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Carbon sequestration potential of post-mining reforestation activities on the KwaZulu-Natal coast, South Africa

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Restoration of former mined land can potentially capture large quantities of atmospheric carbon dioxide if appropriate reclamation techniques and post-reclamation management strategies are applied. The objectives of the current study were: to quantify carbon stocks in five pools; to develop empirical relationships between stand age and carbon stocks; to compare the carbon sequestration potential of rehabilitated land under different land uses and to recommend management practices to maximize carbon sequestration. The carbon stocks in five pools (aboveground, belowground, litter, debris and soil), of the rehabilitated vegetation were quantified. For this purpose, 18 sites were selected including both commercial plantations and rehabilitated indigenous forests. The relationship between total, aboveground and belowground carbon stocks in the *Casuarina equisetifolia* plantation and stand age was sigmoidal, whereas the relationship was linear for the rehabilitating indigenous forest. The rehabilitated indigenous forest exceeded the mean net carbon storage of *C. equisetifolia* plantations after ∼19 years. Maximum carbon accumulation in the rehabilitated indigenous forest compared well with values reported for reclaimed ecosystems in the USA and Europe. Carbon sequestration potential of the mined land could be optimized and natural capital restored through reforestation of harvested *C. equisetifolia* plantations with indigenous forest.

Introduction

The recognition that terrestrial ecosystems have the potential either to increase or decrease the concentration of greenhouse gases in the atmosphere has lead to an increasing interest in estimating the carbon budget of terrestrial ecosystems.[1] While significant progress has been made in quantifying the carbon sequestration potential of forests, grasslands and agricultural land, the long-term changes in carbon pools in reclaimed mined soils are still poorly documented and understood.[2–6]

Mining methods that destroy the existing vegetation result in large-scale carbon losses. Restoration of former mined land can therefore potentially capture large quantities of atmospheric carbon dioxide if appropriate reclamation techniques and post-reclamation management strategies are applied.[7,8] Land-use has a large effect on the carbon content of ecosystems, and to design restoration practices that maximize carbon sequestration, it is necessary to investigate and compare the dynamics of carbon accumulation on reclaimed mined sites with alternative land-uses.

The coastal dunes along the KwaZulu-Natal coast of South Africa have been mined for the heavy minerals, ilmenite, rutile, zircon and monazite since 1977.[9] When mining operations commenced, the mining lease area comprised 60% plantations (*Eucalyptus grandis* and *Pinus elliottii*), 20% grassland and 20% coastal dune forest.[9–11] During the mining process, the existing vegetation is cleared and the biomass burnt. After extracting the heavy minerals from the soil, the tailings are returned and landscaped to resemble pre-mining topography.[9] In terms of the conditions set by the lease contract, Richards Bay Minerals established a programme to rehabilitate one-third of the area to coastal forest and the rest to commercial *Casuarina equisetifolia* (Australian beefwood) plantations.[12] To assist the regeneration of natural coastal forest, topsoil (to a depth of 100–150 mm) is collected ahead of the mining face and spread across the newly contoured dunes together with a seed mixture of short-lived annual species to provide an early cover.[13] The annual species are soon replaced by indigenous grass species, such as *Eragrostis curvula* and *Cymbopogon nardus*.[13,14] Over a 2- to 3-year period, this grassland cover is replaced by an indigenous thicket dominated by *Acacia kosiensis* (≡*Acacia karroo*),[12] which progressively develops into an *A. kosiensis* forest. In turn, the *A. kosiensis* forest is gradually colonized by indigenous coastal forest species, indicating the succession of the rehabilitated forest towards indigenous dune forest.[12,15–19]

The objectives of this study were: (1) to quantify the carbon stocks in five different pools along a chronosequence of rehabilitated mined land; (2) to develop empirical relationships between the age of the rehabilitated stand and carbon stocks in the different pools; (3) to compare the carbon sequestration potential of rehabilitated land under commercial forestry to rehabilitated land undergoing a natural successional pathway towards indigenous coastal forest and (4) to recommend future forest management practices that could maximize carbon sequestration.

Materials and methods

Study area

The Tisand and Zulti-North mining lease areas of Richards Bay Minerals are located on the northeastern coast of KwaZulu-Natal and extend from Richards Bay in the south to Mapelane in the north between latitudes 28° 30.30′ and 28° 45.45′ South and longitudes 32° 08.30′ and 32° 24.00′ East. To the east, the area is fringed by the Indian Ocean and in the west the boundary follows more or less the main road from Richards Bay to Mapelane. To the north of the lease areas lies the Isimangaliso Wetland Park, a World Heritage Site, in a region known as Maputaland. The Maputaland Centre of Endemism is a remarkable area of biodiversity in Africa and has a high number of endemic species spread over almost the entire taxonomic spectrum.[20]

The region is classified into Köppen's humid, subtropical climate zone (Cfa climate zone) and is characterized by a warm to hot, subtropical climate with hot summers and cool to warm winters.[21] The mean annual temperature recorded at Richards Bay is 21.7°C with the mean daily temperature for the hottest month (January), 25.2°C, and that for the coldest month (July), 17.6°C (electronic data supplied by the South African Weather Services). The mean annual rainfall at Richards Bay is 1228 mm of which 76% falls in the summer months from September to April.

The natural vegetation in the area is dominated by dune or coastal forest.[22] Three strata can mostly be distinguished *viz*. canopy trees up to 16 m, an understory layer up to 8 m and a herbaceous layer up to 1.5 m.[23,24] The vegetation in the region has a long history of human-induced disturbances ranging from slash-and-burn agriculture to sand dune mining.[15,25] Aerial photographs indicate that the coastal forests in the area were highly degraded in 1937 as a result of human-induced disturbances, such as settlements, forest clearing for cropland, firewood collecting, cattle grazing and fire.[26,27] Such disturbed sites are often initially colonized by almost pure stands of *A. kosiensis*. A secondary dune forest gradually develops as an advanced stage following the *A. kosiensis* woodland stage in the succession to dune forest proper.[26,28–32] Aerial photographs of 1974 show that after the local inhabitants had been relocated in the early 1950s, many of the previously disturbed areas had since developed into secondary dune forest.[27,30] This natural *A. kosiensis* successional pathway is the method used to facilitate dune forest recovery on reclaimed mined land.

Soils in the region consist mainly of fine and medium-grained sand and have a low silt and clay content. On un-mined vegetated dunes, the soil profile consists of a thick layer of litter on an orthic A horizon underlain by regic sand, which is described as the Namib Soil Form.[11,25,33,34] At the mined sites that have been rehabilitated with *C. equisetifolia*, there is a distinct interface between the litter layer and the yellow mined subsoil.[11] On the mined sites that are being returned to indigenous forest, the development of the dark topsoil layer beneath the litter layer depends on the age of the rehabilitated stand.

Table 1 Vegetation type, date rehabilitation was commenced, age of stand and size of plots of post-mining sites surveyed to quantify carbon pools at Richards Bay Minerals

Vegetation type	Date rehabilitation commenced	Age (years)	Code	Plot size ($m \times m$)[a]	
				Vegetation	Debris
Casuarina equisetifolia plantation	1986	18	Cas 18	10 × 10	10 × 10
	1989	15	Cas 15	10 × 10	10 × 10
	1992	12	Cas 12	10 × 10	10 × 10
	1995	9	Cas 9	10 × 10	10 × 10
	1998	6	Cas 6	10 × 10	10 × 10
	2001	3	Cas 3	10 × 10	10 × 10
	2003	1	Cas 1	10 × 10	10 × 10
	2004	0.5	Cas 0.5	10 × 10	10 × 10
Rehabilitating indigenous forest	1977	27	Aca 27	10 × 10	10 × 10
	1980	24	Aca 24	10 × 10	10 × 10
	1983	21	Aca 21	10 × 10	10 × 10
	1986	18	Aca 18	10 × 10	5 × 5
	1989	15	Aca 15	10 × 10	5 × 5
	1992	12	Aca 12	10 × 10	5 × 5
	1995	9	Aca 9	5 × 10	5 × 10
	1998	6	Aca 6	5 × 5	5 × 5
	2001	3	Aca 3	5 × 5	5 × 5
Eucalyptus grandis plantation	1992	12	Euc	15 × 15	15 × 15

[a]Four replicates of these dimensions at each site.

