viticulture)
		9	Annual semi-commercial / subsistence crops
		10	Permanent crops (sugarcane, irrig & dry)
3	Settlements	11	Settlements
4	Wetlands	12	Wetlands
5	Grasslands	13	Grasslands (remaining untransformed biome)
6	Other lands	14	Mines
		15	Water Bodies
		16	Bare Ground
		17	Other
		18	Fynbos (remaining untransformed biome)
		19	Nama Karoo (remaining untransformed biome)
		20	Succulent Karoo (remaining untransformed biome)

Table 1 Land-cover classes included in the national land-cover datasets for 2001, 2005 and 2010.

4. METHODOLOGY: GENERAL OVERVIEW

Coarse resolution MODIS time series satellite data has been used to model the various land-cover classes in each assessment year, in conjunction with high resolution geographic masks of specific land-cover types. The MODIS dataset was sourced from the Remote Sensing Research Unit, Meraka Institute, CSIR. Note that the MODIS time-series dataset does not form part of the final deliverables, and is supplied under a restrictive license specifically for use in only the analysis and preparation of the 2001, 2005 and 2010 SA land-cover datasets. A full description of the MODIS data is supplied in the Appendices.

The MODIS time series imagery represents summarised biomass data for each 32-day period within the period 2001 – 2010. Biomass is represented by the Enhanced Vegetation Index (EVI) dataset. Using the EVI time series dataset it was possible to model and therefore identify on a cell-by-cell basis, for example areas that show continuously or periodically high or low vegetation cover, either in all years and all seasons, or in specific years or seasons.

The high resolution geographic masks were used to define *known* areas of specific land-cover types as mapped in independent provincial (and other) land-cover mapping projects. These high resolution reference land-cover datasets cover the full extent of the country, but not in terms of a single standardised time-frame, having been compiled through unrelated, independent projects undertaken between 2000 and 2010. In some cases these datasets are available as public-access data (with permission), whilst others are proprietary products, generated, owned and sold under license by GeoTerraImage. None of these datasets form part of the final deliverables, and have only been used during the analysis and preparation of the 2001, 2005 and 2010 SA land-cover datasets. A summary list of the source image data used to generate the geographic masks is supplied in the Appendices, listed by image date and image type per province.

Using the MODIS time-series vegetation data in combination with the higher resolution cover class geographic masks, it was thus possible to model the extent of a particular cover class in each of the three assessment years, using standardised assumptions about how such a cover class is represented by the MODIS vegetation profiles.

Note however that the physical extent of each geographical mask was not used to define the *exact* boundary of that specific cover class, but rather the results of the associated (MODIS EVI) modelling process *within that geographic mask* were used to define which cells were finally representative of that cover class. This approach ensured that standardised modelling assumptions could be applied independently and repeatedly to each MODIS dataset, for each assessment year.

For example, for the "cultivated annual commercial crops" (# 5), the following modelling rules and assumptions were applied:

- All national field boundary vector data circa 2006 – 2010 (available from the Department of Agriculture, Forestry and Fisheries, DAFF) were amalgamated into a single dataset representative of the maximum extent of cultivated lands across SA in approximately the last 10 years.
- The amalgamated field vector dataset thus represented the maximum potential area of cultivated lands in each of the assessment years.
- To define the actual extent of cultivated land (w.r.t. an annual crop cover) in each assessment year, the MODIS data cell must (a) be located within the potential cultivated land mask area, and (b), exhibit a period of low / non-vegetation at some time during the (crop) growth cycle, representative of the soil preparation / planting period,
- Any MODIS cell unit not exhibiting such a pattern is not classified as an active (annual) crop cover in that assessment window.

Thus the final extent of annual commercial crops defined for each assessment period will be represented by the output from the MODIS EVI-based vegetation modelling process and *not* the original field boundary geographic mask.

Full descriptions of all the modelling rules and assumptions for each land-cover class are supplied in later sections of this report, as well as indications of the time frames for the reference datasets used as for the sources of the different geographic masks.

Note that each land-cover type is modelled separately and the outputs are then merged into a final multi-class land-cover for that specific assessment year, using prescribed orders of dominance. The order in which each of the land-cover classes is merged (i.e. overlaid) with the other land-cover types is defined below in Table 2.

Overlay sequence	Land-Cover Class
this cover always overwrote classes below ...	Settlements
this cover always overwrote classes below ...	Indigenous Forest
this cover always overwrote classes below ...	Plantations (*incl clearfelled*)
this cover always overwrote classes below ...	Permanent crops (sugarcane, irrig & dry)
this cover always overwrote classes below ...	Permanent crops (viticulture)
this cover always overwrote classes below ...	Permanent crops (orchard)
this cover always overwrote classes below ...	Annual commercial crops (pivot)
this cover always overwrote classes below ...	Annual semi-commercial / subsistence crops
this cover always overwrote classes below ...	Annual commercial crops (non-pivot), incl other non-pivot irrigation
this cover always overwrote classes below ...	Mines
this cover always overwrote classes below ...	Water Bodies
this cover always overwrote classes below ...	Wetlands
this cover always overwrote classes below ...	Bare Ground
	Other (biomes)
Other (biomes)	Thicket (remaining untransformed biome)
Other (biomes)	Woodland / Savanna (remaining untransformed biome)
Other (biomes)	Grasslands (remaining untransformed biome)
Other (biomes)	Fynbos (remaining untransformed biome)
Other (biomes)	Nama Karoo (remaining untransformed biome)
Other (biomes)	Succulent Karoo (remaining untransformed biome)

Table 2 Hierarchical Overlay Sequence for Land-Cover Classes

4.1 LIMITATIONS OF MODELLING APPROACH: AREA ESTIMATIONS

It is important to realise that the MODIS EVI modelling is based on 500 x 500 m pixels where as the geographic masks are based on 30m resolution pixels (derived independently from either Landsat or SPOT imagery). It is quite feasible that spatial misrepresentations have been introduced within the final land-cover outputs since the area for the single cover class allocated to each 500 x 500 km cell is rounded up to the nearest 0,5 km^2 regardless of the actual extent of that cover type (i.e. geographic mask) within the 500 x 500 m cell. This may be further exacerbated by the sequence in which the individual cover classes are overlaid / merged during compilation of the final land-cover product (see Table 2). For example, plantation forestry always over-writes (i.e. dominates within a cell) all cover types listed below it in the sequence presented in Table 2, regardless of the actual area of plantation forestry in that cell.

4.2 LIMITATIONS OF MODELLING APPROACH: ACCURACY & VALIDATION

It is important for end users to be aware that this has been a desk-top only modelling exercise, the results of which are directly dependent on the validity and accuracy of the modelling data inputs, theoretical assumptions and associated modelling rules. As such no statistical verification of final land-cover change detection accuracy can or has been be provided. Full transparency in terms of the MODIS data modelling rules and assumptions has however been provided should future users and / or analysts wish to re-calculate components of the land-cover data.

