CARBON STORAGE IN EUCALYPTUS
AND PINE PLANTATIONS IN SOUTH AFRICA

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Abstract. Carbon (C) is stored by plantation forests either when ecosystems with a low C density (such as tropical grasslands) are afforested or when timber is converted to semipermanent products. If the afforestation rate is relatively constant and the plantations are not harvested immediately upon reaching maturity, the amount of C stored in trees as a result of afforestation can be calculated by a simple "static" approximation. Rotation forestry requires a mean C storage method that averages C density over the rotation. Plantation forestry as practiced in South Africa requires a more detailed dynamic approach that accounts for time-varying rates of afforestation and the age-dependence of C accumulation rates in plantations. To determine C storage in products, the output of long-lived plantation products and their C content once all processing losses are accounted for must be known. The South African case study shows that new afforestation stored approximately 2.54 Tg C in 1990, and storage in forest products accounted for an additional 1.15 Tg C. Together, these two activities offset approximately 3.8% of the carbon dioxide emissions from South Africa.

1. Introduction

Carbon dioxide (CO_2) that is removed from the atmosphere and stored as carbon (C) may be considered to be sequestered in terms of the United Nations Framework Convention on Climate Change, and can be offset against the CO_2 emissions for that country. One mechanism of C storage is through its assimilation in vegetation. Numerous authors have estimated the potential of forests and agroforestry management practices to store C (Dixon *et al.,* 1994; Harmon *et al.,* 1990; Schroeder, 1992; and Winjum *et al.,* 1992).

When an ecosystem with a low C density (the amount of organic C per unit of land area, in Mg C ha^{-1}) is converted to an ecosystem with a high C density, there is a net increase in C storage equal to the difference in C densities over a period equal to the time taken to reach the new state. Such conversions take place in southern Africa when grasslands or sparse savanna woodlands (low-C-density ecosystems) are afforested to produce pulpwood, mining timber, sawtimber, or fuelwood. The amount of C stored will depend on both the forest management practices (that is, species planted, espacement, thinning, and rotation length) and the bioclimatic region (Winjum *et al.,* 1992).

Plantations are a common land use in Africa, but constitute only a small fraction of the land surface (1.2% in South Africa, one of the most extensively planted African countries). They almost invariably consist of exotic (that is, non-African) species of fast-growing trees, generally drawn from the genera *Pinus* or *Eucalyptus*. Most of these plantations are managed on a rotational basis; when the growth rate of the trees begins to decline, they

are clearfelled and another crop of trees is planted. Because of the favorable growing conditions in the tropics, the rotation length can range from 6 to 25 years, depending on the nature of the end product.

Even though the plantation is eventually felled, it nevertheless constitutes a net C storage if the mean C density over the rotation is greater than that of the vegetation it replaces. Furthermore, if any tree products are processed into a form where C is stored for a lengthy duration (for C-containing products of the fossil fuel industry, the Intergovernmental Panel on Climate Change considers a minimum life of 20 years), they constitute storage whether or not the forest area is expanding (or even if it is contracting, because in that case they must be subtracted from the C emission due to land use change).

The objective of this paper is to demonstrate, through the example of South Africa, the methods used to calculate C storage from the activities of the plantation forestry industry.

2. Materials and methods

2.1. Carbon Storage due to Afforestation

In the absence of more locally specific data, the C density of plantations can be based on the published averages (for example, OECD, 1991; IPCC/OECD, 1994; UNEP et $al.$, 1995). Most countries in which forestry is practiced will have data on final harvestable roundwood yields, which can be used to improve the default estimates. The total biomass of forests is about 50% greater than the mass of extractable timber at harvest because total biomass also includes branches, bark, leaves, and roots. Many tree species have been used in planation forests in South Africa. The softwood plantations are predominantly $Pinus$ $patula$, while the hardwoods are predominantly $Eucalyptus$ $grandis$. These two species have been taken as representative of all softwoods and hardwoods in South Africa, respectively.

