Current carbon stock estimation capability for South African commercial forest plantations

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Executive Summary

Commercial forest plantations have the capacity to sequester atmospheric carbon dioxide (CO_2) and thus play a role in mitigating the effects of climate change. There is a need to develop algorithms and high resolution activity data (plantation inventory and management records) for quantifying and monitoring carbon stocks in the South African commercial forest plantations. This is important to demonstrate and quantify the extent of the contribution of the South African Forestry Industry towards mitigation response measures to climate change. Carbon sequestration and/or emission of forest plantations can be calculated by estimating the size of the carbon stocks and comparing changes in these stocks between years. Carbon stocks at a site are comprised of pools within each component of the plantation. The total carbon stock is the sum of above-ground tree components (stem, bark, branches, leaves), below-ground root system, forest floor litter layer, dead material, and soil carbon pools. Fluxes within each pool can vary according to various site, plantation and management influences. For example, tree biomass (and carbon) can be higher on hot humid sites than on cooler dryer sites whereas litter biomass (and hence carbon) can be less on hot humid sites than on cooler dryer sites. Soil carbon variation can be dependent on climate and management practices, but it is also influenced by numerous other factors, such as parent lithology and slope position. Carbon stocks therefore need to be calculated separately for each pool within a model that integrates site factors (climate, topography and soils) with measures/inventories of tree growth and management practices.

A short scoping review

The South African forest plantation industry requires country-specific carbon accounting/ estimation methods that are compatible with a wide range of existing local and/or regional forest plantation inventory and management systems. For this reason the Institute for Commercial Forestry Research (ICFR) was commissioned by the Department of Environmental Affairs (DEA) to conduct a scoping study to assess data availability for the development of local carbon estimation equations for all commercial plantation sites and species within the three major genera grown (i.e. pine, eucalypt and wattle), as well as the availability and access to grower activity data. Together these are required to develop of mechanisms and systems for carbon reporting across the industry and prioritisation of further research. The scoping review addresses five inter-related objectives:

Objective 1: Review existing data and available information on tree, forest floor litter and soil carbon for the South African commercial forest plantations.

A review assessment of South African forest plantation biomass and soil data was conducted to determine its availability and suitability to describe carbon sequestered in the trees, roots, litter layer and soil. Most of the available data is from the ICFR, but some data were also sourced from public domains at the Council for Scientific and Industrial Research (CSIR), various university projects and post-graduate theses. These data were originally collected for a range of purposes which included nutrient cycling studies, growth and yield modelling, process-based modelling, and ecosystem research.

Above-ground single tree data was found for 480 eucalypt, 157 pines and 66 wattle trees sampled throughout the summer rainfall areas of South Africa over the last 20 years. Eucalypt data represented an adequate age and site range for pulpwood stands for a number of the main species grown. Pine data represented pulp and saw-timber stands of two major pine species. Those data were consolidated for use in developing biomass expansion factors to convert standing tree volume to biomass. Some preliminary regression analysis suggests these datasets would be suitable to predict above-ground tree biomass from simple tree measurements. However, important species and hybrids have limited data and would require further data collection through field sampling. In addition, a large number of biomass equations were sourced from international literature for the same set of dominant tree species.

Below-ground biomass (root) data for pines was limited to comprehensive *Pinus patula* research carried out on Swaziland pulpwood stands. Pine growth in Swaziland is similar to that in South African plantations. Root data for eucalypts and wattle could not be found, other than for an *E. grandis* coppice crop at one site in the KwaZulu-Natal Midlands. Suitable international published literature derived root equations and root : shoot ratios were found.

Forest floor litter data and models were found for one pine species (*P. patula)* from studies across the summer rainfall areas of South Africa and Swaziland. No forest floor litter data was found for any other pine species. Eucalypt forest floor litter data was limited to 19 samples collected across the summer rainfall region of South Africa. Some preliminary correlation analysis indicates that similar good predictive relationships between broad climatic variables and forest floor litter biomass reported for pines can be derived for eucalypt plantations.

A soil analysis database exists at the ICFR with some 6000 entries acquired over 20 years including soil carbon content measurements for up to 1 m depth at 428 forest plantation sites in South Africa. These data could be used to generate a baseline soil carbon map of soil to 1 m depth.

Objective 2: Consult with forestry companies to identify existing commercial forest plantation tree growth information in current use.

Information was sourced from private plantation owners and owner representatives as two information requests:

1. Provide a description/overview of land area planted to each tree species or clonal hybrid; and
2. Provide an overview of the planning and inventory measuring, recording and reporting systems in use by the company or landowner.

Forest plantation information was derived from various public domain sources and interviews representing 87% of South African commercial forest plantations. Private sector forestry companies and co-operatives were contacted and their specialists in planning and inventory systems interviewed.

Information for small growers was obtained from Forestry South Africa (FSA). No information was available the remaining 13% of planted land area.

Tree species that comprise the current planted area are dominated by five eucalypt species (33% of total), three eucalypt clones (9.5% of total plantations), five pine species (41% of total plantations) and one wattle species (12% of total plantations). Tree growth inventory information currently exists as proprietary and business sensitive information within larger forestry companies. Private forest plantation company inventory systems are based on statistically valid, periodic sampling of tree growth and locally developed growth modelling systems. These are used by most large and medium forest plantation companies and to a limited extent by large co-operatives to measure current and forecast future forest stocks and to plan management operations. Typically, standard outputs from these systems include forest volume, tree size measures and various merchantable components of a stand. Inventory data is collected at a compartment level which is the basic land management unit and each compartment often has some basic soil and climate information available. However, as these data are proprietary, representing business sensitive information, they were not available for collection by the ICFR and are not available to any organisation outside each respective company.

The Department of Agriculture, Forestry and Fisheries (DAFF) is mandated to report on the state of commercial forests to the cabinet of the Republic of South Africa. This publically available report contains data on genera, planted area and age class for the commercial forest plantation industry. This information represents the base level at which information is available across the forest resource including large private companies and smaller scale tree farmers.

Given the diversity of forest data available no one method of estimating carbon stocks will suit all situations. The following methods would be necessary to develop an estimate of carbon stocks for the entire sector;

1. The DAFF summary information can be used to estimate plantation carbon stocks for the whole sector. However, such estimates would be sensitive primarily to changes in planted area and average age of crops. Estimates would be insensitive to changes in species composition across site productivity classes and any incremental improvement forestry growth and productivity derived from improved forestry practice.
2. For estimates sensitive to site, species and changes in forestry practice more detailed annual tree growth data is required, such as collected by private companies in their inventory programmes. A methodology compatible with existing forest inventory, growth and yield will be required for this type of estimate.
3. For smaller scale tree farmers who lack comprehensive planning systems generic models based on species, age and site productivity class estimates would be the most suitable methodology.
4. Additional methods can also be used as a measure of plantation volume growth and from this carbon stocks. These include process-based model predictions that can be improved

using remote sensing and general site quality indices that can be spatially extrapolated from company inventory data. These methods draw upon climatic and geographic information available in the public domain and would represent the most imprecise estimates.

Objective 3: Recommend methods for development of a suite of carbon stock estimation equations that will be compatible with existing commercial forest management information, to allow company industry level estimation of carbon stock in commercial forest plantations.