Sampling procedures

The Intergovernmental Panel on Climate Change (IPCC) has created guidelines to assess carbon stocks and their changes. The current study was based on Volume 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories,[35] which is applicable to the Agriculture, Forestry and Other Land Use (AFOLU) sector. These guidelines integrated and elaborated on the Revised 1966 IPCC Guidelines for National Greenhouse Inventories,[36] Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories[37] and Good Practice Guidance for Land Use, Land-Use Change and Forestry.[38]

The five carbon pools assessed in this study were defined as follows[35]:

(1) The aboveground carbon pool consisted of the carbon contained in all the aboveground strata of the vegetation, i.e. the tree, shrub, herb and creeper strata and included all stems, twigs, bark, leaves, flowers and fruits. Standing dead trees were included in this carbon pool.
(2) The belowground carbon pool constituted the carbon in the belowground biomass of the vegetation, i.e. roots, tubers, rhizomes and bulbs. Fine roots of <2 mm diameter are often excluded because these can often not be distinguished from soil organic matter or litter.
(3) The litter carbon pool included the carbon in all dead organic matter lying on the soil surface, e.g. dead leaves, twigs, fruits, flowers, bark, insect detritus, animal scats, charcoal and woody debris with a cross-sectional diameter of <25 mm.[39]
(4) The debris carbon pool constituted the carbon contained in the coarse woody debris (CWD), i.e. logs and branches lying on the ground, with a cross-sectional diameter of ≥25 mm.[39]
(5) The soil carbon pool comprised all the soil organic material, charcoal and fine roots with a diameter of <2 mm within the soil profile. The default depth is 300 mm.[38]

Eighteen sites were selected, in a stratified random manner, in the post-mining rehabilitated area (Table 1): eight in the *C. equisetifolia* plantations (aged 0.5, 1, 3, 6, 9, 12 and 18 years), nine in the rehabilitated indigenous forest (3, 6, 12, 15, 18, 21, 24 and 27 years) and one in the *E. grandis* plantation (age 12 years). The ages of the stands were obtained from a map, provided by Richards Bay Minerals, indicating the type of rehabilitation and the year in which the rehabilitation was commenced.

Sampling of the aboveground, litter and CWD carbon pools was conducted in 2004. At each sampling site, at least four representative replicate plots were sampled. Plot size for the vegetative survey varied depending on the tree density and is given in Table 1. The following measurements and notes were made for each tree in a plot:

(1) Stem circumference (10 mm increments) of forestry species (*C. equisetifolia* and *E. grandis*) was measured at breast height (1.37 m above ground level). If a tree had >1 stem, the circumference of each stem was recorded.
(2) Stem circumference (10 mm increments) of indigenous species was measured at ground level.
(3) Tree height was estimated with a Suunto PM-5 (Suunto Oy Finland) or measuring rods (0.5 m increments for trees ≥5 m tall and 0.1 m increments for trees <5 m tall).
(4) A note was made if the tree or stem was dead.

Where *Chromolaena odorata* and/or *Lantana camara* formed dense undergrowth, individual plants could not be separated. In these cases a biomass estimate was obtained per surface area. This was accomplished by harvesting all the aboveground plant material in a 0.25-m^2 sub-plot. Four replicate sub-plots were harvested within each plot. To derive a plot level value, the sub-plot value was multiplied by the surface area occupied by these species.

Dracaena aletriformis plants were classified into three size classes: plants <0.5 m tall; plants 0.5–1.5 m tall and plants >1.5 m tall. In each sampling plot, the number of *D. aletriformis* plants per size class was counted. Several plants in each class were harvested to obtain a dry mass estimate for each size class.

Scramblers were defined as herbaceous plants that cover the undergrowth but do not reach the tree canopy. An estimate of the percentage cover of scramblers per plot was recorded and the mean height of the scramblers was noted. The cover and height values were used to calculate a mean volume of the scramblers in the plot. All plant material of scramblers was harvested in a cubic frame 0.5 m × 0.5 m × 0.5 m within a representative portion of the scrambler canopy. Four replicate samples of scramblers were harvested. The cubic frame data were multiplied by the volume of the scramblers to obtain a plot level value.

The stem circumference (0.5 cm increments) of thick woody vine stems was measured at breast height and the height (0.5 m increments) of the stem noted. Leaves and small twigs of vines were harvested in a cubic frame 0.5 m × 0.5 m × 0.5 m. An estimate of the percentage cover of the leaves and small twigs of the vine stratum was recorded and the mean height noted. Six replicate samples of the leaves and small twigs of vines were taken. To obtain a plot level value, the same procedure was followed as for the scramblers.

Four representative ground cover samples, each with a surface area of 0.25 m^2, were harvested per sampling site. Harvesting of all living herbaceous plant material for the ground cover estimate was done at 10 mm above ground level. Similarly, four litter samples, each with a surface area of 0.25 m^2, were collected per sampling site. Sand particles in both ground cover and litter samples were removed by sieving through a 2-mm mesh sieve in the field.

All harvested plant material (i.e. *C. odorata*, *L. camara*, *D. aletriformis*, ground cover, litter, scramblers and leaves and small twigs of vines) was dried at 70°C until constant mass. After drying, the remaining soil particles in the ground cover and litter samples were removed by sieving through a 1-mm mesh sieve.

The dimensions measured for each piece of CWD were the length (10-mm increments) and the diameter in the midsection (1-mm increments).

Soil samples were collected in 2005 at the same plots where the vegetation surveys had been conducted in 2004. The soil carbon values therefore represent stands that are ~1 year older than indicated in the tables. Unfortunately, the 18-year-old *C. equisetifolia* and *E. grandis* stands had been harvested when returning to the sites in 2005. No similar-aged stands were available for soil sampling.

Soil was sampled with a soil corer with an inner diameter of 55 mm to the default depth of 300 mm.[38,40] Four random samples were taken per plot, avoiding the area within a radius of 0.5 m from a large tree trunk because of the dense root mass. Surface debris and litter were removed prior to taking the sample with the soil corer. Both necro and live fine roots with a diameter of less than 2 mm were included in the sample (IPCC Guidelines[35]); however, larger roots and other non-soil organic material, such as litter and debris, were removed by sieving the samples through a 2-mm mesh sieve. The organic carbon content was determined by means of the Walkley-Black wet chemical oxidation method.[41,42] Carbon content and soil bulk density were determined at the soil laboratory, Department of Plant Production and Soil Science, University of Pretoria, Pretoria, South Africa.