The C density of the biomass standing crop can be calculated as

$$C_i = V_{stem} \rho_{wood} F_{carbon} F_{stem}^{-1},$$

where

C = tree biomass C density (Mg C ha^{-1}),

V_{stem} = stem wood volume (m^3 ha^{-1}),

ρ_{wood} = density of wood (the density of wet wood is 0.86 Mg m^{-3} for $E.$ $grandis$ and 0.88 Mg m^{-3} for $P.$ $patula;$ the moisture content of wood at harvest is 66% for $E.$ $grandis$ and 115% for $P.$ $patula$ (van Vuuren et $al.$, 1978)),

F_{carbon} = fraction of oven-dry mass that is C (assume 0.5 for all species), and

F_{stem} = fraction that stemwood contributes to whole tree biomass ha^{-1} (0.667 for $E.$ $grandis$ and 0.704 for $P.$ $patula;$ see Table I).

Values for the C contents of plant tissues vary in the literature from 45% to 54% (Kinerson et $al.$, 1977). A conversion factor of 50% is commonly used to estimate the organic C content of plant tissues (Brown and Lugo, 1982; Harmon et $al.$, 1990). Table I

TABLE I

Biomass components of *P. patula* and *E. grandis* in southern Africa at harvest maturity
(Christie, 1991; Herbert and Robertson, 1991; Morris, 1992)

Component	Percent of total dry biomass		
	Pinus patula	*Eucalyptus grandis*	
	20 years	8 years	7 years
Bole wood	70.7	66.6	75.2
Branch wood	10.1	9.4	2.7
Bark	5.9	7.5	7.1
Leaves	1.5	3.6	2.3
Roots	11.5	(13.0)[a]	(12.7)[a]

[a]Root biomass was not measured but is estimated to constitute 15% of the total aboveground biomass.

presents the data used to estimate F_{stem} for typical *Pinus* and *Eucalyptus* species growing in plantations in South Africa.

In South Africa, afforestation replaces montane grasslands, which have an aboveground biomass averaging 6 Mg DM ha^{-1} (Everson *et al.*, 1988). Assuming an equal amount of biomass belowground and 50% C content, this converts to a C density of 6 Mg C ha^{-1}. The method as applied assumes that soil C is not affected by the land-use change. This is certainly not true, but there are insufficient data to make a generalization about the magnitude (or even the sign) of the changes.

Three methods are described below for calculating C storage by plantations. The first two are static methods that do not account for the history of afforestation, while the third (dynamic) method does.

2.1.1. The static method using final carbon density
This is the simplest approach, and is the default in the *IPCC Guidelines for National Greenhouse Gas Inventories* (UNEP *et al.*, 1995). In essence, it credits the country with the full final biomass of the plantation on the date on which it is planted (about a decade or two before it actually accrues). This is not a serious source of error if the area planted annually is relatively constant and the trees are not harvested until some long time after they reach maturity. The calculation is as follows:

$$C_s = \sum_{j=1}^{m} A_j (C_{p,j} - C_g),$$

where

C_s	=	total C stored (Mg),
A_j	=	area planted per year of plantation type j (ha),
C_p	=	C density at maturity of the plantation type j (Mg C ha^{-1}),
C_g	=	C density of the preceding land use (Mg C ha^{-1}), and
m	=	number of different plantation types (including different species and management regimes).

Table II presents the estimated C density at maturity for *P. patula* and *E. grandis* sawtimber and pulpwood management regimes for both coniferous and broadleafed forests. The area planted per year is obtained from national or regional statistics (Figure 1). Where it is highly variable, a 3- or 5-year average centered around the reference year should be used.

