Soil Science and Plant Nutrition (2009) 55, 132–141 doi: 10.1111/j.1747-0765.2008.00340.x

ORIGINAL ARTICLE/SHORT PAPER

Eucalyptus camaldulensis and *Pinus caribaea* growth in relation to soil physico-chemical properties in plantation forests in Northern Nigeria

Yoshinori WATANABE[1], Tsugiyuki MASUNAGA[1], Oluwarotimi Omotola FASHOLA[2], Adeniyi AGBOOLA[2], Peter K. OVIASUYI[3] and Toshiyuki WAKATSUKI[4]

[1]*Faculty of Life and Environmental Science, Shimane University, Matsue 690-8504,* [4]*Faculty of Agriculture, Kinki University, Nara 332-7204, Japan,* [2]*International Institute of Tropical Agriculture, 5320, Ibadan, and* [3]*Forestry Research Institute of Nigeria, Afaka, Kaduna, Nigeria*

Abstract

The present study described the relationship between growth and soil physico-chemical properties in *Eucalyptus camaldulensis* (Myrtaceae) and *Pinus caribaea* (Pinaceae), two important species in Nigerian forest recovery programs. The study sites were located in a 17-year-old plantation in a Northern Nigeria forest reserve. The soils at the study sites were nutrient poor compared with other plantations. Growth of *E. camaldulensis* was positively correlated with exchangeable K content in soils 0–20 cm deep, and negatively correlated with total N and exchangeable Na in soils 20–150 cm deep. Growth of *P. caribaea* was positively correlated with available P in soils 0–20 cm deep, and volumetric water content in soils 20–150 cm deep. Soils in the top layers were very hard and plinthite layers were well developed at shallow soil depths at most sites. *E. camaldulensis* exhibited a comparatively high survival rate, and its growth was comparable to that in other plantations. However, the survival rates of *P. caribaea* were low and its growth was lower than that in other plantations. The survival rate of *E. camaldulensis* was lower at sites where plinthite layers were found within 50.8 cm of the surface. These results indicated that *E. camaldulensis* is suitable for afforestation in Northern Nigeria. However, it is not recommended for sites where the plinthite layer occurs at shallow soil depths.

Key words: *Eucalyptus*, *Pinus*, plinthite layer thickness, soil physico-chemical properties, tree growth.

INTRODUCTION

The area occupied by forest in the tropical and subtropical zones of many developing countries has seen rapid decline in recent years. Poor forest management, including over or clear cutting, animal grazing and periodic bush burning have accelerated the complete loss of natural savanna vegetation in Northern Nigeria (Kadeba 1994). Restoration efforts to establish native tree plantations have had little success, evidenced by low yields (approximately 1 m^3 ha^{-1} $year^{-1}$) and the choice of species unsuitable for the growing conditions of the region (Kemp 1970). To circumvent these obstacles, fast-growing exotic tree species have been chosen to initiate forest recovery. Typically, eucalyptus and pine, two exotic tree species, are the most common components of forest plantations in tropical Africa. Plantations supporting eucalyptus and pine were reported to occupy 0.79 and 0.61 million hectares, respectively, in 1990 (Ball 1995). In rural communities, eucalyptus plantations have increased the local fuel wood supply, resulting in a reduction in the pressures imposed on natural forests (Schonau 1991). Therefore, eucalyptus and pine have been recognized as the most suitable exotic tree species for afforestation in Northern Nigeria (Adegbehin *et al.* 1988).

In Nigeria, the area occupied by plantations increased to as much as 1573 km^2 in 1993 (Olufemi and Ameh 1999), and these newly developed ecosystems deserve effective management. To date, research providing growth and yield data for eucalyptus and pine has been conducted in several regions of Nigeria (Adegbehin *et al.* 1988; Otegbeye 1985; Otegbeye and Samarawira 1991, 1992). In addition, the influence of eucalyptus and pine plantations on soils (Jaiyeoba 1998, 2001; Kadeba

Correspondence: Y. WATANABE, Faculty of Life and Environmental Science, Shimane University, Shimane 690-8504, Japan. Email: d06a2006@matsu.shimane-u.ac.jp

Received 22 September 2008.
Accepted for publication 19 October 2008.

and Aduayi 1985a), tree nutrition and nutrient cycling (Egunjobi and Onweluzo 1979; Kadeba 1991; Kadeba and Aduayi 1985b) has been explored in Nigeria. Buckley (1988) reported that soil factors affected the yield of *Eucalyptus camaldulensis* in former tin mining and farming sites in Northern Nigeria. However, reports evaluating the soil characteristics impacting on plantation yield in forest reserves are lacking, despite the fact that several reports in other regions of the world indicate that soil traits are significantly correlated with tree growth (Coile 1952; Klinka *et al.* 1994; Lowry 1975; Mader 1976).