4.3 LIMITATIONS OF MODELLING APPROACH: DATA APPLICATION

Due to the modelling processes and data inputs described, it should be clearly understood and communication to all end-users that the land-cover and land-cover change products have been developed *specifically* in support of the DEA-WITS GHG / IPCC reporting requirements, and that the products should *not* be considered new national land-cover datasets for wider application without full knowledge and understanding of the manner and process with which they have been generated.

5. MODIS MODELLING: DETAILED DESCRIPTION & LOGIC TESTS

Cover-class specific upper and / or lower EVI data thresholds were determined from the MODIS data for each land-cover type using appropriate Landsat and/or high resolution thematic land-cover classifications for reference. Class specific modelling was restricted to specific geographic areas using digital masks extracted from a range of pre-existing land-cover classifications. A single reference mask was created for each cover class. The masks were created to represent the maximum geographical area of that particular cover class in all three assessment years. EVI modelling rules and assumptions were first developed on a year by year basis.

Since the geographic masks were generated from several independent reference sources, the geographical extent of each mask was not necessarily mutually exclusive, and masks could overlap. A specific sequence of priority overlaps was therefore established in order to compile the final SA land-cover datasets from each of the individual cover classes (see Table 2). For example modelled water pixels over-wrote all modelled natural vegetation pixels.

The results of the individual year modelling outputs were then tested for logical sequence across all three assessment years, and adjusted as and where deemed necessary. For example, if a cell was classified as “Water” in both 2001 and 2010, but “Plantation” in 2005, then the assumption will be that a modelling / rule error has occurred and that the logical sequence should be “Water” in all three assessment years. Only after this Quality Check has been completed was the final land-cover change assessments undertaken between the assessment years.

5.1 MODIS MODELLING: COVER-CLASS MODELLING RULES

5.1.1 Indigenous forests

EVI modelling assumptions

Indigenous forests were defined as pixels which consistently exhibited EVI values representing forest during every month of a year, within the pre-defined forest geographical mask.

EVI modelling thresholds

A pixel was defined as representing forests if the EVI values exceeded a minimum threshold of 0.21 during every month of a single year. This threshold value was taken to be representative of a closed canopy tree cover. Thresholds were determined visually using comparison to equivalent seasonal and year date Landsat imagery and existing small scale land-cover classifications.

Source of geographic mask

The forest geographic mask was created by merging indigenous forest classes from previously mapped land-cover datasets and the 2006 SANBI biomes vector data (see appendix).

Land-cover class modelling assumptions

Unlike plantations, indigenous forests are never cleared and replanted therefore it was assumed that pixels must contain forestry equivalent EVI values for every month of a year for that pixel to be classified as indigenous forests. If a pixel contained EVI values less than the indigenous forest threshold for one or more months of a year then it was assumed that the area had been cleared and was no longer indigenous forest.

Final logic test

A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 indigenous forest datasets. It was assumed that if a pixel was defined as forest in 2010 then the same pixel also had to be forest in 2005 because indigenous forests are not replanted if cleared and therefore the forest needed to have existed prior to the assessed date. Similarly, if a pixel was defined as forest in 2005 then the same pixel also had to be forest in 2001. It was therefore also assumed that if an EVI pixel value showed forests for 2010, but not for 2001 and 2005 then the 2010 forest is incorrect and had been removed from the class. Similarly if a pixel was defined as forest in 2005 and 2010 then that pixel had to have been forest in 2001.

5.1.2 Thicket

The thicket class boundary was extracted from the 2006 SANBI vector biome dataset, since it was outside the scope of the project and the available data to derive a MODIS EVI generated thicket boundary. Therefore the extent of thicket within the final land-cover datasets represents the biome boundary rather than the actual vegetation cover extent.

5.1.3 Woodland / Savanna

The **woodland / savanna** class boundary was extracted from the 2006 SANBI vector biome dataset, since it was outside the scope of the project and the available data to derive a MODIS EVI generated **woodland / savanna** boundary. Therefore the extent of **woodland / savanna** within the final land-cover datasets represents the biome boundary rather than the actual vegetation cover extent.

5.1.4 Plantations

EVI modelling assumptions

Plantations were defined as pixels which consistently exhibited EVI values representing forest plantations during every month of a year, within the pre-defined plantation geographical mask.

EVI modelling thresholds

A pixel was defined as representing plantations if the EVI value exceeded a minimum threshold of 0.21 during every month of a year. This threshold value was taken to be representative of closed canopy tree cover (mature stands).

Thresholds were determined visually using comparison to equivalent seasonal and year date Landsat imagery and existing small scale land-cover classifications.

Source of geographic mask

The plantation geographic mask was created by merging plantation classes from previously mapped land-cover datasets (see appendix).

Land-cover class modelling assumptions

To separate temporary clear-felled stands from permanent, non-tree covered areas, a maximum period of 4 years of undetectable tree cover was allowed, before which plantation re-growth had to become evident in terms of the EVI threshold. The 4 year period was defined from the first month of detectable non-tree cover on the EVI data, for pixels which previously contained a detectable tree cover. This 4 year period was deemed sufficient to represent a 40% canopy closure for the slowest plantation growth curves. Pixel EVI values exhibiting a lack of detectable tree re-growth after 4 years were assumed to no longer be representative of the plantation class (i.e. no re-planting).

Final logic test

A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 plantation datasets. It was assumed that if a pixel was defined as plantation in 2001 and

2010 then the same pixel also had to be plantation in 2005. Similarly, if no plantation was defined in a pixel during 2001 and 2010, then that pixel could not contain plantations during 2005 because of tree growth rates.

5.1.5 Annual commercial crops (non pivot)

EVI modelling assumptions

Annual crops were defined as pixels which exhibited EVI values representing both bare ground and mature crops within a 12 month crop cycle, within the pre-defined annual crop geographical mask.

EVI modelling thresholds

A pixel was defined as representing annual commercial crops (non pivot) if the EVI dataset met both the bare field threshold and the mature crop threshold during a single growth year. Bare field status (i.e. bare ground prior to planting) was defined as a pixel having an EVI value below a maximum threshold of 0.148 (excluding zero as this represented “no data”) during at least one month of a year. The mature crop condition was defined as a pixel with an EVI value exceeding a minimum threshold of 0.362 during at least one month of a year. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask

The annual crop geographic mask was created by merging annual crop classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions

Annual commercial crops (non pivot) were determined by analysing the 12 month crop cycle within the annual crop mask. For a pixel to be considered as cultivated annual crop fields the EVI data had to exhibit both the bare field minimum threshold and the mature crop maximum threshold within the annual crop geographical mask, within that crop cycle.