2.1.2. The static method using mean carbon storage

If the trees are harvested before or soon after they reach maturity, the mean carbon storage (MCS) method (Schroeder, 1992) is more appropriate than the peak biomass method described above. The MCS method determines the average amount of C on a site over a full rotation. It assumes that the plantation management system is sustainable and no yield reduction in the second and subsequent rotations. The calculation is made by summing

TABLE II

Carbon density at maturity in average South African plantations
of *P. patula* and *E. grandis* under different management regimes (van Vuuren *et al.*, 1978)

Plantation type	Rotation length (years)	Final yield (m³ha⁻¹)	Mean Annual Increment (m³ha⁻¹yr)	Final C density (Mg C ha⁻¹)	Mean C storage (Mg C ha⁻¹)
African coniferous forests (OECD 1991)[a]36.8–67.6					
P. patula, sawtimber	25	217 (172–563)	14.8	62.6	32.6
P. patula, pulp	15	206 (166–439)	14.8	59.2	31.7
African broadleafed forests (OECD, 1991)[a]72.8–117.0					
E. grandis, sawtimber	25	695 (439–695)	31.6	269.9	140.3
E. grandis, pulp	10	122 (114–465)	21.3	47.4	26.1

[a]Aboveground biomass only.
Note: The Mean Average Increment (MAI) is determined at age 20 for sawtimber regimes and at rotation length for pulpwood. The MAI values used are the area-weighted means for South Africa (FOA, 1994). The final yields were from tables in Loveday and Kassier (1993); and the range is given in brackets.
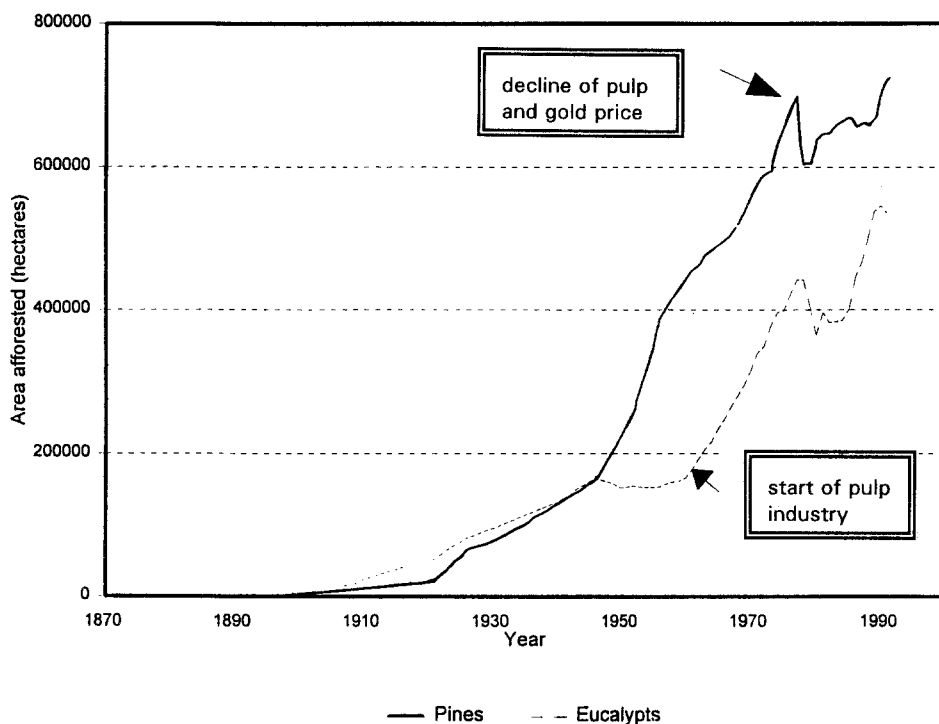
Figure 1. Cumulative afforested area in South Africa.
Sudden changes in the rates of afforestation can usually be ascribed to economic factors.

the C content of the standing crop for each year in the rotation and dividing by the rotation length.

$$C_m = n^{-1} \sum_{i=1}^{n} C_i,$$

where

C_m = mean C stored (Mg C ha^{-1}),

C_i = C density of the standing crop for year i (the values are obtained from equations 6 and 7), and

n = rotation length (years).

Table II also presents the C densities for *E. grandis* and *P. patula* calculated using the MCS method. Multiplying the mean C density by the mean rate of afforestation for the respective species and management regimes is an improved static method estimate of C stored, because it allows for the fact that the plantations are harvested rotationally.

$$C_s = \sum_{j=1}^{m} C_{m,j} A_m \,,$$

where

C_s =   total C stored (Mg),

$C_{m,j}$ =   mean C density for plantation type j (Mg C ha^{-1}), and

A_m =   mean rate of afforestation over a reference period.