Carbon stocks can be predicted using an integrated model to account for each carbon pool within a forest plantation stand. The components of such a model will rely on equations developed from local and international data applied to site and stand data. The certainty of prediction depends on the data source and the statistical error reported with the equations. Highest certainty will be through applying the equations directly to company inventory data (high resolution data). Lowest certainty will occur where tree and site data are predicted from national summary data or growth models (low resolution data).

The common use of forest plantation volume as a final assessment of stand productivity amongst growers, models, and reporting mechanisms enables the development of a suite of carbon equations to convert tree volume to an estimate of total tree biomass (and carbon). A climate and genus based forest floor litter model can be developed to predict forest floor litter carbon stocks based on site (climatic) and species data. Soil carbon stocks can be derived from a spatial dataset derived from the existing soil database and also further sample collection.

An integrated model approach can be developed to use a geographic information system to predict carbon stocks. Climatic, topographic and lithology information can be sourced from spatial information databases and used as factors to predict soil carbon, forest floor litter carbon and tree growth from tree carbon pools and hence total carbon stocks can be derived. Forest plantation volume can be calculated from company inventory data or derived from a forest site classification that predicts site productivity classes. The lowest level of stand information required will be genus, age and area planted. Where stand data exists it can be used to supersede any model derived predictions. It is recommended that:

- A comprehensive model framework is formulated to incorporate all the carbon pools for individual forest plantations. This model must be able to utilise actual site and tree data (where available) or predictions based on site information to estimate carbon stocks. An error term must also be included in the predictions around each carbon pool and total carbon stock. The framework must include the ability to simultaneously model multiple plantations;
- Volume based above-ground biomass and carbon equations are developed from existing data identified in this review;

- Site based forest floor litter biomass and carbon equations are developed from existing data identified in this review;
- A baseline soil carbon map is created using existing data in the current ICFR soils database and a predictive equation developed to estimate soil carbon from site, climatic and management data. This can be improved as more data is sourced or collected;
- A literature-derived equation be used for root biomass and carbon estimation;
- Process-based models, site quality indices and existing DAFF annual statistics, are utilised to source area, age classes and genera/species information for areas where inventory data is not recorded. Existing industry growth models can be applied to estimate tree volume for each tree age for average growth plantations;
- Equations for tree, forest floor litter and soil carbon estimation be incorporated into the large and medium company planning systems, aggregated and reported to a service provider, who can audit the data before releasing to other parties;
- An independent and confidential data collection and management service is used for collection, processing and collating all carbon or tree growth data supplied from growers across the industry. This will protect any proprietary or business sensitive information of private companies, while providing a carbon estimation service to smaller scale tree growers. Crop standing value is reported as part of the annual accounts of a forestry company (fair value reporting system) and this is audited by accountancy firms on a strict confidentiality basis. Such an approach to carbon stock reporting would need similar.

Objective 4: Identify parameters that should be monitored over time that affect carbon stock changes in South African commercial plantations:

As carbon in forest plantation is held in three primary pools, above-ground, below-ground and forest floor litter, these pools can be monitored though a multi-site network of monitoring plots. Tree volume measurements, forest floor litter biomass and total soil carbon analysis at periodic intervals will required to track carbon stocks in the long-term. Heavy and light fractions of soil carbon should be monitored as a more meaningful measure of changes in soil carbon pools. Harvested area, burned area (prescribed or wildfire), and area lost through biotic or abiotic influences should be recorded in addition to basic stand information. A network can be initiated that utilises current industry owned tree growth monitoring plots (with the necessary permissions and approvals) or new plots representing zones of homogeneity within plantations. Additional monitoring plots can be set out in areas under agricultural, conservation or other land uses within the forest plantation land holdings and monitored for changes in soil (and above-ground where possible) carbon. Remote sensing can be used to detect changes for areas where growth and management is not measured and recorded, specifically land area planted, species changes, and land use change.

Objective 5: Recommend further research in carbon stocks (tree, forest litter, soil) that will enable improved estimations suitable for monitoring change at an appropriate time frame:

When considering opportunities to improve estimations of carbon stocks it is necessary to consider the relative importance of various components of carbon stocks in the system;

- Above-ground tree biomass can comprise 15 to 75 % of the total, a major portion of which is stem wood.
- Tree roots can comprise up to 70% of the total tree carbon, with the larger numbers relating to coppiced crops.
- Forest floor carbon pools can be between 10 to 40% of the total carbon stocks.
- Limited South African forest plantation data suggests that the soil can hold up to four times more carbon than the trees and litter combined, and implies that soil can constitute 50 to 80 % of total carbon stocks.

Each of these pools represent a major uncertainly for estimating trends in carbon stock over time. At present, data identified in this scoping review are available to generate a set of standard genera, and in some cases, site and species/hybrid-specific equations applicable across the commercial forest plantation industry to predict carbon stocks. However, those data are either incomplete or non-existent for certain major species in the three main tree genera grown, and some major site types for plantation biomass and soil components. It is recommended that:

- Field data biomass data collection occurs for important species and hybrids currently having only limited data.
- Root biomass data is particularly lacking and should be quantified through collaborative partnerships with academic and research institutions.
- Forest floor and soil carbon models are developed and improved through field sampling and long-term monitoring that in particular evaluates the impact of forest management practices.

Conclusions

A robust methodology to account for carbon stocks in commercial forest plantations in South Africa does not exist. Data and information identified in this review is of high quality and can be used to generate equations to predict some of the carbon pools. International literature and further research can be used for pools where knowledge gaps exist. A comprehensive modelling framework can be set out based on a combination of South African data and models and international literature derived models to predict carbon stocks directly or through extrapolation. This methodology must be able to use a range of input data ranging from basic information (species and age only) available to small scale tree growers to the detailed tree growth available from tree growth inventory measurements as collected by larger forestry companies. Further research can be used to incrementally improve estimates and the predictive capability of such a modelling framework by targeting knowledge gaps for specific carbon pools and through multi-site monitoring.

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Background

The South African government, in response to the global challenge of climate change, has committed to becoming a climate resilient and lower-carbon economy through initiatives that assist ecosystems and society to adapt to and mitigate the effects of greenhouse gas (GHG) emissions, and the monitoring and evaluation of these initiatives (DEAT 2006; DEA 2010). South Africa's National Climate Change Response Policy (NCCRP), or the White Paper on National Climate Change Response, recognises that accurate, complete and up-to-date data are the foundation of an effective response (DEA 2010,2011). Regarding the GHG inventory, the NCCRP directs that it will be prepared annually, conform to the Intergovernmental Panel on Climate Change (IPCC) guidelines, be reviewed periodically by international team of recognised experts, and will undertake and report analyses of emission trends (IPCC 2003; DEA 2011). South Africa, as a party to the United Nations Framework Convention on Climate Change (UNFCCC), has an obligation to report on its current monitoring, mitigation and adaptation to the effects of climate change initiatives (DEA 2011; UNFCCC 2011). Reports to this end are submitted as national communications every four years with biennial updates. These reports are required to reflect the relative contribution of the agriculture, forestry and other land use (AFOLU) industry to GHG emissions, as well as adaptation and mitigation interventions through assessment of emissions and carbon stock changes (DEA 2011). Forests (which includes natural forests, woodlands and plantations) as a component of AFOLU are considered by the IPCC to play a vital role in mitigating GHG emissions through absorption of atmospheric carbon dioxide, which is stored in the tree biomass and the soil (IPCC 2006). Cyclical harvesting of forest plantations removes the timber portion (and in some cases the bark) of the forest carbon stock while the remaining portions are typically left on the re-planted site which continues to sequester carbon through new tree growth. However, in recent years the demand for renewable energy and mechanised harvesting systems have led to removal of additional biomass from plantations such as tree bark, branches and, in some cases foliage. Residue burning, carried out to reduce wildfire risk and improve access for silvicultural operations, also results in on-site loss of biomass and carbon.