The objective of the present study was to evaluate soil physico-chemical properties relative to the growth of *E. camaldulensis* and *Pinus caribaea* plantations in Northern Nigeria.

MATERIALS AND METHODS

Study area

The study area was located in the Japan International Cooperation Agency and Forest Research Institute of Nigeria project (1986–1991) in the Afaka Forest Reserve (10°34′N, 7°20′E) near Kaduna in Northern Nigeria (Fig. 1). The elevation ranges from approximately 600 to 700 m a.s.l. with a slope of less than 8%. The mean annual rainfall was approximately 1,209 mm from 1987 to 2005, with most precipitation occurring between April and October, and dry conditions between November and March. The monthly mean temperature ranged from a minimum of 23°C in December to a maximum of 29°C in April, with an annual mean of 25°C recorded at the Kaduna Airport.

The soil parent materials include gneiss, migmatite and granite. Schist, phyllite, quartzite and pegmatite are a common soil component of specific locales; and amphibolites, diorites and gabbros are also present (Barrera and Amujo 1971). A plinthite is characteristic of the C-horizon. The soils at the study sites were classified as Plinthustalfs and Kandiustalfs using the US Department of Agriculture (2003) soil taxonomic system. The soils were primarily loam to sandy loam in texture (Barrera and Amujo 1971). The original native vegetation was classified as Northern Guinea Savanna (Keay 1959).

Plantations of *E. camaldulensis* and *P. caribaea* were planted in 1989. The planting space was 5 m × 3 m or 3 m × 3 m in square. Before planting, the ground was cleared by a disk harrow and a ripper. No significant influences from the two ground clearance methods have been documented (Japan International Cooperation Agency and Forest Research Institute of Nigeria 1991). Weeding and shrub clearing were conducted 1–2 years after planting in the study area, with the exception of site E4. Tree thinning was not conducted during the study.

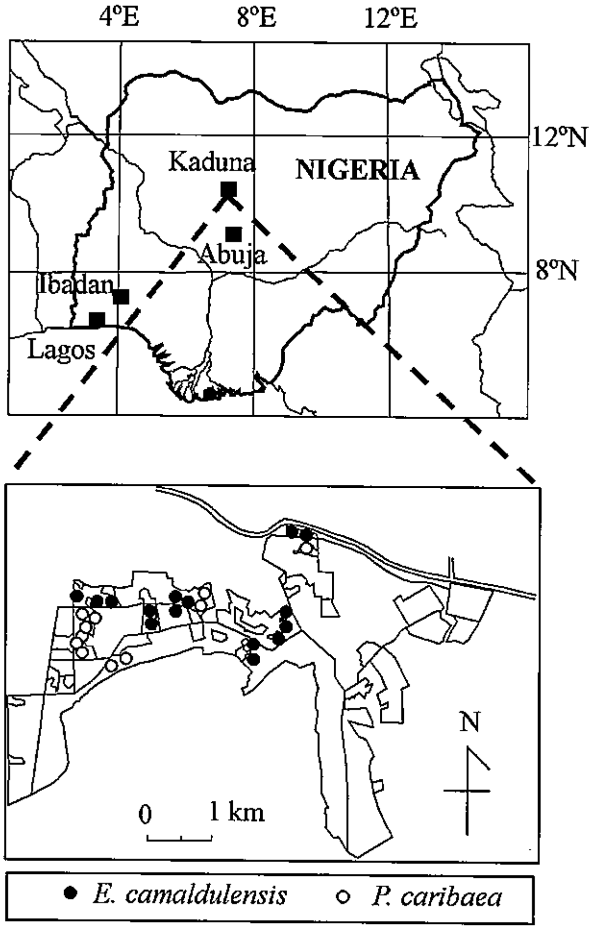

Figure 1 Study site location in the Japan International Cooperation Agency and Forest Research Institute of Nigeria Trial Afforestation Project of the Afaka Forest Reserve in Kaduna, Nigeria.

Field survey

A field survey was conducted at selected study sites from September to November 2006. Fifteen study sites were established for *E. camaldulensis* and 11 sites were established for *P. caribaea* plantations. Tree enumeration was carried out in a 25 m × 25 m quadrat plot for each study site. Tree volume for each site was calculated using Smalian's formula (Japan International Cooperation Agency and Forest Research Institute of Nigeria 1991). Survival rates were determined based on the initial 1989 planting densities (Japan International Cooperation Agency and Forest Research Institute of Nigeria 1991) and the densities obtained from the 2006 data. In addition, the five trees exhibiting the greatest diameter at breast height in each 25 m × 25 m quadrat plot at the site were measured for tree height. The mean height of the five trees was considered the top height, following a modified method of Friday (1987). Mean height, top height, survival rate and tree volume were used as tree growth indicators. A soil profile to a depth of 150 cm was prepared for soil observations at each study site. Soil samples were collected from each soil profile layer using a 100 cm^3 core sampler. Samples were subsequently analyzed for physico-chemical properties. Soil hardness was also examined for each layer using a Yamanaka-type soil hardness meter (Fujiwara, Tokyo, Japan). The depth of the apparent plinthite layer was also recorded during the soil profile observations.