Data analysis

Calculation of dry biomass for forestry species in managed plantations

All the values of stem circumference at breast height were converted into those of diameter at breast height (DBH). The volumetric equation for *C. equisetifolia*, developed for South African conditions,[43] was used to calculate the total underbark volume (V):

$$\log_{10} V = -4.4013 + 1.7137\ (\log_{10} D) + 1.1656\ (\log_{10} H) \tag{1}$$

where V is underbark volume (m^3), D the overbark DBH (cm) and H is tree height (m). The volume was converted into biomass using a wood density for *C. equisetifolia* of 810 kg m^{-3}.[38] The contribution of the bark was calculated by using the allometric equation of Rana *et al.*[44]:

$$ln \text{ bark dry mass (kg)} = -1.092 + 0.808\ ln(D) \tag{2}$$

where D is the overbark DBH (cm).

The sum of the underbark mass and bark dry mass was taken as the trunk dry biomass.

To calculate the contribution of the branches, foliage and roots to the total biomass, allometric biomass equations were used to derive trunk-to-branch, trunk-to-foliage and root-to-shoot ratios (Chen, 1988, cited in 45):

$$\text{Trunk dry mass (g)} = 56.948(D^2H)^{0.875} \tag{3}$$

$$\text{Branch dry mass (g)} = 3.009(D^2H)^{1.203} \tag{4}$$

$$\text{Foliage dry mass (g)} = 0.659(D^2H)^{1.026} \tag{5}$$

$$\text{Root dry mass(g)} = 6.614(D^2H)^{1.030} \tag{6}$$

where D is the overbark DBH (cm) and H is tree height (m). These trunk-to-branch, trunk-to-foliage and root-to-shoot ratios were subsequently applied to the trunk dry mass (obtained from equation (1) and (2)) to calculate the branch, foliage and root dry mass of the particular tree. Although cumbersome, this approach was followed to allow for size-dependent variation in these ratios. In this way, the volumetric equation developed for South African conditions[43] could be used to estimate the trunk dry mass on which all the other values depended.

The same approach was followed to calculate the biomass of *E. grandis*. A volumetric equation for *E. grandis*, grown on the coastal plain of KwaZulu-Natal, was applied to estimate the underbark volume (V) to a thin-end diameter of 75 mm.[46,47]

$$ln\ V = -9.7464 + 1.7154\,(ln\ D - 2) + 1.1070\,(ln\,H) \qquad (7)$$

where V is underbark volume (m^3), D is overbark DBH (cm) and H is tree height (m). The underbark trunk volume of *E. grandis* trees was converted into dry mass using a wood density of 640 kg m^{-3}, being the value quoted by the IPCC[38] for *E. citriodora*.

Biomass equations of Bradstock (1981, cited in 45) were used to determine the dry mass allocation pattern of *E. grandis* trees:

$$\log_{10} \text{sapwood dry mass (kg)} = 2.16\ (\log_{10} D) - 0.99 \qquad (8)$$

$$\log_{10} \text{heartwood dry mass (kg)} = 3.26\ (\log_{10} D) - 2.14 \qquad (9)$$

$$\log_{10} \text{bark dry mass (kg)} = 2.81\ (\log_{10} D)\ - 2.26 \qquad (10)$$

$$\log_{10} \text{branch dry mass (kg)} = 2.53\ (\log_{10} D)\ - 0.90 \qquad (11)$$

$$\log_{10} \text{foliage dry mass (kg)} = 2.67\ (\log_{10} D)\ - 0.23 \qquad (12)$$

where D equals DBH (cm). The sum of the sapwood and heartwood dry mass values was regarded as equal to the underbark trunk dry mass from equation (7). Ratios calculated from equations (10) to (12) (underbark-to-bark, underbark-to-branch, underbark-to-foliage) were then used to estimate the contributions of bark, branches and foliage to the total aboveground dry mass.

Standing dead trees, for the most part, consisted only of the stem. The biomass of these dead tree trunks was calculated by applying the species-specific volumetric equations and multiplying it by the density value.

Belowground biomass of *C. equisetifolia* was calculated using equation (6). A root-to-shoot ratio of 0.20 was used to calculate the belowground dry mass of *E. grandis*, based on the mean ratio quoted for eucalypt plantations with an aboveground dry mass exceeding 150 t ha^{-1}.[38]

Calculation of dry biomass for indigenous species

The following allometric equations developed by Shackleton[48] for South African savanna trees and shrubs were used to calculate the dry mass of indigenous species:

$$\log_{10} M_{\text{tree}} = 2.397\,(\log_{10} C) - 2.441 \qquad (13)$$

$$\log_{10} M_{\text{shrub}} = 2.320\,(\log_{10} C) - 2.30 \qquad (14)$$

where M_{tree} and M_{shrub} equal tree and shrub dry masses (kg), respectively, and C is stem circumference at ground level (cm).

The dry mass was calculated for each individual in a plot and the sum obtained for the total plot.

The trunk volume of standing dead indigenous trees was calculated as the volume of a cylinder. This volume was converted into dry mass using the wood density of *A. karroo* (800 kg m^{-3}).[49]

Following the guidelines of the IPCC, the belowground dry mass was derived by using root-to-shoot ratios. A root-to-shoot ratio of 0.42 was applied to all woody individuals in the rehabilitated indigenous forest as well as *D. aletriformis* plants and woody vines. This value is quoted by the IPCC as the mean root-to-shoot ratio in secondary tropical/subtropical forest.[38] Belowground dry mass of the ground cover, which consisted predominantly of grasses and some ferns, and of the herbaceous scramblers was calculated by using the root-to-shoot ratio of 1.58 indicated as the mean for temperate/tropical/subtropical grassland.[38]

To obtain the dry mass of the CWD, the volume of each piece of CWD was calculated as a cylinder. This volume value was converted into dry mass using a wood density value of 810, 640 and 800 kg m^{-3} for *C. equisetifolia*, *E. grandis* and *A. kosiensis*, respectively. Because this value assumes no decay of the dead material, it overestimates the mass of the CWD. The magnitude of the overestimate will depend on the age of the debris.

Conversion of dry mass to carbon

Studies of the carbon content of tree mass have suggested that it does not vary greatly between different species or in different parts of a plant. Extensive studies in Australia in a variety of tree species showed that aboveground dry mass generally contains 50% carbon, whereas roots contain 49%.[50] An overall value of 50% carbon was used in this study for the aboveground, belowground, litter and debris carbon pools.

Soil carbon

Soil carbon mass (C_{soil}) (t to a depth of 0.3 m) per hectare was calculated with the following equation:

$$C_{\text{soil}} = 3000\ (m^3) \times \text{bulk density}\ (t\ m^{-3}) \times \%\ \text{soil carbon}/100 \qquad (15)$$

Mean net carbon storage method

This method was developed for dynamic systems such as plantations where harvesting operations take place. The method entails averaging the quantity of carbon stored over the long-term with the following equation[51]:

$$\text{Mean net } C \text{ storage} = \sum_{t=0}^{t=n} (C \text{ stored in forest} - C \text{ stored in baseline}/n \text{ (years)})$$

where t is time, n is project time frame and measurements are expressed in t carbon per hectare. Because a time series of carbon accumulation was determined for *C. equisetifolia* plantations, the mean storage method could be applied. With this method, the mean carbon storage will have a fixed value if the calculation is performed for one, two or more rotations, as long as the denominator chosen for the equation coincides with the last year of a rotation.[51]

Statistical analysis

Curve-fitting, either by linear regression or the Boltzmann sigmoid function, was conducted in GraphPad Prism 4.03 for Windows (GraphPad software, San Diego, CA, USA). One-way analysis of variance (Tukey's *post hoc* test) was performed to determine significant differences between values using the STATISTICA computer package (StaSoft, Inc., Version 8, Tulsa, OK, USA).