An evidence-based approach to carbon accounting is required that will necessitate knowledge and expertise to be mobilised through partnerships between government departments, non-governmental organisations, research institutes, business and academic institutions. A three tiered hierarchical approach has been adopted by the 2006 IPCC Guidelines for Carbon Accounting, with higher tiers providing estimates of greater certainty than lower tiers (IPCC 2006).

Tier 1 uses default estimation parameters and simple methods that are based on national and global production statistics and land cover maps of land use change. The simplified default Tier 1 methods, amongst other shortfalls, have large uncertainty around the default values used to estimate carbon stocks, particularly above-ground biomass and soil carbon (Newell and Vos 2012).

Tier 2 is similar to Tier 1 but includes national or regional (country specific) activity data, improved equations and emission/removal factors producing estimates at a higher resolution (IPCC 2006; Bird et al. 2010).

Tier 3 uses more complex higher resolution equations and often includes process-based models for carbon stock estimation that are based on region and species specific models and inventory data that generate information at a far higher resolution than Tier 1 or 2 estimates (IPCC 2006; Bird et al. 2010). Tier 3 methods require detailed national forest inventory data with dynamic models or allometric equations that directly calculate biomass increments and hence changes in carbon stocks. Tier 3 systems can include modular combinations of the forest and soil management systems that are integrated using various types of monitoring so that carbon stock changes can be tracked over time (IPCC 2006; Bird et al. 2010).

Information to satisfy the requirements for higher tier estimation of carbon stocks for forest plantations reside within two distinct categories within the industry; namely business-sensitive and proprietary forest inventory data, and institutional scientific knowledge that is, at present, owned by the private industry and certain academic institutions. There is limited inventory data available in the public domain.

Data requirements to calculate carbon stocks and change

Forest carbon is held in five primary carbon pools within a forest stand. These pools are not static, but accumulate or release carbon over time as a function of climatic, edaphic, biotic and management influences. The major carbon pools comprise above- and below-ground living tree biomass, dead wood, litter and soils (IPCC 2006; Picard et al. 2012). Dead wood and understory vegetation are minor carbon pools in plantation forests that are limited by current management regimes and close stand structures (Bird et al. 2010). Soil carbon is accounted to 1 m depth (IPCC 2006), but soil carbon storage can extend to far greater depths under forests through deep root/soil interactions and dissolved organic carbon leaching (Usuga et al. 2010; Newell and Vos 2012; Shi et al. 2013).

Carbon sequestration and emission can be calculated as a change in carbon stock for a particular land unit of forestry (Picard et al. 2012). Calculating annual carbon stock difference is a preferred method for calculating sequestration or emission of carbon from the plantation areas (IPCC 2006). A second method can be through process-based model estimates of net balance of carbon additions and removals (Saint-André et al. 2007). Carbon efflux using eddy-covariance techniques can also be used, but due to expense, is constrained to research (Saint-André et al. 2007; Picard et al. 2012). Although this review specifically addresses carbon stored in the planted forest areas, calculations for the forest plantation industry should also include permanently unplanted areas within plantation landholdings.

Carbon stocks can be estimated through the use of allometric equations, models or expansion factors that are applied to measures of stand inventory and site parameters. To perform such calculations two types of data are required:

1. Site and tree-species specific equations or expansion factors to convert forest inventory data and site information to carbon pools and total carbon stock;
2. Stand and site data that described stand inventory and growing stocks changes, harvested area and management practices (activity data), and general site and climatic information. Ideally, annual growing stock, activity data and soils data are required across all forest plantation areas at a compartment or land unit level. This will enable an accurate carbon stock and change calculation across the forest plantation industry.

Aims and scope of this review

This review considers the type and availability of data to formulate higher tier carbon estimates. This requires an understanding of the South African forest plantation industry in terms of site data, inventory, activity data, and research data available to construct country specific carbon models. The aims of this review are to:

1. Review existing data and available information on tree, forest litter and soil carbon in South African commercial plantations;
2. Consult with forestry companies to identify existing commercial forest plantation tree growth information in current use;
3. Recommend methods for development of a suite of carbon stock estimation equations that will be compatible with existing commercial forest management information, to allow company industry level estimation of carbon stocks in commercial forest plantations;
4. Identify parameters that should be monitored over time that affect carbon stock changes in South African commercial plantations;
5. Recommend further research in carbon stocks (tree, forest litter, soil) that will enable improved estimations suitable for monitoring change at an appropriate time frame

An understanding of the commercial forest industry is required so that the relevance of existing data and available information around tree component carbon estimation (Objective 1) can be determined. A brief description of the various components of the forest plantation industry is given below to enable an understanding of the diversity and similarities within the industry drawing on information gathered for Objective 2. This will provide context for the objectives of this review by enabling an understanding of the representivity of data collected, aiding in prioritising gathering of further data through research.

The South African Commercial forest plantation industry

Commercial forest plantations in South Africa are recognised as an important part of the economy, contributing 1.27% to the GDP, providing employment to 0.5 million people and supplying South African forest and fibre needs of approximately 17 million air dry tons per annum (DAFF 2012). A total of 2.41 million hectares of land is currently listed under commercial forest ownership, of which 53% is planted to trees (unpublished data, FES (2011)). The unplanted portion of land remains under various other land uses, including agriculture, infrastructure and conservation. Planted forests comprise approximately 1.27 million hectares of land or 1.1% of South African land area (**Figure 1**), and are spread across a broad range of site types, each with distinctly different climatic, topographic and soil properties (Smith et al. 2005; FSA 2011) (**Table 1**). This diverse landscape has been divided into site classification units in Smith et al. (2005) that has divided climate into 27 classes based on rainfall and temperature and 23 lithologies in six formation groups, each with distinctive soil forms. Mean annual temperatures (MAT) range between 12.1 and 22.5 °C, mean annual rainfall (MAP) between 498 and 1976 mm, and altitude between 0 and 2118 m for areas under commercial forest plantations (Schulze et al. 1997; Smith et al. 2005; Louw et al. 2011). Total soil organic carbon ranges between 0.2 and 6.0%, based on the standard deviation for the first metre of soil (unpublished (ICFR 2014 soils database, n=428)).