Final logic test

A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 annual crops (non pivot) dataset. It was assumed that if a pixel was defined as annual crops in 2001 and in 2010 then the same pixel was also likely to be an annual crops in 2005 due to crop rotation cycling. Similarly, if a pixel was defined as not being annual crops in 2001 and 2010 then that same pixel was unlikely to be cultivated in 2005. Note that the 2001 EVI dataset contained several areas of “no data” values during the rain months in the Western Cape, over areas of likely annual crops. In these no data value areas, if a pixel was defined as annual crops in 2005, then it was assumed that the same pixel was annual crops in 2001, in order to maintain a logical sequence.

5.1.6 Annual commercial crops (pivots)

EVI modelling assumptions

Pivots were defined as pixels which exhibited EVI values representing both bare ground and mature crops during a 12 month crop cycle, within the pre-defined pivot geographical mask.

EVI modelling thresholds
A pixel was defined as representing pivots if the EVI dataset met both the bare field threshold and the mature crop threshold requirements during a single growth year. Bare field status (i.e. bare ground prior to planting) was defined as a pixel having an EVI value below a maximum threshold of 0.148 (excluding zero as this represented “no data”) during at least one month of a year. The mature pivot crop condition was defined as a pixel representing a maturely grown crop if the EVI value exceeded a minimum threshold of 0.362 during at least one month of a year.

Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The pivot geographic mask was created by merging pivot classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions
Pivots were determined by analysing the 12 month crop cycle within the pivot mask. For a pixel to be considered as a cultivated pivot the EVI data had to exhibit both the bare field minimum threshold and the mature crop maximum threshold within the pivot mask, within that crop cycle.

Final logic test
There was no logic test because the logic is covered by the initial EVI modelling and the geographic masks were spatially explicit.

5.1.7 Permanent crops (orchards)

EVI modelling assumptions
Orchards were defined as pixels which consistently exhibited EVI values representing orchard trees during every month of a year, within the pre-defined horticulture geographical mask.

EVI modelling thresholds
A pixel was defined as representing orchards if the EVI values were between a minimum threshold of 0.35 and a maximum 0.45 during every month of a year. This threshold value was taken to be representative of a canopy cover for mature orchard trees. Deciduous orchard crops were included on the basis of achieving the EVI threshold in at least one month as explained in the modelling assumptions. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The horticulture geographic mask was created by merging horticulture classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions
Orchards were determined by analysing the 12 month crop cycle within the horticulture geographic mask. For a pixel to be considered as cultivated orchards the EVI data had to exhibit at least one month when EVI values were in the designated range.

Final logic test
A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 orchard dataset. It was assumed that if a pixel was defined as orchards in 2001 and 2010 then the same pixel also likely to be orchards in 2005 due to tree growth rates. Similarly, if no orchards were defined in the same pixel during 2001 and 2010, then that pixel would not likely contain orchards in 2005. It was also was assumed that horticulture only disappears if replaced by another manmade land-cover. Therefore orchards would either remain the same in all years based on the 2001 extent or, increase in extent in subsequent years, but only reduce in area if replaced by another man-made (rather than natural) cover class. Thus the 2001 orchard extent was automatically carried through to 2005 and 2010 and similarly an expanded 2005 extent was carried through to 2010, unless replaced in any year by another man-made cover class.

5.1.8 Permanent crops (viticulture)

EVI modelling assumptions
Viticulture was defined as pixels which consistently exhibited EVI values representing vineyards during every month of a year, within the pre-defined viticulture geographical mask.

EVI modelling thresholds
A pixel had to display both EVI values representing the leaf off period and the mature, leaf on period within one growth year for it to be considered to represent a viticulture crop. The leaf off period representing bare ground was based on a EVI threshold range between 0.17 and 0.4, which must occur during at least one month of a year. The mature, leaf on crop period was defined as an EVI value range between 0.2 and 0.45, during at least one month during a year. The leaf on EVI data range was capped at 0.45 in order to exclude any surrounding areas of dense vegetation that exceeded the biomass of the viticulture crop. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The viticulture geographic mask was created by merging viticulture classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions
Viticulture was determined by analysing the 12 month vine cycle within the viticulture mask. For a pixel to be considered as cultivated viticulture land the EVI data had to exhibit at least one month of bare vine (leaf off) cover and at least one month of leaf on cover within the viticulture mask.

Final logic test
A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 viticulture dataset. It was assumed that if a pixel was defined as viticulture in 2001 and 2010 then the same pixel also had to be viticulture in 2005 due to vine growth rates. Similarly, if no viticulture was defined in a pixel during 2001 and 2010, then that pixel could not contain viticulture during 2005. It was also was assumed that viticulture only disappears if replaced by another manmade land cover using the same assumptions as orchards.

5.1.9 Annual semi-commercial / subsistence crops

EVI modelling assumptions

Subsistence crops were defined as pixels which exhibited EVI values representing both bare ground and mature crops characteristics within a 12 month crop cycle, within the pre-defined subsistence crop geographical mask.

EVI modelling thresholds

A pixel was defined as representing subsistence crops if the EVI dataset met both the bare field threshold and the mature crop threshold during a single growth year. Bare field status (i.e. bare ground prior to planting) was defined as a pixel having an EVI value below a maximum threshold of 0.148 (excluding zero as this represented "no data") during at least one month of a year. The mature crop condition was defined as a pixel with an EVI value exceeding a minimum threshold of 0.362 during at least one month of a year. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask

The subsistence crop geographic mask was created by merging subsistence crop classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions

Subsistence crops were determined by analysing the 12 month crop cycle within the subsistence crop mask. For a pixel to be considered as cultivated annual crop fields the EVI data had to exhibit both the bare field minimum threshold and the mature crop maximum threshold within the subsistence crop geographical mask, within that crop cycle.

Final logic test

A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 subsistence crops dataset. It was assumed that if a pixel was defined as subsistence crops in 2001 and in 2010 then the same pixel was also likely to be subsistence crops in 2005 due to crop rotation cycling. Similarly, if a pixel was defined as not being subsistence crops in 2001 and 2010 then that same pixel was unlikely to be cultivated in 2005. Note that the 2001 EVI dataset contained several areas of "no data" values during the rain months in the Western Cape, over areas of likely annual crops. In these no data value areas, if a pixel was defined as annual crops in 2005, then it was assumed that the same pixel was subsistence crops in 2001, in order to maintain a logical sequence.

5.1.10 Sugarcane

EVI modelling assumptions

Sugarcane was defined as pixels which exhibited EVI values representing mature sugarcane during at least one month in an 18 month crop cycle, within the pre-defined sugarcane geographical mask.

EVI modelling thresholds

A pixel was defined as representing sugarcane if the EVI value exceeded a minimum threshold of 0.55 during at least one month in the 18 month crop cycle. This threshold value was taken to be representative of mature sugarcane. For 2001 the 18 month period was defined from the first 2001 EVI monthly dataset forward. For the 2005 dataset it was defined as from July 2004 to December 2005. For the 2010 dataset it was defined as from July 2009 to December 2010. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask

The sugarcane geographic mask was created by merging sugarcane classes from previously mapped land-cover datasets and previously mapped field boundary datasets (see appendix).