Results

Carbon stock estimates in C. equisetifolia plantations

The total carbon stock in the *C. equisetifolia* plantations revealed an asymptotic relationship with the age of the plantation (Figure 1a; Botzmann sigmoid function, $r^2 = 0.99$; $y = 1.555 + (217.1 - 1.555)/(1 + \exp((7.361 - x)/1.411)))$, with carbon accumulation levelling off more or less at a plantation age of 12 years.

The aboveground carbon pool constituted the bulk of the total carbon stock (Table 2, Figure 2) and from a stand age of 9 years ranged from 72 to 74% of total carbon. The accumulation of aboveground carbon followed the same trend described for the total carbon stock (Figure 1a; Boltzmann sigmoid function $r^2 = 0.99$; $y = 0.909 + (160.5 - 0.909)/(1 + \exp((7.527 - x)/1.364))$). Maximum aboveground carbon (170.41 t ha^{-1}) was achieved at a stand age of 12 years. A small proportion of the aboveground carbon stock in plantations of 12 years and older was found in standing dead trees, or in dead stems if the tree was multi-stemmed. Ground cover (herbs and grass) in all stands, with the exception of the 15-year-old plantation, was absent or negligible (Table 2).

The size of the belowground carbon pool was derived by applying root-to-shoot ratios and is thus a function of the size of the aboveground carbon pool. Although the root-to-shoot ratio gradually declined with an increase in the size of the tree, the increase in the belowground carbon pool with stand age followed the same basic trend described for the aboveground carbon pool (Figure 1a; Boltzmann sigmoid function $r^2 = 0.99$; $y = 0.131 + (37.00 + 0.131)/(1 + \exp((7.606 - x)/1.372))$).

The litter carbon pool increased up to a plantation age of 9 years, whereafter it declined (Table 2). Log-transformed litter values (power function) showed a significant linear increase with stand age ($\log_{10} y = 0.8262 \log_{10} x + 0.1243$; $r^2 = 0.81$; $P = 0.006$). On a percentage basis, the litter carbon declined from

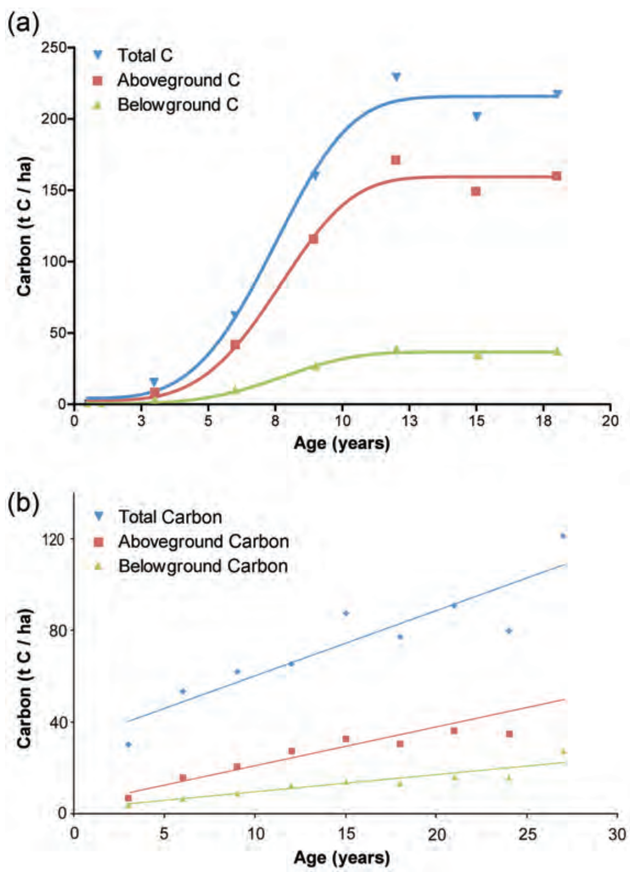

Figure 1 Total, aboveground and belowground carbon stocks versus stand age for (a) *Casuarina equisetifolia* plantations and (b) rehabilitating indigenous forest in post-mining rehabilitation sites at Richards Bay Minerals.

29% of the total carbon stock in a 3-year-old plantation to 3% in a 15-year-old plantation (Figure 2). No debris carbon pool was found in the *C. equisetifolia* plots sampled.

Soil carbon showed a significant positive linear relationship with stand age to a maximum of 11.55 t ha^{-1} at a stand age of 15 years ($y = 0.687x$; $P = 0.001$; $r^2 = 0.78$). The sharp decline in soil carbon in the 18-year-old *C. equisetifolia* stand was as a result of the samples being taken after the stand had been harvested and this value was therefore not used in the regression.

E. grandis plantation

Only one *E. grandis* plantation, aged 12 years, had been established in the post-mining area. The total carbon stock per hectare in this plantation (208.14 t ha^{-1}) compared well with an equally old *C. equisetifolia* plantation (229.39 t ha^{-1}) (Table 2, Figure 2). Although *E. grandis* trees were significantly taller ($P < 0.001$) than *C. equisetifolia* trees, this advantage was offset by the lower value for its wood density (0.64 t m^{-3} for *E. grandis* as opposed to 0.81 t m^{-3} for *C. equisetifolia*) and stand density (1444 trees ha^{-1} for *E. grandis* opposed to 1800 trees ha^{-1} for *C. equisetifolia*). As a result none of the total, aboveground and belowground carbon pools of the *E. grandis* plantation was significantly different ($P = 0.320$; $P = 0.459$ and $P = 0.054$, respectively) from those of the *C. equisetifolia* plantation. However, the carbon contained in the litter pool of the *E. grandis* plantation (13.34 t ha^{-1}) was significantly higher ($P = 0.013$) than in an equal-aged *C. equisetifolia* plantation (10.78 t ha^{-1}).

Indigenous forest rehabilitation

Up to a stand age of 27 years, a positive linear regression best described the relationship between total carbon stock and stand age for the rehabilitating indigenous forest (Table 3, Figure 1b; $r^2 = 0.82$; $P = 0.001$; $y = 2.842x + 31.565$). These regressions were not forced through zero because of the input of carbon-rich topsoil in the rehabilitation process. A maximum total carbon stock of 121.23 t ha^{-1} was achieved in the 27-year-old stand (Table 3).

As was the case for the commercial plantations, the aboveground carbon pool constituted the bulk of the total carbon stock in the stands that were being rehabilitated to indigenous forest (Figure 3). Carbon stock in the aboveground carbon pool was positively linearly related to the age of the forest (Figure 1b; $r^2 = 0.86$; $P < 0.001$; $y = 1.693x + 3.968$). The aboveground carbon pool was comprised of the carbon in the living trees, ground cover, standing dead trees, scramblers, vines and *D. aletriformis* (Table 3). The living trees contributed most to the aboveground carbon storage and in most cases, the living trees were almost pure stands of *A. kosiensis*. Carbon storage in the ground cover was the highest in the open vegetation of the 3-year-old shrubland. It showed a sharp decline in the dense 6-year-old forest, whereafter it gradually increased again with forest age (Table 3). Carbon contained in the standing dead trees increased with forest age to an age of 15 years, whereafter it declined again. Vines and scramblers were recorded only from a stand age of ~9 years. The carbon contained in the vines, scramblers and *D. aletriformis* reached a maximum in the oldest (27 years) rehabilitating forest.