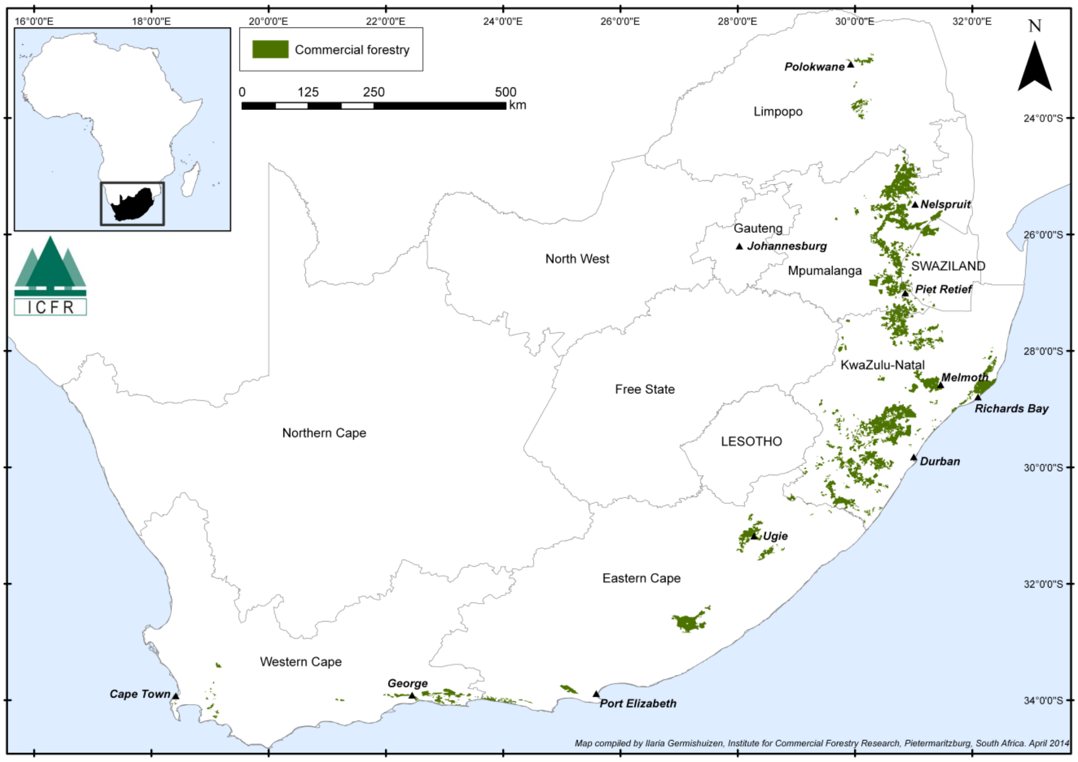

Figure 1: Wide geographic distribution of South African commercial plantation land holdings

Land ownership

Land ownership can be grouped into three classes of land ownership based on company size, tree growth and management objectives, adapted from FSA, (2011), and level of inventory data collection and information availability (Objective 2 data described later):

1. Large corporate companies/growers that grow and process their own timber (**Table 1**).
2. Smaller co-operatives, medium sized companies that have some processing ability, but also sell to local and international processors (**Table 1**).
3. Independent private or small growers who sell into various niche markets.

Land ownership is driven by economies of scale with smaller land areas generally under small company or private individual ownership and larger areas under larger company ownership (FSA 2011; DAFF 2012). A diverse market for products has also driven land ownership patterns and has resulted in a wide range of site management practices. The larger grower-processor companies and some smaller growers supply the bulk of pulp and fibre demand. The medium and smaller growers supply pulp wood and the sawtimber, board and wood chip markets. Smaller companies and growers produce charcoal, mining timber and poles in addition to opportunistically supplying the larger markets (Crickmay 2005).

Table 1: Percentage land ownership and afforestation amongst the 2.41 million ha owned by the forest plantation industry and the planted 1.27 million ha component of this (unpublished data, FES (2011)).

Ownership type	% land ownership	% planted forests
Large companies	29	36
Co-operatives	36	24
Medium/ Small Companies	24	26
Other/public	11	14

Species distributions and management regimes

A diversity of products, site types and growers, in addition to biotic and abiotic factors has led to a very broad range of species choices under three dominant genera, and a range in growing and plantation management regimes (**Table 2**). Rotation lengths vary from short (6-12 years) to long (up to 35 years), **Table 2**. Long rotation regimes are dominated by *Pinus* spp grown for solid wood (sawtimber). Short rotation crops are predominantly *Eucalyptus* spp followed by *Pinus* spp and *Acacia mearnsii*; grown for a variety of solid wood and fibre products. Rotation lengths within these broad categories vary according to tree growth and site productivity, with felling age generally determined by market demand or planned objectives. Species distributions are relatively similar across companies/owners, only differing in the winter rainfall area of South Africa (Objective 2 data, unpublished). Species planted are generally chosen from a subset according to market or processor demand and site suitability. These species choices will change dramatically in the future with changing market demand, biotic and biotic pressures, improved genetics and new clonal advances (Objective 2 unpublished data)

Table 2: Major species under each dominant genus including clonal hybrids and land area by rotation length for each dominant genus (unpublished report, FES (2011))

Species	Planted land area %	% Short rotation	% Long rotation
***Eucalyptus* spp**		40.3	0.3
E. grandis	13.20		
E. dunnii	10.30		
E. macarthurii	4.00		
E. nitens	3.90		
E. smithii	1.80		
Other *Eucalyptus spp*	2.60		
Clonal *Eucalyptus* hybrids			
E. grandis x E. urophylla	4.8		
E. grandis x E. nitens	2.7		
E. grandis x E. camaldulensis	2.0		
***Pinus* spp**		16.5	34.7
P. patula	20.70		
P. elliottii	13.70		
P. radiata	2.90		
PECH[1]	2.00		
P. taeda	1.30		
Other *Pinus spp*	2.00		
***Acacia* spp (wattle)**		7.8	0.1
A. mearnsii	12.30		

[1] PECH – *Pinus elliottii* x *Pinus caribaea* hybrid

Objective 1: Review existing data and available information on tree, forest litter and soil carbon in South African commercial plantations

Carbon models

Changes in carbon stocks (stock change method) in a given area of forest plantation are the sum of carbon changes in each of the above-ground, below-ground, litter and dead material and soil carbon pools. They include removals though harvesting and other management practices and can be described by the following function:

$$\Delta C_{TP} = \Delta C_{AB} + \Delta C_{BB} + \Delta C_{DW} + \Delta C_{LI} + \Delta C_{SO} + \Delta C_{HWP}$$

Where:

ΔC_{TP} is carbon stock change for an area of forest plantation

AB = above-ground biomass pool

BB = below-ground biomass pool

DW = dead wood biomass pool

LI = litter biomass pool

SO = soil carbon pool

HWP = harvests woody products

Each of these pools is estimated independently and the change is determined as the annual average difference between the estimates.

Above-ground biomass and carbon (AB)

Carbon in the growing portion of a stand (living trees) is estimated using mathematical equations that convert tree or stand inventory data to biomass and then carbon. These can be allometric equations that convert tree diameter at 1.3 m height (dbh) and/or total tree height to biomass, or biomass expansion factors that convert standing volume to biomass (IPCC 2006)**.** Tree biomass is converted to carbon through laboratory determined carbon content or using a standard conversion factor of 0.5 g of carbon per g of biomass (Bird et al. 2010; Newell and Vos 2012).

Site and tree species specific models have been described in the Southern African context in Henry et al. (2011). Tree volume and biomass equations have been summarised for sub-Saharan Africa citing 38 allometric equations for two *Eucalyptus* spp, one *Pinus* sp., and a few indigenous species. The work by Henry et al. (2011) is based on a small subset of data that includes preliminary data of Schönau and Boden (1982) and *P. patula* functions sourced from Dames et al. (2002), originally sourced from Morris (1986).