Land-cover class modelling assumptions

Sugarcane was determined by analysing the 18 month crop cycle within the geographic sugarcane mask. The mature crop threshold had to be present within this cycle for the area to be classified as sugarcane from the EVI data.

Final logic test
A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 sugarcane dataset. It was assumed that sugarcane fields only disappear if replaced by another manmade land cover. Therefore if a pixel was defined as sugarcane in 2001 then that pixel was also defined as sugarcane in 2005 and 2010. Similarly, if a pixel defined as sugarcane in 2005 then it would also contain sugarcane in 2010.

5.1.11 Residential (modelling sub-component of Settlements)

EVI modelling assumptions
Residential areas were defined as pixels which consistently exhibited EVI values representing high reflectance bare ground characteristics during every month of a year, within the pre-defined urban geographical mask.

EVI modelling thresholds
A pixel was defined as representing residential areas if the EVI values were below a maximum threshold of 0.5 during every month of a year. This threshold value was taken to be representative of residential buildings and man-made, artificial surfaces and structures within the geographic mask. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The residential geographic mask was extracted from land-use datasets (see appendix).

Land-cover class modelling assumptions
Residential areas were determined by analyzing the sequence and pattern of bare ground areas within the urban geographical mask for each assessment year by analysing the data across the full 10 year period. Urban areas were modelled, within the geographical residential mask, on the basis of the following assumptions:

(a) the maximum geographical extent of the residential area in one assessment year can not exceed the maximum extent in the following assessment year,
(b) all bare ground within the residential geographic mask is representative of residential areas irrespective of land use ,
(c) areas exhibiting a new phase of bare ground (after being previously vegetated) are assumed to be new development residential areas,
(d) vegetated areas occurring prior to a new phase of bare ground are representative of previously un-developed areas,
(e) areas that are consistently vegetated from 2001 through to 2010 (within the urban geographical mask) are considered established residential areas with mature garden foliage, and
(f), areas that are residential in 2010 were never previously industrial or commercial in previous years (although modelled industrial and commercial areas were allowed to over write residential areas on the assumption that these were new developments).

Final logic test
A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 residential datasets. It was assumed that a residential area could expand in size or remain

static from 2001 to 2010, but it could not decrease in size. Therefore if a pixel was defined as residential in 2001, that same pixel had to be defined as residential in both 2005 and 2010. Similarly, a pixel defined as residential in 2005, had to be residential in 2010, unless reclassified as industrial or commercial.

5.1.12 Commercial and industrial (modelled sub-component of Settlement)

EVI modelling assumptions

Commercial and industrial areas were defined as pixels which consistently exhibited EVI values representing high reflectance bare ground during every month of a year, within the pre-defined commercial and industrial geographical mask.

EVI modelling thresholds

A pixel was defined as representing commercial and industrial areas if the EVI value was below a maximum threshold of 0.28 during every month of a year. This threshold value was taken to be representative of commercial and industrial buildings and man-made, artificial surfaces. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask

The commercial and industrial geographic mask was extracted from land-use datasets (see appendix).

Land-cover class modelling assumptions

Modelling assumptions were that (a) all bare ground areas represented only commercial or industrial areas within the mask, and (b) commercial or industrial areas never reverted to residential once classified as commercial or industrial.

Final logic test

A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 commercial and industrial areas. It was assumed that a commercial or industrial area could expand in size or remain static from 2001 to 2010, but it could not decrease in size. Therefore if a pixel was defined as commercial or industrial in 2001 then that same pixel had to be defined as commercial or industrial in 2005 and 2010 as well. Similarly, if a pixel was defined as commercial and industrial in 2005, then it was also defined as commercial and industrial in 2010.

5.1.13 Creation of final settlement class

The final SA land-cover datasets for 2001, 2005 and 2010 do not contain separate categories for residential and commercial/industrial classes. A single "settlement" class is defined which represents the combined spatial extent of both the residential and commercial/industrial classes.

5.1.14 Wetlands

EVI modelling assumptions

For initial modelling purposes, the wetland class was split into dry, wet and vegetated wetlands. Dry wetlands were defined as pixels which consistently exhibited EVI values representing bare ground during every month of a year, within the pre-defined wetlands geographical mask. Wet wetlands were defined as pixels which exhibited EVI values representing water for a minimum of one month of a year within the pre-defined wetlands geographical mask. Vegetated wetlands were defines as pixels which did not exhibit EVI values representing bare ground or water within the pre-defined wetlands geographical mask.

EVI modelling thresholds

The EVI modelling thresholds vary depending on the nature of the wetland. A dry wetland threshold was defined as pixels with EVI values below a maximum threshold of 0.14 during every month of the year. A wet wetland threshold was defined as pixels representing water if the EVI values were below a maximum threshold of 0.18 during at least one month during a year. The vegetated wetlands threshold was defined as pixels with EVI values exceeding a threshold of 0.14, but which had not been previously classified as wet during any month of a year. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask

The wetland geographic mask was created by merging wetland classes from previously mapped land-cover datasets (see appendix).

Land-cover class modelling assumptions

Since wetlands can become drier or wetter through out different seasons, it is assumed that if a wetland is defined by the water threshold for at least one month within a year, then that wetland is classified as wet. The dry wetland is defined by a pixel representing bare ground for every month of the year. Vegetated wetlands are defined as pixels that correspond to the vegetation threshold for at least one month in a year, but are never represented by water within the same year.

Final logic test

The vegetated and dry wetlands were collapsed into a single wetland class for use in the final SA land-cover datasets. The wet wetlands were recoded as water pixels.

5.1.15 Grasslands

The grassland class boundary was extracted from the 2006 SANBI vector biome dataset, since it was outside the scope of the project and the available data to derive a MODIS EVI generated grassland boundary. Therefore the extent of grassland within the final land-cover datasets represents the biome boundary rather than the actual vegetation cover extent.

5.1.16 Mines

EVI modelling assumptions

Mines were defined as pixels which consistently exhibited EVI values representing bare ground during every month of a year, within the pre-defined mine geographical mask.

EVI modelling thresholds

A pixel was defined as mines if the EVI values were below a maximum threshold of 0.24 during every month of a year. This threshold value was taken to be representative of bare ground characteristics that are found within a mining environment. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The mine geographic mask was created by merging mine classes from previously mapped land-cover datasets and topographic vector data (see appendix). This included tailings, dumps and extraction sites.

Land-cover class modelling assumptions
The modelling process for mines did not identify flooded mine pits or surface water on tailings, although this was identified within the water modelling process and was incorporated into the final land-cover data compilations. It was assumed that mines contained bare surfaces throughout every month of the year for 2001, 2005 and 2010. Mine dumps/tailings containing a large covering of algae during the rainy season may have been misidentified.