Table 2 Mean tree height, stem circumference, density and carbon stock (t ha^{-1}) in the aboveground, belowground, litter, debris and soil pools in areas rehabilitated with commercial plantations at Richards Bay Minerals

Stand age	*Casuarina equisetifolia*								*Eucalyptus grandis*
	0.5 year	1 year	3 years	6 years	9 years	12 years	15 years	18 years	12 years
Tree characteristics									
Tree height (m)	0.8 ± 0.0	1.2 ± 0.1	5.7 ± 0.2	12.3 ± 0.4	16.0 ± 0.4	18.1 ± 0.4	18.3 ± 0.7	20.0 ± 0.6	26.2 ± 0.4
Tree stem circumference (cm)	2.6 ± 0.1	3.8 ± 0.3	20.2 ± 0.4	30.7 ± 2.8	42.0 ± 3.1	48.5 ± 1.4	44.5 ± 0.8	44.7 ± 0.6	59.7 ± 1.2
Tree density									
Density of living trees (ha^{-1})	1800 ± 0	1656	1800 ± 0	1602 ± 54	1800 ± 0	1728 ± 51	1746 ± 18	1710 ± 45	1345 ± 44
Density of dead trees (ha^{-1})	0 ± 0	0 ± 0	0 ± 0	0 ± 0	0 ± 0	54 ± 54	18 ± 18	18 ± 18	0 ± 0
Aboveground carbon pool (t ha^{-1})									
Living trees (t ha^{-1})	0.01 ± 0.00	0.88 ± 0.02	9.02 ± 0.28	42.03 ± 7.45	115.24 ± 16.63	170.28 ± 11.43	147.28 ± 6.12	159.35 ± 4.75	155.90 ± 4.11
Standing dead trees (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.10 ± 0.09	0.08 ± 0.08	0.18 ± 0.18	0.01 ± 0.01
Ground cover (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.48 ± 0.06	0.00 ± 0.00	0.00 ± 0.00
Dead branches (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.03 ± 0.03	0.74 ± 0.46	0.00 ± 0.00	0.00 ± 0.00
Total aboveground carbon (t ha^{-1})	0.01 ± 0.00	0.88 ± 0.02	9.02 ± 0.28	42.03 ± 7.45	115.24 ± 16.63	170.41 ± 11.37	148.58 ± 6.48	159.53 ± 4.62	155.91 ± 4.11
Belowground carbon pool (t ha^{-1})									
Living trees (t ha^{-1})	0.00 ± 0.00	0.14 ± 0.00	1.82 ± 0.04	9.32 ± 1.71	26.15 ± 3.84	38.83 ± 2.62	33.54 ± 1.41	35.90 ± 1.09	31.18 ± 0.82
Ground cover (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.76 ± 0.10	0.00 ± 0.00	0.00 ± 0.00
Standing dead trees (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.02 ± 0.02	0.02 ± 0.02	0.04 ± 0.04	0.00 ± 0.00
Total belowground carbon (t ha^{-1})	0.00 ± 0.00	0.14 ± 0.00	1.82 ± 0.04	9.32 ± 1.71	26.15 ± 3.84	38.85 ± 2.61	34.32 ± 1.41	36.97 ± 1.06	31.18 ± 0.82
Litter carbon (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	3.64 ± 1.46	8.13 ± 2.39	14.66 ± 1.73	10.78 ± 0.57	6.17 ± 1.40	13.68 ± 1.42	13.34 ± 0.46
Debris carbon (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Soil carbon (t ha^{-1})	1.00 ± 0.28	0.74 ± 0.24	0.50 ± 0.00	3.19 ± 0.81	3.75 ± 0.53	9.35 ± 1.15	11.55 ± 1.41	6.97 ± 1.73	7.70 ± 0.71
Total carbon in five pools (t ha^{-1})	1.01 ± 0.28	1.76 ± 0.14	14.98 ± 1.54	62.67 ± 10.93	159.80 ± 21.40	229.8 ± 12.67	200.62 ± 7.14	217.15 ± 5.93	208.14 ± 6.01

Data for aboveground, belowground, litter and debris pools are based on a survey conducted in 2004, and the soil carbon pool was determined in 2005.
All values are for means ± SE.

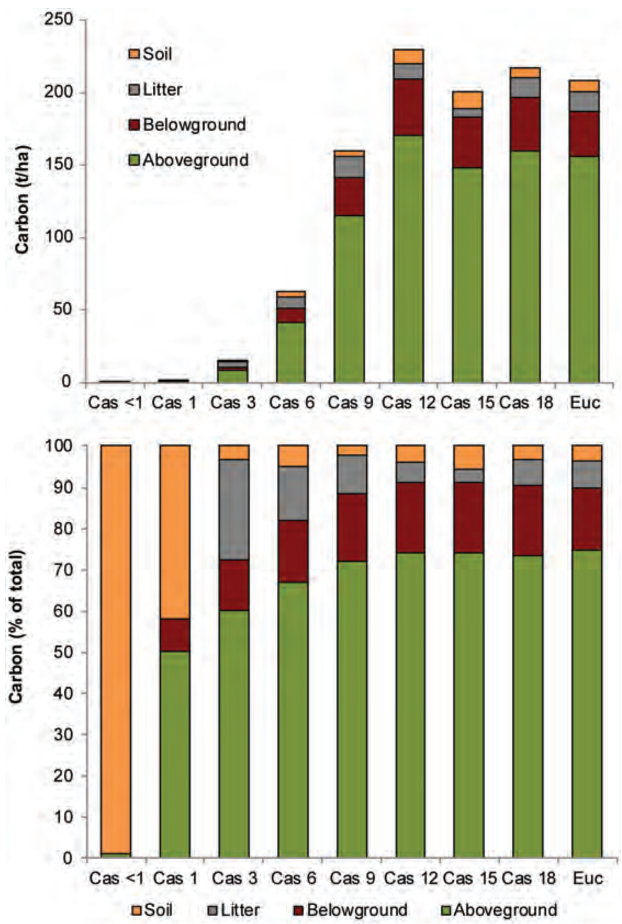

Figure 2 (a) Carbon stocks in the aboveground, belowground, litter and soil carbon pools (in t ha^{-1}) and (b) percentage contribution of the aboveground, belowground, litter and soil carbon pools to the total carbon stock in post-mining rehabilitated *Casuarina equisetifolia* (Cas) plantations of different ages as well as *Eucalyptus grandis* plantation at Richards Bay Minerals.

As was the case for the aboveground carbon pool, the carbon stock in the belowground carbon pool showed a significant, positive linear relationship with forest age (Figure 1b; $r^2 = 0.86$; $P < 0.001$; $y = 0.754x + 1.951$), whereas the power function expressed the relationship in the case of the CWD pool ($\log_{10} y = 0.9377 \log_{10} x - 0.5817$; $r^2 = 0.61$; $P = 0.013$). In contrast, neither the litter nor the soil carbon pools showed a significant linear, power, exponential or sigmoid relationship with stand age.

Comparison of C. equisetifolia *crop rotation with rehabilitated indigenous forests*

The total carbon stock in the *C. equisetifolia* plantations far exceeded that of the stands being rehabilitated to indigenous forest at a comparable age, except for stands 6 years old and younger (Tables 2 and 3). If *C. equisetifolia* is harvested at 12 years of age and replanting commences after a year (i.e. a total of 13 years for each crop rotational cycle), the total carbon accumulated would follow a 'zig-zag' pattern (Figure 4). The mean net carbon storage[51] in all the five pools for the *C. equisetifolia* plantations under crop rotation, at a value of 87.06 t ha^{-1} of carbon, is indicated by the hatched horizontal line in Figure 4. The latter value averages the quantity of carbon stored over the long term and assumes that all carbon accumulated during a crop rotation is lost at harvesting and that there is no build-up of belowground, litter, debris or soil carbon. The rehabilitated indigenous forest reached the level of mean net carbon storage ha^{-1} of *C. equisetifolia* plantations after ~19 years.