Some simple expansion factors were published in Dovey (2009) for a few commercially important species to convert timber volume into tree component biomass. This was later included in a detailed review of allometric equations and tree volume functions for use in predicting forest residue resources as a bioenergy feedstock in southern Africa (Ackerman et al. 2013). Ackerman et al. (2013) gives a comprehensive summary of peer reviewed research which includes equations derived from local and international literature for the majority of species shown in **Table 3**. These equations were sourced from studies carried out at South African university and research institutions. The raw-data originally used to generate the equations and expansion factors cited in Ackerman et al. (2013) and Dovey (2009) were compiled into a data file as part of Objective 1 and summarised in **Table 3**. The research for which the raw data was originally developed included growth and yield modelling, development of tree taper and volume functions, wood density determination, process-based modelling, nutrient cycling research and bio-fuel production potential. Some differences in methodology between studies (e.g. sample collection and drying methods) need to be considered and accounted for when formulating new equations. Data in **Table 3** have value for developing allometric equations or biomass expansion factors that, when combined, represent a wider range of site types, age classes and plantation stand structures than the original studies afforded, but may need to be extended in some cases to cover a broader age and climate range.

Considering the dominant species given in **Table 2:**

- *Eucalyptus grandis* data cover a broad age and climatic range that represents the majority of growing areas. No further sampling is required as the data are adequate and *E. grandis* is also being phased out as a pure species in commercial plantations.
- Data for *E. dunnii*, *E. macarthurii* and *E. smithii* may require additional sampling to extend the age range of the datasets.
- Data for clonal hybrids are limited to *E. grandis x E. camaldulensis* (G x C) which is currently being phased out across the industry despite covering large planting areas.
- A field sampling programme is current underway to collect data for *E. grandis x E. urophylla* with Stellenbosch University (SUN) across the Zululand Coastal plain.
- No data exists for the *E. grandis x E. nitens (*G x N) clone, and therefore a complete sampling programme is needed.
- Eucalypts, generally lack long-rotation (sawtimber regime) allometric data.
- A wide age and climatic data range is available for *P. patula.* It requires no further sampling as the data are adequate and land area planted to this species is being reduced.
- *Pinus radiata* is currently well represented in the winter rainfall growing area, with data currently residing at SUN. A postgraduate study is currently underway at the Nelson Mandela Metropolitan University (NMMUI), co-supervised at the ICFR to develop sawtimber regime data (for the winter rainfall area).
- No data were found for *P. elliottii*, *Pinus elliottii x Pinus caribaea* hybrid (PECH) and *P. taeda*.
- *Acacia mearnsii* covers an adequate climatic range, but requires data for younger age classes.

Equations developed internationally can be used as a further resource for equation comparison or as an interim measure whilst developing locally relevant carbon equations. An example is a database of numerous international equations that has been assembled by the Food and Agriculture Organization of the United Nations (FAO), Agricultural Research for Development (*Centre de coopération internationale en recherche agronomique pour le développement* - CIRAD), and the Department for Innovation in Biological, Agro-Food and Forest System (DIBAF) at Tuscia University (*Università degli Studi della Tuscia* - UNITUS). (GlobAllomeTree 2014).

Table 3 Data available and extracted to formulate biomass equations across major species under each dominant genus, showing age and mean annual precipitation (MAP) and mean annual temperature (MAT) ranges and publications in which the data were used.

Species	No. samples	Age range (years)	No. sites	Size range (dbh cm)	MAP Range (mm)	MAT Range (°C)	Publication
					Eucalyptus spp		
E. grandis	262	2-12	21	3.0-21.7	784-1403	14.4-21.9	1, 2, 3, 4
E. dunnii	15	6-7	5	12.4-24.6	870-960	14.4-16.9	2
E. macarthurii	15	6-7	5	13.8-20.7	870-960	14.4-16.9	2
E. nitens	86	4-9	10	2.0-38.7	848-960	13.1-16.9	2, 5
E. smithii	21	4-7	5	4.0-29.9	870-960	14.4-16.9	2
Other	95	4-9	5	4.0-22.7	870-960	14.4-16.9	2
					Clonal Eucalyptus hybrids		
E. g x u	30	0-2	1	3.0-10.4	920	21.7	6
E. g x n				No Data			
E. g x c	66	2-20	14	6.2 – 36.5	432-1390	16.2 -22.1	2, 7, 13
					***Pinus* spp**		
P. patula	46	1-28	12	1-33	825-1645	15.5-19.5	8,9
P. elliottii				No Data			
P. radiata	143	1-29	2	30-55.7			10
PECH				No Data			
P. taeda				No Data			
Other	1 species	28	1				10
					***Acacia* spp (wattle)**		
A. mearnsii	66	6-12	5	5.1-20.0	708-1111	16-18.6	11, 12

1. Esprey and Sands (2004), 2. Herbert (2003), 3. Campion et al. (2006), 4. du Toit and Dovey (2005), 5. Rietz and Smith (2004), 6. Dovey (2012), 7. Dye et al. (2004), 8. Morris (1992), 9. Carlson and Allan (2001),10. Ackerman et al. (2013), 11. Dovey et al. (2003), 12. Dicks (2001), 13. Phiri (2013)

Litter layer carbon

Carbon is also stored in litter layer biomass on the forest floor. The mass of this layer varies with site, species and management regime. Climate, topography and management regimes (burning, thinning, pruning, rotation length) can affect the rate of accumulation and decomposition of litter biomass (Morris 1995; Dames et al. 1998). Other factors can also contribute to litter accumulation or breakdown, such as litter moisture, litter structure, size distribution, nutrient status and chemical makeup (Salah and Scholes 2011). Productive sites have high litterfall rates due to rapid tree canopy growth and turnover. This has potential to increase forest floor litter biomass where rates of litter addition exceed litter decomposition rates. Litter accumulates on cool sites due to slow decomposition, while remaining at low levels on warm sites. Different species have different litterfall and litter accumulation rates. This is related to growth rate, residence time of branches and foliage on the trees, and litter size distribution. A dependence of litter biomass on site factors enables models to be developed to predict and extrapolate litter biomass spatially.

Forest floor litter biomass data in South Africa are limited to a few South African studies. Estimates of litter layer biomass under short-rotation *P. patula* stands includes studies carried out in Swaziland, (Morris 1995), KwaZulu-Natal Midlands (de Ronde 1997) and Mpumalanga (Dames et al. 1998). Studies under long rotation *P. patula* are reviewed in Ross and du Toit (2004) and Ross et al. (2005). These studies were carried out to describe litter accumulation, decomposition and litterfall in selected pines as a result of site differences and fertilisation (Morris 1995; Dames et al. 1998; Odiwe 2009). These studies also developed equations to predict litter depth from altitude and litter biomass from litter depth for *P. patula*. These data covering tree ages ranging from 5 to 34 years, a climatic range of 825 to 1645 mm for MAP and 14.6 to 19.5 ºC for MAT have been collated into a single data file. Litter data is given in Odiwe (2009) for one 18 year-old *P. elliottii* stand (MAP 1333 mm, MAT 17 ºC). Further *P. patula* data has been collected for 87 sites by the ICFR for nutrient pool estimation (unpublished ICFR data). These data were collated from the respective sources and reports by each author.