Final logic test
A final logic test was used to check and edit (if required) the modelled 2001, 2005 and 2010 mine datasets. It was assumed that if a pixel was defined as mines in 2001 and 2010 then the same pixel also had to be mines in 2005, due to the semi-permanent nature of most mines. Similarly, if no mines were defined in a pixel during 2001 and 2010, then that pixel could not contain mines during 2005. However pixels representing mines could disappear (rehabilitation) if the disappearance was permanent within the assessment year range. This included acceptance that a mine pixel could be evident in 2001 and 2005, but not evident in 2010.

5.1.17 Water bodies

EVI modelling assumptions
Water bodies were defined as pixels which exhibited EVI values representing all types of open water (i.e. man-made and natural) within the pre-defined water geographical mask.

EVI modelling thresholds
A pixel representing water was defined as EVI values which were below a maximum threshold of 0.18 during any month of the year. This threshold value was taken to be representative of a body of water. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Source of geographic mask
The water geographic mask was created by merging water classes from previously mapped land-cover datasets and Chief Directorate: National Geospatial Information topographic vector data (see appendix). The dry river beds were excluded from the water geographic mask since the water threshold and bare ground thresholds overlap, which would have resulted in dry, bare river beds appearing as permanently flooded.

Land-cover class modelling assumptions
The water bodies were modelled on the basis of a candidate pixel containing at least one month in the assessment year having an EVI data value equivalent to the threshold defined for water. Therefore the modelled water output always represented the maximum geographic area of water occurrence in any of the assessment years. Note that there may be an over estimation of water pixels since the water threshold is similar to the bare ground threshold and there was no way of separating these two classes with only EVI data.

Final logic test
There was no logic test because the logic is covered by the initial EVI modelling and the geographic masks were spatially explicit.

5.1.18 Bare ground

EVI modelling assumptions

Bare ground was defined as pixels which consistently exhibited EVI values representing bare ground during every month of a year. This was modelled across the entire country without geographical masks and formed a backdrop upon which all other modelled cover classes were over laid. The final extent of bare ground in the national datasets thus represented very sparse vegetation covers and desert areas not covered by other cover classes.

EVI modelling thresholds
A pixel was defined as bare ground if EVI values were below a maximum threshold of 0.14 during every month of a year. This threshold value was taken to be representative of bare ground. Thresholds were determined visually using comparison to equivalent date Landsat imagery and the existing small scale land-cover classifications.

Land-cover class modelling assumptions
The bare ground was defined as pixels that exhibited non-vegetated / bare ground EVI characteristics for all months consistently in any assessment year. There may be an under estimation of bare ground that occur within the geographic water masks as the water and bare ground EVI thresholds are similar.

Final logic test
There was no logic test because the logic is covered by the initial EVI modelling.

5.1.19 Fynbos
The fynbos class boundary was extracted solely from the 2006 SANBI vector biome dataset, as an additional request outside the scope of the original ToR. Therefore the extent of fynbos within the final land-cover datasets represents the un-transformed extent of the potential biome boundary rather than the actual vegetation cover extent (which may or may not contain local areas of non-fynbos vegetation cover).

5.1.20 Nama-karoo
The nama-karoo class boundary was extracted solely from the 2006 SANBI vector biome dataset, as an additional request outside the scope of the original ToR. Therefore the extent of nama karoo within the final land-cover datasets represents the un-transformed extent of the potential biome boundary rather than the actual vegetation cover extent (which may or may not contain local areas of non-karoo vegetation cover).

5.1.21 Succulent karoo
The succulent karoo class boundary was extracted solely from the 2006 SANBI vector biome dataset, as an additional request outside the scope of the original ToR. Therefore the extent of succulent karoo within the final land-cover datasets represents the un-transformed extent of the potential biome boundary rather than the actual vegetation cover extent (which may or may not contain local areas of non-karoo vegetation cover).

---------------------------- END ----------------------------------

APPENDIX 1: Source Data for Geographic Masks

		2000		2001		2002		2003		2004		2005		2006		2007		2008		2009		2010	
		Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT	Landsat	SPOT
Eastern Cape	*full coverage*	✓																					
	partial coverage																				✓		✓
Free State	*full coverage*	✓																			✓		
	partial coverage																						✓
Gauteng	*full coverage*	✓																			✓		
	partial coverage																						✓
KwaZulu Natal	*full coverage*	✓																	✓				
	partial coverage											✓									✓		✓
Limpopo	*full coverage*	✓																			✓		
	partial coverage											✓					✓						✓
Mpumalanga	*full coverage*	✓																					
	partial coverage									✓		✓									✓		✓
North West	*full coverage*	✓													✓								
	partial coverage																						✓
Northern Cape	*full coverage*	✓																					
	partial coverage																		✓				✓
Western Cape	*full coverage*	✓																					
	partial coverage												✓	✓							✓		✓

national land-cover datasets

provincial land-cover datasets

area specific land-cover datasets (GTI proprietary data)

other area specific land-cover datasets (public access data)

Note all datasets used in combination in the creation of the class specific geographic masks, except for the 2000 National Land-Cover Dataset which was ONLY used in the absence of other more detailed / recent land-cover data.

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APPENDIX 2: MetaData for CSIR Meraka Supplied MODIS Data

Final Report: **DEA GHG Land cover change Project – MODIS change detection product.**

Waldo Kleynhans and Konrad Wessels
Remote Sensing Research Unit, CSIR-Meraka, Pretoria

October 2012

Background
The Department of Environmental Affairs (DEA) need to report on greenhouse gas emissions, including the contribution of land cover change. Currently there is not sufficient land cover data available to do this analysis. The CSIR-Meraka has developed an automated land cover change detection algorithm based on 500m MODIS satellite data (Kleynhans et al. 2011) that can be applied to the entire country to highlight areas with a high probability of change. GeoTerraImage (GTI) has devised a method for interpreting the MODIS change product and other MODIS data in conjunction with their provincial detailed land cover data sets to meet DEA's reporting needs to a limited, but useful extent.

About the data products
The datasets products are 1) change statistics and 2) EVI statistics. The change statistics aims to provide areas of change "hotspots" for the entire South Africa using the Autocorrelation change detection method described in (Kleynhans et. al. 2011). The EVI statistics provides maximum, mean and range statistics for approximate monthly increments. Both datasets are based on MODIS data during the period 2001-2010 (using the 8-day MCD43A4 500m resolution data product). Each of these datasets will be discussed in more detail in the following sections.