Discussion

Carbon dynamics in reclaimed mined soils

The relationship between stand age and total, aboveground and belowground carbon stocks in the *C. equisetifolia* plantation could best be described by a sigmoid function, whereas the relationship was linear for the rehabilitating indigenous forest (Figure 1). This implies that carbon accumulation in *C. equisetifolia* plantations reaches an asymptote (approximately after 12 years), whereafter there are no further increases accrue with time. In the case of the rehabilitating indigenous forests, carbon stocks keep on increasing and could potentially increase to the level of a secondary indigenous forest (150.98 t ha^{-1}, Van Rooyen, unpublished data) or even to the level of a primary indigenous forest (227.14 t ha^{-1}, Van Rooyen, unpublished data). The time frame for the latter successional developments is currently unknown. Analysis of aerial photographs and quantification of carbon stocks at sites of known age could assist in establishing plausible estimates of time frames.

Litter accumulation in the *C. equisetifolia* plantations was significantly (power function) related to stand age, whereas this was not the case for the rehabilitated indigenous forests. Likewise, the carbon content of the soils in the *C. equisetifolia* plantations showed a significant increase with time up to a stand age of 15 years, whereas no significant relationship between soil carbon and stand age could be demonstrated for the rehabilitated indigenous forests where a layer of carbon-rich topsoil is initially added. The debris carbon pool was present only in the rehabilitated indigenous forest, where it showed a significant positive accumulation of carbon with time.

The rate at which the total carbon increased in the rehabilitating indigenous forest decreased from a mean of 9.9 t ha^{-1} y^{-1} in the first 5 years to 4.5 t ha^{-1} y^{-1} over the entire 27-year period. The apparent high rate of carbon sequestration in the first few years is as a result of the input of carbon-rich topsoil. In *C. equisetifolia* plantations, the rate at which the total carbon increased showed a parabolic relationship: in the first 5 years, the mean annual rate of increase was 7.1 t ha^{-1} y^{-1}; the maximum rate was achieved at 10 years (18.8 t ha^{-1} y^{-1}), whereafter it decreased again to 12.1 t ha^{-1} y^{-1} over 18 years.

Comparisons of carbon stocks in different post-mining vegetation types

Maximum total carbon, 121 t ha^{-1}, that accumulated in the 27-year-old rehabilitated indigenous forest stand was of the same magnitude as values reported for other reclaimed ecosystems: for example, 126 t ha^{-1} in a 25-year-old site under forest in Ohio, USA;[3] 133 t ha^{-1} after 35 years in Scots pine stands in

Table 3 Carbon stock in five pools in the rehabilitated indigenous forest at Richards Bay Minerals

	Rehabilitated indigenous forest								
	3 years	6 years	9 years	12 years	15 years	18 years	21 years	24 years	27 years
Aboveground carbon pool (t ha^{-1})									
Indigenous trees (t ha^{-1})	5.50 ± 0.40	15.34 ± 2.36	17.66 ± 0.57	24.62 ± 0.39	26.66 ± 2.59	26.46 ± 4.28	32.13 ± 0.98	33.08 ± 7.75	55.43 ± 9.24
Ground cover (t ha^{-1})	1.14 ± 0.39	0.06 ± 0.02	0.48 ± 0.16	0.56 ± 0.05	0.33 ± 0.04	0.66 ± 0.09	0.75 ± 0.05	0.85 ± 0.11	0.81 ± 0.00
Standing dead trees (t ha^{-1})	0.10 ± 0.04	0.36 ± 0.13	2.31 ± 0.48	1.97 ± 1.00	4.81 ± 0.35	2.72 ± 1.02	2.56 ± 1.82	0.26 ± 0.26	1.02 ± 0.98
Scramblers (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.03 ± 0.02	0.21 ± 0.04	0.02 ± 0.02	0.08 ± 0.03	0.14 ± 0.06	1.14 ± 0.25
Vines (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.03 ± 0.03	0.13 ± 0.06	0.55 ± 0.14	0.43 ± 0.14	0.63 ± 0.25	0.43 ± 0.17	1.42 ± 0.48
Dracaena aletriformis (t ha^{-1})	0.00 ± 0.00	0.01 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	0.05 ± 0.03	0.00 ± 0.00	0.00 ± 0.00	0.03 ± 0.03	0.25 ± 0.08
Total aboveground carbon (t ha^{-1})	6.74 ± 0.41	15.76 ± 2.35	20.48 ± 0.77	27.32 ± 1.29	32.62 ± 1.90	30.28 ± 5.37	36.16 ± 3.27	34.78 ± 8.69	60.06 ± 9.41
Belowground carbon pool (t ha^{-1})									
Indigenous trees (t ha^{-1})	2.31 ± 0.17	6.44 ± 0.99	7.42 ± 0.24	10.34 ± 0.17	11.20 ± 1.09	11.11 ± 1.80	13.50 ± 0.41	13.89 ± 3.25	23.28 ± 3.88
Ground cover (t ha^{-1})	1.80 ± 0.06	0.10 ± 0.03	0.76 ± 0.25	0.89 ± 0.08	0.52 ± 0.03	1.045 ± 0.15	1.19 ± 0.09	1.34 ± 0.17	1.28 ± 0.00
Standing dead trees (t ha^{-1})	0.04 ± 0.02	0.15 ± 0.05	0.97 ± 0.20	0.83 ± 0.43	2.02 ± 0.15	1.14 ± 0.43	1.08 ± 0.76	0.11 ± 0.11	0.43 ± 0.41
Scramblers (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.05 ± 0.03	0.32 ± 0.06	0.02 ± 0.02	0.13 ± 0.04	0.23 ± 0.09	1.76 ± 0.35
Vines (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.05 ± 0.03	0.23 ± 0.07	0.18 ± 0.06	0.27 ± 0.10	0.18 ± 0.07	0.60 ± 0.20
Dracaena aletriformis (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.00	0.02 ± 0.01	0.00 ± 0.00	0.00 ± 0.00	0.01 ± 0.01	0.10 ± 0.04
Total belowground carbon (t ha^{-1})	4.16 ± 0.17	6.69 ± 0.99	9.16 ± 0.29	12.16 ± 0.58	14.31 ± 1.06	13.51 ± 2.21	16.15 ± 1.34	15.76 ± 3.34	27.45 ± 3.99
Litter carbon (t ha^{-1})	2.55 ± 0.21	3.00 ± 0.50	5.21 ± 1.24	5.42 ± 0.68	2.89 ± 0.15	3.71 ± 0.70	2.99 ± 0.15	3.01 ± 0.56	6.65 ± 1.29
Debris carbon (t ha^{-1})	0.00 ± 0.00	0.00 ± 0.00	1.03 ± 0.34	2.75 ± 0.41	7.54 ± 1.70	3.30 ± 0.47	10.01 ± 3.27	3.97 ± 1.07	3.62 ± 2.32
Soil carbon (t ha^{-1})	16.44 ± 3.89	28.52 ± 2.45	26.28 ± 1.49	17.81 ± 2.98	30.12 ± 0.79	26.17 ± 3.19	25.62 ± 4.63	22.18 ± 4.29	23.46 ± 5.76
Total carbon in five pools (t ha^{-1})	29.89 ± 4.36	53.96 ± 5.54	62.15 ± 1.46	65.47 ± 4.65	87.48 ± 4.73	76.97 ± 10.24	90.93 ± 5.11	79.70 ± 13.80	121.23 ± 15.24

Values for indigenous trees were calculated by applying Shackleton's[48] equation to the indigenous tree component. Data for aboveground, belowground, litter and debris pools are based on a survey conducted in 2004, and the soil carbon pool was determined in 2005. All values are for means ± SE.