2.1.3. The dynamic method

If the rate of afforestation varies greatly from year to year, the carbon density increment in a given reference year due to growth in that year must be tracked by each age-cohort of trees of each plantation type. This is known as a *dynamic* method.

$$C_s = \left(\sum_{i=1,j=1}^{m,n} C_{i,j} A_{(r-i,j)} \right) - C_g A_r$$

where

$C_{s,r}$ =   C stored in reference year r (Mg C),

$C_{i,j}$ =   C density of plantations of age i and type j (Mg C ha^{-1}), and

$A_{r-i,j}$ =   Area of type j planted in year $r - i$ (ha).

The growth rate of a given cohort for a given year can be calculated using an empirical growth function that starts at close to zero on the date of planting and reaches a given final biomass at a specified harvest date. Examples of such functions, determined from forestry trial data in South Africa, are shown below.

Harrison *et al.* (1994) give the following result for *P. patula* in Nelshoogte, South Africa:

$$V_{stem} = V_{final}\left(1 - \exp\left(-0.1411\left(1 - 0.6782\exp(-0.0013TP)\right)i\right)\right)^{3.0935}$$

with $n = 218$, $R^2 = 0.99$, and $S_{y,x} = 44.72$ m^3.

Kotze (1991) gives the following result for *E. grandis* in Langepan, South Africa:

$$V_{stem} = V_{final}\left(1 - \exp\left(-\left(0.063471 + 0.0000089299TP\right)i\right)\right)^{1.85873}$$

with $n = 86$, $R^2 = 0.94$, and $S_{y,x} = 52.65$ m^3.

For these equations,

V_{stem} =   Utilizable timber volume (m^3 ha^{-1}), and

V_{final} =   Final stem volume (m^3 ha^{-1}) under optimal conditions (657.94 for *P. patula* and 274.79 + 41.7375 × S for *E. grandis*) in South Africa, where S is the site index defined as the height reached after 10 years growth in pulpwood (20 m) or 20 years in saw wood (30 m).

j =   Stand age (years).

TP =   Surviving stems per hectare (for *P. patula* sawtimber is 1200 at planting, thinned to 650 at year 9, 400 at year 14, and 250 at year 19; for *E.*

> *grandis* sawtimber is 1,200 at planting, thinned to 750 at year 4, 500 at
> year 7, and 300 at year 10. Pulpwood has no thinnings and commences
> at 1,200).

Although these functions are in volume units, they can be expressed in C density units
by substituting for volume in Equation 1 (Figure 2).

2.2. CARBON STORAGE IN TIMBER PRODUCTS

Carbon storage in timber products is estimated by summing the C content of final forestry
products have an expected life of more than 20 years. In South Africa most construction
timber falls into this category, as well as timber destined to be permanently buried
underground as mine supports. The C stored in timber products can be calculated as:

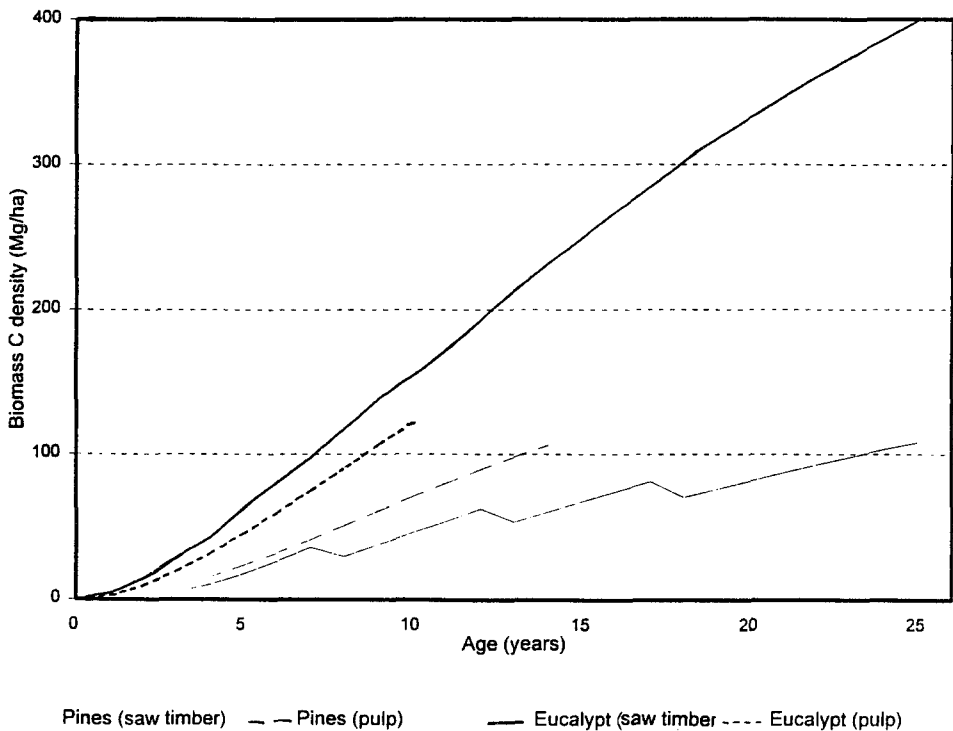$$C_p = \sum_{k=1} V_k \rho_k \in_k F_{carbon} ,$$

Figure 2. The biomass C density in the four main plantation types in South Africa.
The dips in C density in the sawtimber plantations are due to thinning operations.

where

C_p = C stored in timber products (Mg yr⁻¹),
V_k = annual volume of roundwood timber used for product k (m³ yr⁻¹),
ρ_k = density of air-dried timber product k (Mg m⁻³), and
$\hat{a}_k$ = milling efficiency (fraction of roundwood that ends up in product k).

Estimates of the amount of C stored in sawtimber, board and panel products, and mining timber are given in Table III Volumes are obtained from LHA Management Consultants (LHA, 1993). If timber output is quoted on a volume basis, it must be converted to an oven-dry mass basis. The mean density at 10% moisture content (air dry) for *P. patula* is 0.45 Mg m⁻³ (range is 0.35 – 0.61); for *E. grandis* it is 0.57 Mg m⁻³ (range is 0.5 – 0.8). If the product data are quoted as roundwood (that is, unsawn logs), they must be reduced according to the milling efficiency (the ratio of the mass of sawn timber to input roundwood is 46 to 55% for pine and 26 to 30% for eucalyptus). The milling efficiency for mining timber is estimated at 80%. In general, wood-based products have a C content of 50% by mass. It is assumed that sawmill residue is generally burnt, and therefore C is not stored. However, this is not strictly true, as increasingly large amounts of waste from sawmills are utilized in the board and panel manufacturing sector.

3. Results and discussion

The time series of afforestation in South Africa is illustrated in Figure 1. Wattle (principally *Acacia mearnsii*) was formerly extensively planted but now comprises less than 10% of the afforested area and 6% of new plantings. The impact of economic conditions on the rate of afforestation is clear. The increase in planted area is likely to continue, but ultimately will be limited by environmental and water-use considerations.

Table IV summarizes the forestry C storage calculations for South Africa using different methods. The simplest static approach, which uses the peak biomass to calculate the C

TABLE III

Carbon storage in long-lived (20-plus years) timber products

Product	Volume of roundwood used (× 10⁶ m³)	Oven-dry density (Mg m³)	Moisture content of roundwood (% of air dry mass)	Milling efficiency (%)	C stored (Tg C y⁻¹)
P. patula, sawn timber	3.80	0.45	115	50	0.39
E. grandis, sawn timber	0.05	0.57	66	28	0.05
Boards and panels	0.13	—	—	100	0.13
Mine supports	2.60	0.57	80		0.58
Total	1.15				

TABLE IV

Carbon storage in 1990 in *P. patula* and *E. grandis* plantations (Tg C y^{-1}) growing
under sawtimber and pulpwood regimes, calculated using different methods