Some preliminary *E. grandis* research has been published based on ICFR data, originally collected for nutrient pool estimation (Ackerman et al. 2013; du Toit et al. 2014). These data have been collated across 24 rotation-end (7 - 12 year-old) *E. grandis* sites across a broad climatic range (MAP 618 - 1368 mm, MAT 14.8 - 21.8 ºC).

The *P. patula* and *E. grandis* data can be used across all studies to formulate predictive equations of litter biomass for each species using site and climatic factors. However, litter data needs to be collected to extend the representation across all remaining species in each genus, sites and age classes in **Table 2**. Rates of accumulation and decomposition need to be determined across all genera to add to values developed in the above studies. This will enable the formulation of models to spatially predict litter biomass and carbon specific to site, species and management regime. Such information also needs to include the effects of residue and forest floor management, particularly residue and under canopy burning on litter biomass and carbon stocks (Morris 1995; Dames et al. 1998).

Below-ground biomass and carbon - Root biomass

Roots biomass is of great importance as it can constitute up to a third of the total living tree biomass, storing carbon to great depths in the soil. Root data are scarce in international research and lacking in South Africa. Root biomass and longevity of root systems requires further research, particularly biomass of coppice root systems which accumulate biomass over successive rotations (Herrero et al. 2014). Local studies include a coppiced *E. grandis* root biomass study (du Toit 2003) and a four year planted *E. grandis* stand (Campion et al. 2006), both in the KwaZulu-Natal Midlands. Comprehensive root biomass work was performed on *P. patula* by Morris (1986) and published in (Morris 1992).

Morris (1992) developed an equation to estimate root biomass using tree diameter (dbh) and tree height:

$$Biomass_{roots} = 2{,}75 + 0{,}00155(dbh\ x\ height)$$

The data in this study can be used to generate root : shoot expansion factors for *P. patula* that can predict root biomass across the age and site range given in **Table 3**.

International root biomass models and root : stem ratios developed for similar *Eucalyptus* and *Pinus spp* can be used in the South African context whilst local models are being developed. Herrero et al. (2014) for example, gives a root : stem ratio of 0.2 and 0.9 for planted and coppice eucalypt crops, respectively. International literature-derived root equations and IPCC default values may need to be utilised for tree species with no root data. New research is required to develop locally relevant root biomass expansion factors and equations for the species listed in **Table 3**. This must include *inter alia* the effects of genus, species, hybrid, age, soil, site and management impacts (coppice rotations) on root carbon storage.

Soil carbon

Soil carbon is comprised of organic matter present in the soil; this includes living organisms, organic residues and humus. Soil organic matter is vital for soil quality and health in its influence on nutrients, water relations, and physical soil structure (du Preez et al. 2011).

As soil carbon storage can be much larger than tree and litter carbon pools combined, the consequent mapping of soil carbon sequestration potential has grown internationally in recent years (Minasny et al. 2013). No structured soil carbon study has been carried out in South Africa to spatially describe the nature and changes in soil carbon stocks (du Preez et al. 2011). Spatial representation of soil carbon is limited to a general carbon map of virgin grassland top-soils in Barnard (2000) who used data from a land type survey and a range of published reports. Research on the effects of forest plantations on soil carbon is conflicting. Some studies report a net increase in soil carbon (soil carbon sequestration) and others report a net decrease (soil carbon emission). Reviews of these conflicting studies present arguments around the effects of various forest management practices on soil carbon through the soil depth layers (Guo and Gifford 2002; Buchholz et al. 2014; Hoover and Heath 2014). Soil carbon needs to be investigated in the South African context across all major site types, through multiple rotations of forest plantations and through the full tree rooting depth.

A database 6000 soil samples across 428 unique forest plantation sites is stored at the ICFR (Titshall 2012). This database covers a majority of major lithologies, and climatic ranges and has potential for use in estimating soil carbon storage and to create a base map of soil carbon to 1 m soil depth (**Table 4**). Soil carbon data in **Table 4** is summarised to 30 cm depth as these data are currently being used to test spatial extrapolation techniques (SAPPI/ICFR scoping study). There is scope to expand this database using historical data that can be sourced from archived trial files and reports at the ICFR and reported in other public domain sources. Although this database has value for carbon stock estimation, long-term monitoring of soil carbon is required across all plantation areas to detect change in soil carbon storage (Scholes 2002).

Table 4: ICFR database of 428 geo-referenced soil samples, showing representative lithologies, % of SA timber land ownership, 0-30 cm soil carbon range, number of samples (n), and MAP and MAT ranges

Lithology	% SA Timber area	Carbon % 0 - 30 cm	n	MAP (mm)	MAT (°C)
Arenite	26.3	0.2 - 10.7	76	667 - 1295	12.9 - 21.8
Shale	17.6	0.4 - 8.8	104	681 - 1198	14.4 - 20.9
Granite	13.3	0.3 - 8.6	40	784 - 1248	15.0 - 22.3
Mudstone	11.0	0.3 - 8.6	34	670 - 1020	13.9 - 18.2
Dolerite	6.0	0.2 - 11.1	41	690 - 1233	14.0 - 17.9
Quartz monzonite	4.2	1.6 - 9.9	12	801 - 880	14.0 - 15.3
Sedimentary	4.2	0.2 - 4.5	56	784 - 1186	21.6 - 22.3
Tillite	3.5	1.1 - 4.7	15	744 - 891	14.4 - 18.7
Gneiss	2.8	2.6 - 3.5	2	602 - 828	14.9 - 22.3
Dolomite	2.4	1.1 - 11.1	31	904 - 1248	14.9 - 16.8
Basalt	1.7	1.5 - 1.5	1	922 - 922	17.9 - 17.9
Quartzite	1.6	2.9 - 4.5	3	904 - 1198	14.7 - 16.7
Gabbro	0.9	3.1 - 8	3	790 - 879	14.6 - 16.0
Greenstone	0.2	2.5 - 2.5	1	850 - 850	18.5 - 18.5
Amphibolite	0.2	2.24 - 2.8	2	1029 - 1107	19.3 - 21.3
Siltstone	0.2	0.3 - 0.6	3	744 - 797	22.3 - 22.4
Granodiorite	0.2	2.8 - 2.8	1	935 - 935	16.3 - 16.3
Hornfels	0.1	1.5 - 4.5	3	730 - 730	13.6 - 13.7

Objective 2: Consult with forestry companies to identify existing commercial forest plantation tree growth information in current use

Interaction and data acquisition

Activity data describing forest plantation management and harvesting, as well as tree growth (inventory) data are required for carbon models to have value in determining carbon emission or sequestration. Information was obtained from each company through direct interaction, email requests or phone calls. Forestry South Africa (FSA) and the FSA Environmental Committee were consulted and gave their full support by requesting and encouraging participation from their members. Companies who responded to requests represented 86% ownership of the planted forests in South Africa. All of the companies that responded gave very enthusiastic support for the objectives around carbon monitoring. Carbon sequestration and (emission reductions) towards monitoring and mitigation of GHG are well aligned with the sustainable production and environmental protection goals across all growers. Individual company details, information acquired and sentiments have been aggregated to protect the interests and business sensitive intellectual information of individual companies or grower representatives, such as data in **Table 2**. Much of the information given is sourced from local and international literature or the expert advice of the respondents. In general, methods to record, model, extrapolate, and project stand growth and yield are highly developed and advanced within the South African forest plantation industry. This has resulted in standard empirical growth and yield modelling techniques that are taught at forestry learning institutes and embedded into many company planning systems. A lack of capacity and resources however limits the recording and availability of activity data across certain plantation owners, especially small, private and emerging growers.