Change statistics
The change statistics were composed for the period 2001-2005 and 2005-2010 and are located in the *change* folder. The following list shows all the files in this folder:

- change_2001_to_2005.tiff
- change_2001_to_2005_3band.tiff
- change_2005_to_2010.tiff
- change_2005_to_2010_3band.tiff

The change_2001_to_2005.tiff and change_2005_to_2010.tiff files each consists of 7 bands indicating the level of change associated with each of the seven MODIS land bands for the period 2001-2005 and 2005-2010 respectively. For example, the band 1 value of a pixel in change_2001_to_2005.tiff gives an indication of level of change in MODIS band 1 for that specific pixel over the period 2001 to 2005. A higher pixel value correspond to a higher degree of change. The following parameters are relevant for the change_2001_to_2005.tiff and change_2005_to_2010.tiff files:

Data range: (-5;20)
Bands: 8 (Bands 1-7 are data bands, band 8 is either a 0 or 255 value indicating the outline of South Africa)
Dimensions: 4800x4800 Pixels
Projection information:

```
PROJCS["unnamed",
    GEOGCS["unknown",
        DATUM["unknown",
            SPHEROID["unnamed",6371007.181,0]],
        PRIMEM["Greenwich",0],
        UNIT["degree",0.0174532925199433]],
    PROJECTION["Sinusoidal"],
    PARAMETER["longitude_of_center",0],
    PARAMETER["false_easting",0],
    PARAMETER["false_northing",0],
    UNIT["metre",1,
        AUTHORITY["EPSG","9001"]]]
Origin = (1111950.519667000044137,-2223901.039332999847829)
Pixel Size = (463.312716527708290,-463.312716527708290)
```

Data Type: 32 Bit Floating Point
No Data value: 0

As an illustration, the following figure shows the MODIS band 1 change level for the period 2005 to 2010 for South Africa.

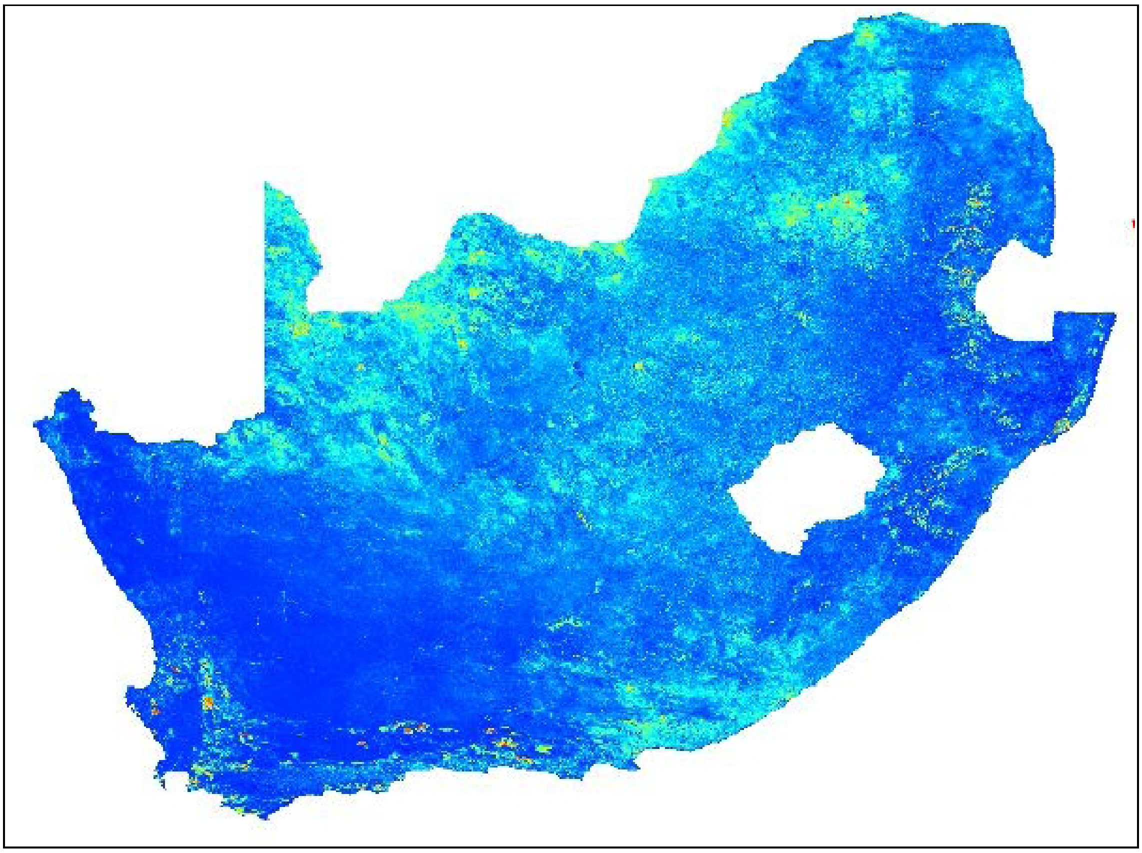

Figure1: Band 1 of the change_2001_to_2005.tiff file showing MODIS band 1 change level for the period 2005 to 2010 for South Africa. Blue indicate low values, associated with very little change whereas red values indicate high values which are associated with a high degree of change.

The change_2001_to_2005_3band.tiff and change_2005_to_2010_3band .tiff is a 3 band combination of change in MODIS band 1(red), 4(green) and 3(blue) found in change_2001_to_2005.tiff and change_2005_to_2010.tiff respectively. Areas undergoing major changes in all three these bands will appear darker whereas areas with little or no change will appear white. The following parameters are relevant for the change_2001_to_2005_3band.tiff and change_2005_to_2010_3band.tiff files:

Data range: (0;255)
Bands: 4 (Bands 1-3 are data bands, band 4 is either a 0 or 255 value indicating the outline of South Africa)
Dimensions: 4800x4800 Pixels
Projection information:

```
PROJCS["unnamed",
    GEOGCS["unknown",
        DATUM["unknown",
            SPHEROID["unnamed",6371007.181,0]],
        PRIMEM["Greenwich",0],
        UNIT["degree",0.0174532925199433]],
    PROJECTION["Sinusoidal"],
    PARAMETER["longitude_of_center",0],
    PARAMETER["false_easting",0],
    PARAMETER["false_northing",0],
    UNIT["metre",1,
        AUTHORITY["EPSG","9001"]]]
```

Origin = (1111950.519667000044137,-2223901.039332999847829)
Pixel Size = (463.312716527708290,-463.312716527708290)
Data Type: Eight bit unsigned integer
No Data value: 0

The following figure shows the 3 band change map for South Africa.