Plantation type	Static methods		Dynamic method
	Peak C density	Mean C storage Tg C	
P. patula, sawtimber	0.14	0.11	0.08
P. patula, pulpwood	0.55	0.44	0.14
E. grandis, sawtimber	1.16	0.59	0.85
E. grandis, pulpwood	0.87	0.44	1.47
Total	2.72	1.58	2.54

Note: For static methods, the area of new afforestation was 11 420 ha of pines and 22 700 ha of eucalyptus.
It was assumed that 19% of both was destined for sawwood and 81% for pulp.

density, overestimates C storage in rotational plantations by a factor of nearly two relative
to the static method using MCS (Winjum *et al.*, 1992).

The dynamic method is most appropriate for situations (such as in South Africa) where
the rate of afforestation varies over time. The static MCS method underestimates C storage
in South Africa by 37%, because the current rate of afforestation is less than it was during
the last decade. The similarity of the estimates by the static peak C density method and
the dynamic method is purely coincidental.

The calculations outlined above do not allow for changes in C density other than changes
due to an increase in biomass. It is more than likely that the C stored in soil organic matter
also changes. Soil C is often assumed to be higher under forests than under grasslands,
but this is not necessarily true; grasses translocate a much larger fraction of their C
belowground than forests do. On the other hand, the amount of C stored on the surface of
the soil as litter can be large in forests, especially under pine plantations. In the Eastern
Transvaal of South Africa, the litter accumulation can reach 150 Mg DM ha^{-1}, or about
half of the stem biomass. However, until there are more reliable data on the magnitude of
soil and litter C pools in tropical plantations, it is conservative to ignore them in the
calculations.

The C stored in various long-lived timber products is given in Table III. The amount
of C stored in these products is comparable to that stored in biomass. The default
assumption in the *IPCC Guidelines for National Greenhouse Gas Inventories* (UNEP *et
al.*, 1995) is that timber products are merely replacing existing timber products that are
decaying or burned, and therefore should not be considered a net storage. However, in
rapidly growing and urbanizing countries such as South Africa, the national pool of timber
is increasing. Most sawn timber and board products are used for construction in South
Africa, so it is reasonable to expect them to have a long life. The mining support timber

is left underground when the mines are abandoned, and can therefore be considered to be securely stored C.

It is unclear how to consider paper pulp for emission inventory purposes, because it is a partially stored product. Although most paper products have a relatively short life (less than 5 years), a large fraction of these disposable products is recycled in some countries (31% in South Africa in 1992 (Gerischer, 1993). Much of the paper that is not recycled ends up in landfills, where it may have a long life. However, only a fraction of the pulp produced in South Africa is used locally.

The forest industry stores a total of 3.69 Tg C yr^{-1}, which is equivalent to 13.5 Tg CO_2, or about 3.8% of the annual CO_2 emissions for South Africa. Although not insignificant, this amount is too small to make a serious impact on the national emission budget. The potential for increasing C storage via this avenue in South Africa is very small because of the adverse environmental impacts of further plantations and the limited area that is bioclimatically suitable for afforestation (Winjum et al., 1993). The potential in wetter African countries is greater, but only if the plantations are established in areas with a low existing C density. The clearing of endemic woodlands for replacement with pines and eucalypts will not necessarily meet this criterion.

4. Conclusions

The methods for calculating C sequestration through afforestation are relatively simple to apply, but obtaining reliable data on biomass C densities and rates of afforestation may be difficult in some countries. Data on nontimber biomass fractions, especially belowground, are generally sparse. The C density and growth data used in this analysis for South Africa are applicable for all of southern Africa.

The use of peak biomass for the calculation of C density is not appropriate for rotation forestry. A mean C storage approach, which averages the C density over the rotation, is recommended (Winjum et al., 1992; Winjum et al., 1993). The dynamic method of C storage calculation, which accounts for the age of various plantations, is recommended where the rate of afforestation varies between years.

Storage of C in long-lived forest products is as important as new afforestation as a C sink in countries where the national pool of timber products is growing, and should be considered as part of the emission inventory. Additional research is needed on changes in C storage in the soil and litter layers and the fate of paper products.

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