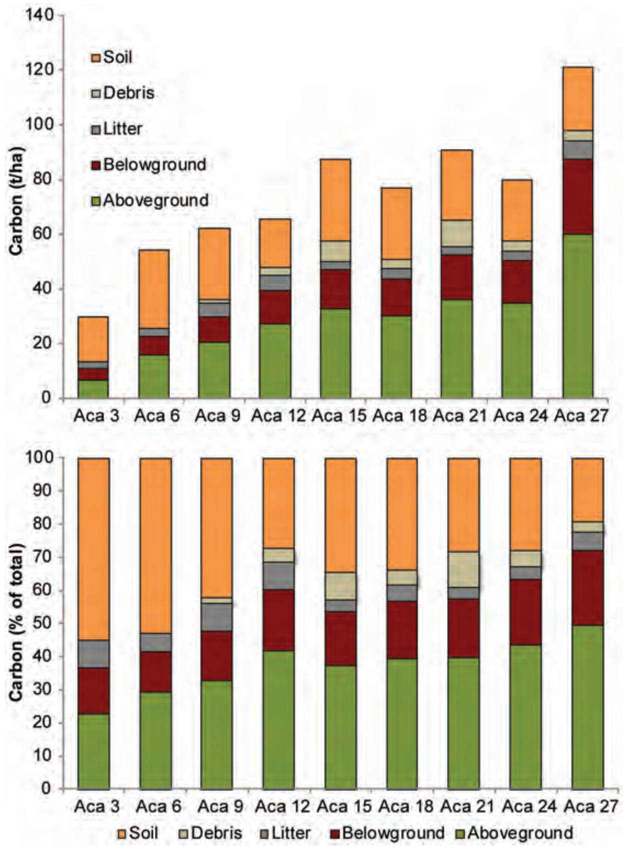

Figure 3 (a) Carbon stocks in the aboveground, belowground, debris, litter and soil carbon pools (in t ha^{-1}) and (b) percentage contribution of the aboveground, belowground, litter, debris and soil carbon pools to the total carbon stock in post-mining rehabilitating indigenous forest stands (Aca) of different ages at Richards Bay Minerals.

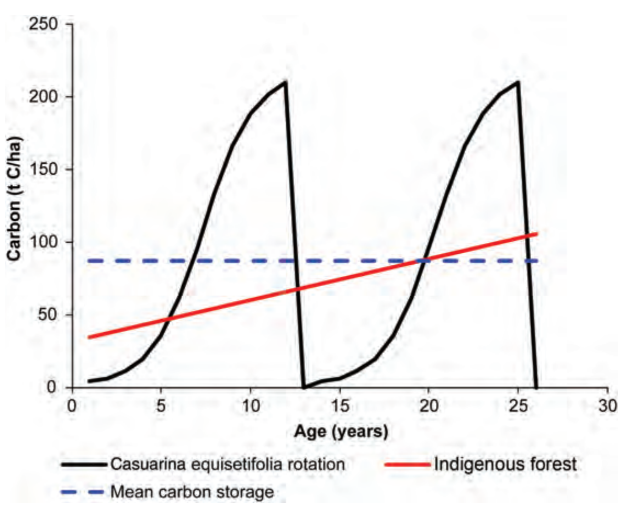

Figure 4 Changes in total carbon stock in a *Casuarina equisetifolia* plantation under a 13-year rotation cycle with mean net carbon storage for such a plantation. The total carbon stock in the *Casuarina equisetifolia* plantation is compared with that in the rehabilitating indigenous forests over a 27-year period.

Estonia[6] and mean values of 148 t ha^{-1} in pine stands, 130 t ha^{-1} in hardwood stands and 118 t ha^{-1} in mixed stands after 30–50 years in Midwestern and Appalachian coal-fields in the USA.[5] The carbon content in the 27-year-old indigenous forest stand exceeded the mean net carbon storage (87.06 t ha^{-1}) of the *C. equisetifolia* plantation under a 13-year crop rotation. However, it should be borne in mind that the mean net carbon storage assumed no build-up of belowground, litter, debris or soil carbon.

The distribution of carbon among the five pools differed between the plantations and the naturally rehabilitating indigenous forests. Aboveground plus belowground biomass constituted ~90% of the total carbon in the *C. equisetifolia* stands from an age of 9 years onwards. In the rehabilitating indigenous forests, aboveground plus belowground biomass contributions showed a steady increase from 36% in the 3-year-old stand to 72% in the 27-year-old stand. Compared with the commercial plantations, the belowground carbon pool in the naturally rehabilitated forest constituted a larger portion of the carbon stock contained in the combined above- and belowground biomass (30–38% for indigenous forest as against 10–19% at comparable ages for *C. equisetifolia*). This can be ascribed to a higher root-to-shoot ratio being applied to the indigenous forest. Furthermore, the ground cover component, with the highest root-to-shoot ratio of all components, was almost absent in the commercial plantations, whereas it was developed to varying degrees in the indigenous forest.

Litter carbon made a fairly large contribution to the total carbon in the 3- and 6-year-old *C. equisetifolia* stands, but thereafter litter contributions were fairly similar for the plantations and the naturally rehabilitated forests. The CWD pool was negligible in the plantations, whereas it contributed up to 11% of total carbon in the rehabilitating indigenous forest. The large fluctuations in both the litter and debris carbon pools were possibly coupled to self-thinning occurring in the rehabilitating indigenous forest stands.

Previous studies have indicated that the sandy soils in the region are naturally low in carbon.[11,33] The values provided in the current study are for the top 300 mm as prescribed by the IPCC for reporting[38] and therefore not directly comparable with previous studies done at the study site where sampling was done only to a 100-mm depth[33] or to a 600-mm depth.[11] The maximum soil carbon value for the *C. equisetifolia* plantations was approximately a third of the maximum of the rehabilitating indigenous forest. However, rehabilitation of the *C. equisetifolia* plantations proceeds on mined tailings without any topsoil dressing (carbon content 0 t ha^{-1}), whereas the rehabilitating indigenous forests rely on the seed bank contained in a 10–15 cm layer of carbon-containing topsoil. A sample of topsoil taken in 2005 from such a newly prepared site had a carbon content of 25.73 t ha^{-1}. The carbon value of the topsoil used for rehabilitation will depend on whether the sample had been stockpiled or not, as there is typically a substantial decrease in soil organic matter content, microbial activity and microbial biomass when topsoil is stockpiled before being spread on rehabilitated land.[34,52] Furthermore, the carbon content of the topsoil will depend on the type of vegetation from which the topsoil was collected with the range 10.8–72.5 t ha^{-1} found for different pre-mining vegetation types (Van Rooyen, unpublished data).

Although the actual soil carbon content of the rehabilitated indigenous forest remained fairly constant across the chronosequence, the percentage contribution of soil carbon to the total carbon gradually decreased from 55% in the 3-year-old indigenous forest to 19% in the 27-year-old forest. Soil carbon in the *C. equisetifolia* plantations ranged within a narrow band from 2 to 6% from an age of 3 years onwards.

Increases in soil organic matter content and microbial activity as aboveground vegetation develops on a site have been reported in many studies[53,54], and at Richards Bay both Van Aarde *et al*.[33] and Graham and Haynes[34] reported an increase in soil carbon content in the top 100 mm of the soil profile during rehabilitation. In contrast, Scott *et al*.[11] reported on the failure of these topsoils and subsoils to recover carbon following mining disturbance. In the current study, there was no evidence for increased soil carbon levels with an increase with stand age in the rehabilitating indigenous forest, although an increase was found for the *C. equisetifolia* plantations.