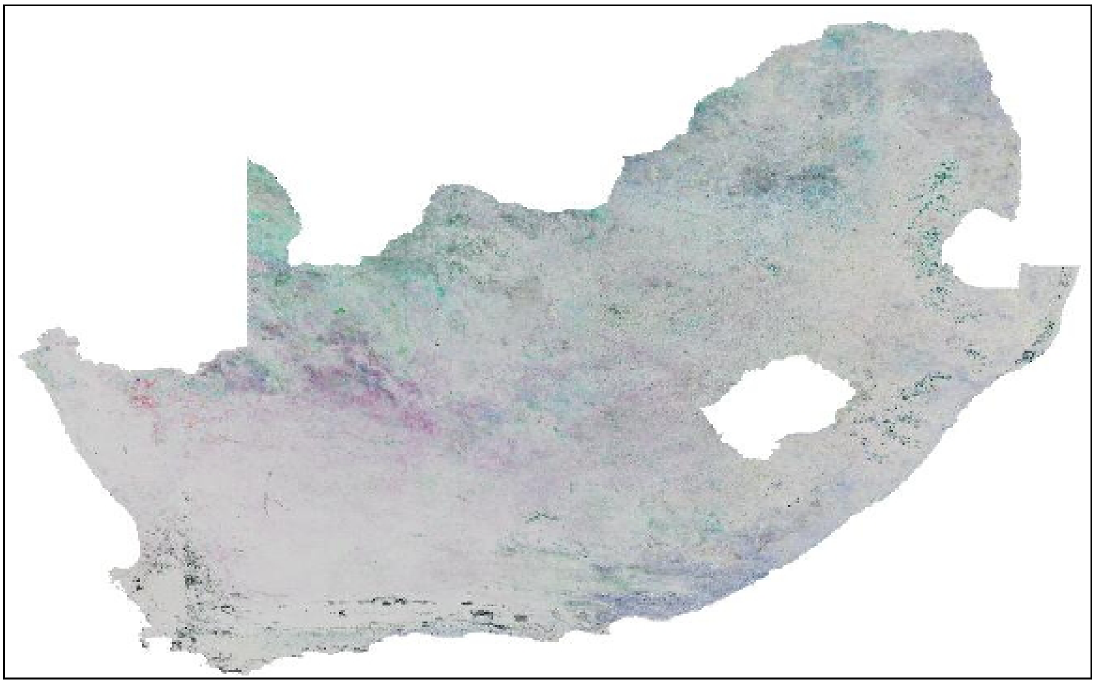

Figure2: Change_2001_to_2005_3band.tiff file showing the 3 band change map for South Africa for the period 2005-2010. Areas undergoing major changes bands appear darker whereas areas with little or no change appear white.

EVI statistics

The EVI statistics were composed for the period 2001 to 2010 and are located in the *EVI_Stats* folder. There are a total of 110 files in this folder having the following naming convention:

yyyy$j_1j_1j_1$-yyyy$j_2j_2j_2$_RSA.tiff

where yyyy is the year , $j_1j_1j_1$ is the Julian day indicating the start of the period and $j_2j_2j_2$ is the Julian day indicating the end of the period. For example, the file *2001001-2001025_RSA.tiff* contains EVI statistics from 2001001 (1 January 2001) to 2001025 (25 January 2001). Each year is partitioned into 11 blocks, the breakdown of these blocks are given in table 1.

Each of the files contain 3 bands.

- Band 1: maximum EVI,
- Band 2: mean EVI
- Band 3: range (max EVI – min EVI).
- The EVI statistics where computed annually for each of the 11 periods (as given in table 1), for the time-period 2001-2010 resulting in a total of 10 X 11 = 110 datasets. Figure 3 shows an example of the maximum EVI for the 10 Jun 2006- 4 Jul 2006 period.

The MODIS EVI data cube that was created at the RSRU, CSIR-Meraka Institute was used in the creation of the EVI statistics (http://wamis.meraka.org.za/time-series-viewer).

Interpolation over temporal data gaps:

- Temporal data gaps, due mainly to clouds, make it difficult for users to conduct time series analyses.
- Where no-data values lasted less than 5 data points (i.e. 4 data points – 32 days), EVI values were linearly interpolated.
- By calculating the statistics (e.g. Max) from 4 consecutive values after interpolation, data gaps were further reduced.

The following parameters are relevant for the EVI Statistics files

Data range: Band 1 (-1;1) Band 2(-1;1) Band 3(0;2)
Bands: 4 (Bands 1-3 are data bands, band 4 is either a 0 or 255 value indicating the outline of South Africa)
Dimensions: 4800x4800 Pixels
Projection information:

```
PROJCS["unnamed",
    GEOGCS["unknown",
        DATUM["unknown",
            SPHEROID["unnamed",6371007.181,0]],
        PRIMEM["Greenwich",0],
        UNIT["degree",0.0174532925199433]],
    PROJECTION["Sinusoidal"],
    PARAMETER["longitude_of_center",0],
    PARAMETER["false_easting",0],
    PARAMETER["false_northing",0],
    UNIT["metre",1,
        AUTHORITY["EPSG","9001"]]]
Origin = (1111950.519667000044137,-2223901.039332999847829)
Pixel Size = (463.312716527708290,-463.312716527708290)
```

Data Type: Eight bit unsigned integer
No Data value: 0

More information on the EVI
We calculated the Enhanced Vegetation Index (EVI) from the Nadir BRDF-Adjusted Reflectances (NBAR) are surface reflectances corrected to a common nadir view geometry at the local solar noon zenith angle of the start of the observation period and uses data from the MODIS sensor on both the Terra and Aqua satellites (MCD43A4, V005). For more information on MODIS Product (MCD43) see http://www.modis.bu.edu/brdf/userguide/intro.html and (Schaaf et. al. 2012).

The original input data (MCD43A4, V005) were processed by NASA and acquired from Land Processes Distributed Active Archive Center (LP DAAC) website: https://lpdaac.usgs.gov/ ftp://e4ftl01.cr.usgs.gov/MOTA/MCD43A4.005/

(For more detail see http://wamis.meraka.org.za/wamis/timeseries/CSIR-Meraka%20-%20Information%20on%20MODIS%20MCD43%20EVI%20data%20set%20for%20Southern%20Africa%20-%202011-03-11.pdf)

References

Kleynhans, W. et. al. (2012). Land Cover Change Detection Using Autocorrelation Analysis on MODIS Time-Series Data: Detection of New Human Settlements in the Gauteng Province of South Africa. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* . 5 (3), 777-783.

Schaaf, C. B. (2002) ,First Operational BRDF, Albedo and Nadir Reflectance Products from MODIS, *Remote Sens. Environ.*, 83, 135-148.

SA LAND-COVER (2001, 2005, 2010) MODELLED FROM TIME-SERIES MODIS IMAGERY : CORE METADATA ELEMENTS (SANS1878)

1(M) **Dataset title:** MODIS generated SA Land-Cover, 2001-2005-2010 Datasets

2(M) **Dataset reference date:** 2013 (production date)

3(O) **Dataset responsible party:** Produced by GeoTerraImage (GTI) Pty Ltd (Mark Thompson, www.geoterraimage.com) for Wits Commercial Enterprise (Pty) Limited, WITS University, Johannesburg.

4(C) **Geographic location of the dataset.**

WestBoundLongitude: -1390558.1477 (Upper Left X)
EastBoundLongitude: 1332794.00 (Lower Right X)
NorthBoundLongitude: -2151993.00 (Upper Left Y)
SouthBoundLongitude: --4438904.5687 (Lower Right Y)

Projection coordinates based on Albers Conical Equal Area, WGS84 (spheroid & datum), metres.