Tree growth measurement and modelling

Standard tree growth and yield models used for predictions and projections of stand growth are parameterised and calibrated using data collected from permanent sampling plots (PSP), inventory plots, long-term trials, and through destructive tree sampling (von Gadow and Bredenkamp 1992; Kotze et al. 2011). The PSPs consist of many plots spread throughout company owned growing regions, each representing a uniform growing area, species and management regime. A portion of the plantation growing stock (around 5% each year) is also measured (cruised) to obtain a real-time measure of stand growth and yield. Stands measured are chosen to reflect homogeneous growing areas, regimes and age classes. Cruising of stands is usually performed two years prior to rotation end in short rotation plantations (pulpwood). Sawtimber stands are enumerated in a similar manner, usually around the time of thinning, again at 20 years and then at 5 year intervals (Kotze et al. 2011). In some instances stands are also cruised at younger ages to audit early tree survival and establishment success, and to refine growth models and estimates. These practices enable a standardised index of growth potential or site quality (Site Index, SI_{age}) to be allocated to each site, based on the dominant tree height at a standard reference index age. This reference age is usually five or 10 years for pulpwood stands and 20 years for sawtimber stands. These data are used to extrapolate tree growth temporally to younger and older ages and spatially to similar areas. Default values, based on previous assessments, are used where parameter data or cruising data are not available.

Large corporate companies

Large corporate companies have well developed and audited activity tracking and inventory systems that form an integral part of their strategic and tactical planning systems. Intensive tree growing stock data are collected through enumeration processes and used with growth and yield models to predict timber supply and plantation asset value. Projections using growth and yield methods are robust and strictly monitored to ensure minimal variance between predicted and observed (timber over the weighbridge) yield measures. This level of control is enforced to ensure an even and continuous timber supply to the processing mills as under or over predictions can have a severe financial impact on mill operations. Plantation value assessments (growing stock assessment) derived from these projections also undergo an annual financial audit. These data have a high level of statistical certainty, but are business-sensitive and thus protected intellectual property, which limits access to outside organisations.

Medium, small companies and co-operatives

Medium sized companies and co-operatives to some extent have limited capacity to perform cruising operations and to monitor PSP systems across their landholdings. They therefore record stand inventory at a lower intensity compared to the large companies. Smaller companies and growers belonging to co-operatives lack capacity to record and model growth rates broadly across their landholdings. They rely on standard growth and yield functions and estimates of production through generalised site based quality classes to predict timber supply. Many smaller companies and co-operative growers rely on contractors for rotation end yield measurements (contractors cruise compartments to assess yield prior to clearfelling). These data are in some cases fed back to the offices of the co-operatives or small companies. Where capacity exists, similar modelling exercises are used as with larger companies to extrapolate yield data spatially and temporally. This practice is more common within the medium sized companies and co-operatives than the smaller companies. Models and growth estimates form part of planning systems supported through external research groups, consultants and institutions. Most of the smaller companies lack comprehensive planning systems.

Independent private growers' and emerging growers

Activity of this group is often not recorded and reported, as timber may be grown more informally and sold into niche or informal markets that have no monitoring systems. Growth in these circumstances may need to be predicted using generalised data and models.

Objective 3: Recommend methods for development of a suite of carbon stock estimation equations that will be compatible with existing commercial forest management information, to allow company industry level estimation of carbon stock in commercial forest plantations

Expansion factors and predictive equations

Similar growing regimes across the three major genera and use of standardised growth and yield modelling systems enable a common set of age, species and regime dependant tree volume based biomass expansion factors to be applicable across all forest plantation landholdings. These expansion factors can be used to convert tree timber volume to above-ground and below-ground carbon. Litter carbon can be predicted using site factors derived from geographic information. Soil carbon stocks can be predicted using site factors or extracted from a soil carbon map. These predictions depend on the development of biomass and carbon equations using the data collected in this review, supplemented with further research, international or default values/equations where applicable. These methods are applicable for the majority of landholdings where trees are grown and managed as a structured monoculture crop. Alternate carbon stock calculation methods may be required where trees are grown under different regimes, such as multipurpose crops or in agro-forestry systems. These alternative growing regimes currently represent a minor fragment of the forestry industry, but are vital to economic empowerment of individual and private growers, and new and emerging growers.

Inventory and activity data reporting

Carbon stock estimates can be calculated within internal company planning and inventory systems and reported as an aggregated value to an external independent data management service. Large companies interviewed expressed a willingness to include such carbon calculation methods into their planning systems and to report on an aggregated value. This is provided their business sensitive information and IP rights are protected, the functions are scientifically robust and accepted by all stakeholders, and formulated to be compatible with their growth and yield modelling systems. A similar mechanism can be used with the medium sized companies and co-operatives that have well developed planning and inventory systems. However, an alternative methods will be required for land owners who do not record or report inventory and activity data.

A proposed carbon stock model

Where no inventory or activity data is reported, carbon stocks will need to be estimated based on general site information. A carbon stock model is proposed to estimate the sizes of the various carbon pools in forest plantations. The model can utilise generic growth and yield functions and biomass/carbon equations derived from the data in this review and literature. The model will need to be adaptive to the level of information available but will have basic minimum input requirements. The most rudimentary level of data required will be genus, age, area planted, stems per hectare and geographic information (site location). These data can be used to predict timber volume production from which above- and below-ground carbon can be derived using the equations and expansion factors mentioned above. Where more detailed information is available it can be used to override predictions derived from the basic data. More detailed information can include species or hybrid planted, site index, stems per hectare, quadratic mean diameter, mean height, mean tree or stand volume and actual biomass, litter or soils data. The model will need to simultaneously perform calculations for multiple sites, but running each site independently from the others. A measure of productivity for each site can be derived through a number of mechanisms that include government reporting mechanisms, remote sensing and process-based modelling. The ICFR is currently developing spatially extrapolated site indices for numerous species and hybrids across the forest plantation industry. These can also be used as a default productivity input to the model. Management operations (harvesting and burning) will need to be sourced either through remote sensing or through government reporting mechanisms.

Further sources of inventory and activity data

The Department of Agriculture Forestry and Fisheries (DAFF) collects timber resource and processing data across the industry at regular intervals. These data are collected through information questionnaires sent to and completed by the majority of growers. Such information can be extended to include more detail on species and growing stock (volume production). Plantation stand compartment data are also collected by the Department of Water Affairs WARMS project. These data are used for water use licensing across all forest plantations areas and may include useful species, age and regional information.

Process-based models and remote sensing

Process-based biomass or stand growth models can be used to predict biomass production or tree growth using site and climatic variables. This requires intensive input data, skills, processing power and ground truthing to ensure accuracy. It also relies on the basic site data mentioned above. Remote sensing (spot imagery, MODIS, LandSat and LIDAR) can be used in conjunction with growth modelling (empirical and process-based) to derive species, age and basic stand growth parameters and predict stand volumes. This can require some site information at a level dependant on the technology used, with a distinct requirement for ground-truthing to check the validity of the models and assumptions. Process-based models and remote sensing can be developed and parameterised with the same set of standard biomass expansion factors and equations above. Uncertainty or error level around activity data increases as the assessment method becomes more remote or based on multiple layers of extrapolation.