The rapid decline in soil carbon in the commercially harvested plantations could be attributed to the low clay content of the soils, which affords little protection of organic matter through the formation of clay–organic matter complexes.[34] Moreover, after harvesting the aboveground biomass, there was no input of fresh organic matter to offset the decomposition of organic matter in the soil.

Comparisons of carbon stocks between pre-mining and post-mining vegetation types

The mean carbon content for all the pre-mining vegetation types is ≈150 t ha^{-1}, with a range from 50 to 227 t ha^{-1} (Van Rooyen, unpublished data). At the time of the survey, a third of the pre-mining area (31%) was under commercial plantations, mainly *P. elliottii*, *C. equisetifolia* and *E. grandis*, and two-thirds were indigenous forest vegetation types. If only the pre-mining area under commercial plantations is considered, then the pre-mining carbon content is ≈90 t ha^{-1}, whereas it is ≈178.6 t ha^{-1} for the area under indigenous forest vegetation types (Van Rooyen, unpublished data). For the rehabilitated areas under commercial plantations, the mean net carbon storage reported for this study (87.06 t ha^{-1}) indicates that the pre-mining levels have basically already been achieved. Pre-mining carbon levels in the indigenous forests are almost double the value of the commercial forests. The 27-year-old rehabilitated indigenous forest had captured 68% of the comparable pre-mining vegetation carbon.

Suggestions for future forest management

Richards Bay Minerals is committed to honouring their obligations contained in their Environmental Management Plan, which prescribes rehabilitation of one-third of the lease areas to indigenous vegetation and revegetation of two-thirds of the lease areas to commercial *C. equisetifolia* plantations.[55] The harvested *C. equisetifolia* is used to set up a charcoal production industry, which has the advantage that the biofuel (charcoal) is a substitute for fossil fuels. However, some CO_2 and non-CO_2 greenhouse gases are released during the manufacturing process. *Casuarina equisetifolia* is also used to supply posts that support the shade netting used as windbreaks during the rehabilitation process.

Alternative land-use and forest management practices may be considered after the first rotation of *C. equisetifolia* plantations have been harvested.[55] Within the current agreement, the mining lease areas will return to the local communities after closure of the mines. In a quest to reduce global atmospheric greenhouse gas concentrations, it would therefore be advisable to negotiate carbon sequestration possibilities at an early stage with the communities. However, it should be appreciated that the needs of the local community may differ from global priorities. Food security in terms of grazing and cropland, fuelwood supply and harvesting of medicinal plants could be more pressing to the local community.

Conversion of C. equisetifolia plantations into indigenous forests

The carbon content in a rehabilitating indigenous forest will exceed the level of mean net carbon storage per hectare of *C. equisetifolia* plantations after ∼19 years. If it is assumed that these forests are developing into natural indigenous forests, they could potentially reach the carbon level of a secondary indigenous forest (150.98 t ha^{-1}) and eventually even that of a primary indigenous forest (227.14 t ha^{-1}) . If maximizing the carbon sequestration potential during rehabilitation was aimed for, then increasing the land under indigenous forest rehabilitation would be called for. However, because of the long time frames involved, this option could best be accommodated if this change in land-use is initiated directly after mining and not after a crop rotation cycle of *C. equisetifolia*. This would imply that the 1:2 ratio of indigenous forest: *C. equisetifolia* rehabilitation, specified in the current Environmental Management Plan, should be revisited. Other advantages of such a conversion would be: increasing and protecting biodiversity; creating a corridor between the un-mined natural forest strip along the coast and Lake Nhlabane; providing limited grazing for the livestock of local communities; enlarging areas for harvesting of medicinal plant species and enhancing provision of ecosystem services such as improved water quality. A disadvantage of such a conversion would be the loss of biofuel (charcoal) production from the *C. equisetifolia* plantation, which could possibly result in a medium- to long-term carbon leakage. Leakage here refers to the situation where the carbon sequestration activity on one piece of land, inadvertently, directly or indirectly, triggers an activity which counteracts the carbon effects of the initial activity.[38] This could be partly offset by accountable harvesting of fuelwood from the indigenous forest.

Conversion of C. equisetifolia plantations into E. grandis

Whether a carbon loss or gain is attained by the replacement of the *C. equisetifolia* plantations with *E. grandis* will depend on the length of the crop rotation cycle. If a 8–9-year crop rotation is implemented for *E. grandis*, the mean carbon storage value would probably be lower than that of *C. equisetifolia* at a 12–13-year rotation. Furthermore, the paper- and pulp-related products derived form *E. grandis* have a short life cycle time frame,[56] whereas charcoal from *C. equisetifolia* has the advantage of avoiding fossil fuel emissions.

Conversion of C. equisetifolia *into grazing land or cropland*

A conversion of the plantations into grazing land or cropland will incur large carbon losses, but may be desirable in terms of food security. Converting parts of the lease area into agricultural land also prevents the destruction of other areas to provide for current and future subsistence needs. Biofuel manufacturing and fuelwood utilization would be possible only during the first rotation harvesting of the *C. equisetifolia* plantation. Another disadvantage of such a conversion is the emission of non-CO_2 greenhouse gases by livestock production and crop fertilization. Grazing land and cropland will reduce biodiversity compared with indigenous forests, but not compared with *C. equisetifolia* plantations.

Biomass burial of C. equisetifolia

Although not recognized as normal forestry practice, an unconventional way to increase the carbon sequestration potential of the plantations would be by biomass burial. Buried woody material is expected to have a long residence time because the low oxygen concentration below the soil surface will slow down decomposition rates.[57–59] Richards Bay Minerals could investigate a unique opportunity of long-term carbon sequestration through the burial of harvested *C. equisetifolia* trees behind the dredger. Such a practice will result in the carbon storage of most of the aboveground carbon in the plantations ($\approx$160 t ha^{-1} in a 12-year-old plantation). Because biomass burial goes beyond the 'business-as-usual' practices, it could potentially qualify as 'additionality'. Biomass burial could continue for a number of crop rotations, or alternatively the plantations could be converted into indigenous forest rehabilitation after a single rotation with the accompanying burial of biomass. Wood burial would, however, result in leakage because the charcoal is no longer reaching markets. A proportion of the plantations could therefore still be utilized for charcoal production. Carbon storage in the mine dredge line could be continued for as long as dredging continues. Decomposition rates, hydrological impacts, wastage as well as logistical and practical feasibility need to be investigated, prior to opting for biomass burial.

Conclusions

The rehabilitation program initiated by Richards Bay Minerals is currently capturing substantial quantities of atmospheric carbon in the vegetation and soils. Compared with pre-mining levels, the rehabilitated areas under commercial forestry have achieved the goal of attaining similar carbon stocks. However, the carbon storage potential of the plantations is fixed at the level of the mean net carbon storage and no further opportunities for increases in carbon levels are available.

Although the 27-year-old rehabilitated indigenous forest has captured approximately two-thirds of the comparable pre-mining vegetation's carbon, the carbon stock in these vegetation types is continuously increasing and ultimately, may be almost double that of the commercial forestry target.

Improvements in the carbon sequestration potential of the mined lands can be achieved through reforestation of the harvested *C. equisetifolia* plantations with indigenous forest. By implementing such a management strategy Richards Bay Minerals could optimize carbon sequestration while at the same time contributing towards protecting biodiversity and restoring natural capital.

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Conflict of interest statement

None declared

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