5(M) **Dataset language :** “English” (eng)

6(C) **Dataset character set:** UTF8 (8-bit data)

7(M)**Dataset topic category:** 010 = Base Map earth coverage

8(O) **Scale of the dataset:** Land-cover dataset suitable for 1:3,000,000 scale mapping and spatial analyses, derived from 500 m resolution MODIS Enhanced Vegetation Index (EVI).

9(M) **Abstract describing the dataset:** Standardised raster-based land-cover datasets, representing modelled national land-cover characteristics across South Africa for 2001, 2005 and 2010. Suitable for 1:3,000,000 scale mapping and spatial analyses. Datasets derived from 500x500m resolution MODIS Enhanced Vegetation Index (EVI) imagery.

10(O) **Dataset format name:** ERDAS *IMG raster formats

11(O) **Dataset format version:** version 07

12(O) **Additional extent information for the dataset: (vertical and temporal)**

Vertical Extent:
Minimum Value: n/a
Maximum Value: n/a
Unit Of Measure: n/a

Vertical Datum: n/a

Temporal Extent: Datasets generated in February 2013, based on MODIS EVI time series data circa 2001 – 2010, sourced from the Meraka Institute, CSIR.

14(O) **Reference system:** Albers Conical Equal Area

CRS:
Projection Used: Albers Conical Equal Area

Ellipsoid used: WGS84
Datum used: WGS84

Ellipsoid parameters:

Ellipsoid semimajor axis
axis units
denominator of flattening ratio

Projection Parameters:

Zone
Latitude of 1st standard parallel: 18:00:00.0000 S
Latitude of 2nd tandard parallel: 32:00:00.0000 S
Longitude of central meridian: 24:00:00.00 East
Latitude of projection origin: 00:00:00.00 East
False easting: 0.00000 metres
False northing: 0.00000 metres
Scale factor at equator: 1.0000
Projection units: metres

15(O) **Lineage statement:** Land-cover datasets generated in-house by GeoTerraImage (Pretoria) in February 2013, based on MODIS EVI time-series imagery 2001 - 2010 (supplied by Meraka Institute, CSIR) and used "as-is" in terms of spatial location and spectral content.

16(O) **On-line resource:** n/a

17(O) **Metadata file identifier:** n/a

18(O) **Metadata standard name:** SANS I878

19(O) **Metadata standard version:** version 01

20(C) **Metadata language:** English (eng)

21(C) **Metadata character set:** 021 (UsAscii)

22(M) **Metadata point of contact:**

Name: Mark Thompson
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Role: Project Leader (Land-Cover)
Organisation Name: GeoTerraImage Pty Ltd

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Zip	0041
State	Gauteng
Country	South Africa

Postal Address :

Box	295

Suburb	Persequor TechnoPark
City	Pretoria
Zip	0020
State	Gauteng
Country	South Africa

23(M) **Metadata time stamp:** 13 February 2013

APPENDIX 2

2020 FUTURE SA LAND-COVER

CORE METADATA ELEMENTS (SANS1878)

1(M) **Dataset title:** 2020 Future SA Land-Cover Dataset

2(M) **Dataset reference date:** 2013 (production date)

3(O) **Dataset responsible party:** Produced by GeoTerraImage (GTI) Pty Ltd (Mark Thompson, www.geoterraimage.com) for The Cirrus Group, on behalf of Department of Environment Affairs, DEA, South Africa.

4(C) **Geographic location of the dataset.**

WestBoundLongitude: -1390558.1477 (Upper Left X)
EastBoundLongitude: 1332794.00 (Lower Right X)
NorthBoundLongitude: -2151993.00 (Upper Left Y)
SouthBoundLongitude: --4438904.5687 (Lower Right Y)

Projection coordinates based on Albers Conical Equal Area, WGS84 (spheroid & datum), metres.

5(M) **Dataset language :** "English" (eng)

6(C) **Dataset character set:** UTF8 (8-bit data)

7(M)**Dataset topic category:** 010 = Base Map earth coverage

8(O) **Scale of the dataset:** Land-cover dataset suitable for 1:3,000,000 scale mapping and spatial analyses, derived originally from 500 m resolution MODIS Enhanced Vegetation Index (EVI), in terms of the base 2010 dataset.

9(M) **Abstract describing the dataset:** Standardised raster-based land-cover datasets, representing modelled future national land-cover characteristics across South Africa for ± 2020. Suitable for 1:3,000,000 scale mapping and spatial analyses. Original 2010 basel dataset derived from 500x500m resolution MODIS Enhanced Vegetation Index (EVI) imagery. Future land-cover changes modelled from various spatial and non-spatial reference datasets sourced from a wide range of representative organisations and companies as defined in the main report.

10(O) **Dataset format name:** ERDAS *IMG raster formats

11(O) **Dataset format version:** version 07

12(O) **Additional extent information for the dataset: (vertical and temporal)**

Vertical Extent:
Minimum Value: n/a
Maximum Value: n/a
Unit Of Measure: n/a

Vertical Datum: n/a

Temporal Extent: Datasets generated in August 2013, using data inputs from a wide range of representative organisations and companies as defined in the main report.

14(O) **Reference system:** Albers Conical Equal Area

CRS:

Projection Used: Albers Conical Equal Area
Ellipsoid used: WGS84
Datum used: WGS84

Ellipsoid parameters:

Ellipsoid semimajor axis
axis units
denominator of flattening ratio

Projection Parameters:

Zone
Latitude of 1st standard parallel: 18:00:00.0000 S
Latitude of 2nd tandard parallel: 32:00:00.0000 S
Longitude of central meridian: 24:00:00.00 East
Latitude of projection origin: 00:00:00.00 East
False easting: 0.00000 metres
False northing: 0.00000 metres
Scale factor at equator: 1.0000
Projection units: metres

15(O) **Lineage statement:** Land-cover dataset generated in-house by GeoTerraImage (Pretoria) in August 2013, using previously generated 2010 MODIS based SA National Land-Cover dataset, modified to represent a possible 2020 landscape using various spatial and non-spatial reference datasets sourced from a wide range of representative organisations and companies as defined in the main report.

16(O) **On-line resource:** n/a

17(O) **Metadata file identifier:** n/a

18(O) **Metadata standard name:** SANS I878

19(O) **Metadata standard version:** version 01

20(C) **Metadata language:** English (eng)

21(C) **Metadata character set:** 021 (UsAscii)

22(M) **Metadata point of contact:**

Name:	Mark Thompson
Position Name:	Director
Role:	Project Leader (Land-Cover)
Organisation Name:	GeoTerraImage Pty Ltd

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Building	Grain Building (1st Floor)
Street	Witherite
Street_Suffix	Street

Street_Nr	477
Suburb	Die Wilgers
City	Pretoria
Zip	0041
State	Gauteng
Country	South Africa
Postal Address :	
Box	295
Suburb	Persequor TechnoPark
City	Pretoria
Zip	0020
State	Gauteng
Country	South Africa

23(M) **Metadata time stamp:** 02 September 2013