Objective 4: Identify parameters that should be monitored over time that affect carbon stock changes in South African commercial plantations

Management activities

Plantation management practices impact on all components of carbon storage in plantations in the short- and long-term. This occurs either directly through management impacts, as an indirect consequence of management or indirectly through natural occurrences. Management-induced losses of carbon occur primarily during harvesting and re-establishment as a factor of prescribed residue burning, residue removal or increased biomass removal. Thinning, pruning operations and under-canopy burning can impact carbon later in the rotation. Species and genus exchange can result in altered growth rates, tree structures and management regimes that can impact on carbon stocks. Indirect uncontrolled causes can include wild fire, pest and disease damage, and adverse weather conditions (Newell and Vos 2012). Inter-rotation decomposition of residues can result in a loss or gain of carbon at a site dependant on climatic conditions. Carbon gain to a site can be increased through increasing tree growth, increased rotation lengths, by retaining or conserving soil carbon pools and residues in some cases, and by increasing the proportional area planted to trees (Newell and Vos 2012). Such changes and management operations are currently partially monitored through company inventory and planning systems (above-ground tree biomass), but need to be monitored on the remaining forest plantation land area. Carbon changes in unplanted areas have not been included in this review, but may form an important component of carbon fluxes in land under forest plantation ownership. A monitoring network is recommended to enable a better understanding of changes in soil and litter carbon pools.

Long-term monitoring networks

Monitoring carbon stock changes in a forest plantation system, particularly soil carbon needs to be carried out through the use of a network of long-term monitoring plots (Scholes 2002). These plots need to be distributed to represent the climatic and topographic variability of the country, include all major species, and management practices. Plots also need to include forest land under conservation and other land uses practices. A geo-referenced network of plots will enable regular collection of soil and litter samples. These should be analysed to determine soil bulk density (once off), soil carbon content and litter biomass. Soil carbon fractions can be determined to understand changes in the various soil carbon fractions, such as the labile and recalcitrant forms in the light and heavy particulate carbon fractions (Scholes 2002). This will have multiple benefits if carried out regularly across a representative number of sites in developing improved soil and litter carbon prediction models and knowledge on carbon conservation. These plots can be re-assessed bi-annually or at rotation end (Scholes 2002). Change in soil carbon stocks of each carbon fraction between each sampling event can be used as an indicator related to site information and management practices, provided monitoring continues over multiple rotations.

Company owned PSPs are ideal for this purpose as they are situated to represent the above criteria. Most companies value the potential additional information gained from such monitoring systems and show support for such work. The terms of access to and use of these and supporting data would need to be negotiated with each company in turn. Alternatively, sampling plots may need to be set out as part of an independent research activity.

Objective 5: Recommend further research in carbon stocks (tree, forest litter, soil) that will enable improved estimations suitable for monitoring change at an appropriate time frame

There is still a need for further field-based data collection and research despite a large amount of data available to generate improved carbon estimation functions. This is due to the variable and dynamic nature of the South African forest plantation industry. Such additional work needs to be prioritised for each carbon pool. Collection of these data is ideally suited to research undertaken through collaborative partnerships between research organisations and through closely supervised postgraduate student projects. This will require all research to be coordinated through a centralised research body. Research priorities to develop more precise carbon stock estimations are thus suggested:

Biomass expansion factors

Carbon held in the above-ground biomass can comprise 15 to 75% of the total carbon stock, a major portion of which is stem-wood. Tree volume taper equations and basic wood density conversion factors are available for all major commercial tree species. These are currently used to predict stemwood volume and mass. Above- and below-ground expansion factors need to be tree volume based.

1. The ICFR can publish equations using data collated to date to predict tree component masses from stem wood volume and other common tree measures (dbh and height). This will include prediction of biomass of each tree component.
2. Further field sampling exercises need to be carried out to generate tree allometric functions and biomass expansion factors for species in **Table 3** with limited or no data. Such research will be proposed for G x U, G x N clonal hybrids for the year 2015.
3. A sensitivity analysis is required to compare functions developed, in order to determine the genus, species or hybrid sensitivity error incurred in using specific, generic local and international expansion factors.

Forest floor litter

Litter carbon pools can be between 10 to 40% of the total carbon stocks, hence require further data and development of predictive models.

1. The ICFR can publish site-related forest litter equations for *P. patula and E. grandis* through combining the collated data sourced.
2. Commissioned field sampling exercises are required to collect forest litter to generate spatial litter biomass models at the genus and species level. This must include monitoring of litter accumulation and decomposing with stand age through chronosequence studies or long-term monitoring.
3. A sensitivity analysis should be performed to test the use of generic against species specific functions.

Root biomass

Although root data is limited, it can comprise up to 20 to 70% of the total tree carbon, with larger values relating to coppiced crops.

1. A review of international literature of root models should be undertaken and supplemented with existing South African root biomass, to provide preliminary root expansion factors.
2. Field sampling of root biomass is required across all species in each genera (except *P. patula*).
3. Carbon storage of roots and stumps under planted and coppice crop rotations needs to be researched under eucalypts.

Soil carbon

A method for predicting surface (0 – 30 cm) soil carbon is being developed by SAPPI and the ICFR. It will be used to predict surface carbon spatially and extended to predict soil carbon to 1 m soil depth. Each of the various carbon pools have importance in contributing to total carbon stocks under forest plantations, but soil carbon is an area of greatest uncertainty. Data collected in this review suggests that the soil can hold up to four times more carbon than the trees and litter combined, and implies that soil can constitute 50 to 80 % of total carbon stocks. A long-term monitoring network is needed for monitoring soil carbon change under forest plantations to further knowledge around this major carbon pool.

Conclusions

The South African commercial plantation timber industry does not have a robust methodology to account for carbon stocks due to variable grower information and unavailability of expansion equations for certain pools, sites and species. Data and information sourced and identified for this review is of high quality and can be used to generate equations to predict some of the carbon pools. International literature and further research can be used for pools where knowledge gaps exist. These can be applied for the portion of the industry that has comprehensive internal inventory reporting systems, but will require further extrapolation for parts of the industry without inventory systems. A comprehensive modelling framework can be set out based on a combination of South African data and models and international literature derived models to predict carbon stocks directly or through extrapolation.

Activity and inventory data will need to be extrapolated for parts of the industry without inventory systems using models, remote sensing and government survey systems. More detailed site and species data need to be collected annually for this part of the industry. Tree growth prediction will be required for parts of the industry not reported on. This can utilise generic site quality classes and tree growth models to project and extrapolate tree growth and volumes. This can then be expanded to carbon stocks using the carbon expansion factors and equations. Further research can be used to incrementally improve the predictive capability of carbon models and equations by targeting knowledge gaps for specific carbon pools and through long-term multi-site monitoring. A recommended mechanism to coordinate such work will be through a consortium of researchers, post-graduate students and industry partners. With appropriate financial support such a consortium can direct research projects to fill knowledge gaps in carbon estimation.

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