Plinthite description

Soil thickness (above the plinthite layer) greater than 36 inches (91.4 cm) was classified as "deep"; between 20 (50.8 cm) and 36 inches as "moderately deep"; and less than 20 inches as "shallow" (Barrera and Amujo 1971). Plinthite abundance was described in terms of classes, which indicated the percentage of exposed surface occupied by plinthite. We expressed plinthite abundance as its cover over an exposed surface of the soil profile horizon as follows: less than 5% "few", 5–40% "common", and more than 40% "many"; common and many were recorded as a plinthite layer. Among the 15 *E. camaldulensis* sites, five sites were deep, one site was moderately deep and nine sites were shallow. The 11 *P. caribaea* sites were classified as two deep, two moderately deep and seven shallow.

We also recorded plinthite hardness as "soft" or "hard", defined by our ability to crush the material between our fingers (following the hardness classification of concretion determined by the Japanese Society of Pedology 1997). The study sites contained soft, hard and a soft–hard mix of plinthite layers.

Laboratory analysis

The volumetric water content and bulk density of the soil was determined by establishing the weight of the core samples after they were oven-dried for 24 h at 105°C. Air-dried soil samples were ground and passed through a 2 mm sieve for laboratory analysis. The glass electrode method (H_2O) was used to evaluate soil pH with a soil to solvent ratio of 1:2.5. Total carbon and total nitrogen contents were determined using a CN corder (MT-700; J-Science, Kyoto, Japan). Exchangeable cations (exchangeable Ca, Mg, K and Na) were extracted from the soil in 1 mol L^{-1} ammonium acetate (The International Institute of Tropical Agriculture (IITA) 1979). Exchangeable Ca and Mg were determined by Inductively Coupled Plasma Emission Photometry (ICPS-2000; Shimadzu, Kyoto, Japan) and exchangeable K and Na were determined using an Atomic Adsorption Spectrophotometer (exchangeable K: Z-5010; Hitachi, Tokyo, Japan; exchangeable Na: AS 680; Shimadzu). Available P was resolved using the Bray-1 method and the contents were determined by colorimetry using a UV/VIS Spectrophotometer (V-530; Jasco, Tokyo, Japan) (Bray and Kurtz 1945). The total C and total N, exchangeable cations, available P and volumetric water content were estimated per hectare and summed separately for depths of 0–20 cm and 20–150 cm (Ali *et al.* 1997).

Statistical analysis

Pearson's correlation coefficients were calculated to examine the relationship between the survival rate of *E. camaldulensis* and *P. caribaea* and mean height, top height and volume, and the relationship between soil properties and *E. camaldulensis* and *P. caribaea* growth. The statistical significance of the mean soil hardness from the soft and hard plinthite layers was determined using a multiple comparisons test; a difference in the mean values was evaluated using Dunnett's C method. A *t*-test was used to determine any statistical difference in mean *E. camaldulensis* and *P. caribaea* growth with thickness above the plinthite layer. All statistical analyses were done using SPSS version 11.0 for Windows (SPSS, Tokyo, Japan).

RESULTS AND DISCUSSION

Tree growth

Mean values for diameter at breast height (dbh) and height, basal area, top height, survival rate and tree volume are indicated in Table 1. Withered trees lacking a closed canopy were observed at some of the sites. The survival rate of *E. camaldulensis* and *P. caribaea* was significantly correlated with mean height, top height and volume ($P < 0.05$). This result indicated that the factor causing low survival rate might prohibit tree growth in both height and volume. Our field observations did not identify any specific cause for the low survival rate of *P. caribaea*. However, the majority of *E. camaldulensis* sites with low survival rates were located on hilltops, ironstone outcrops or near ironstone hills, where shallow soils less than 60 cm deep were present. *Eucalyptus camaldulensis* exhibits a deep root system (Sun and Dickinson 1995); therefore, we speculated that shallow soils influenced *E. camaldulensis* growth. The mean survival rate measured for the 1-year-old plantation was 77.8% for *E. camaldulensis* and 65.8% for *P. caribaea* (Japan International Cooperation Agency and Forest Research Institute of Nigeria 1991). The mean survival rate for the 17-year-old plantation was 63.8% for *E. camaldulensis* and 42.8% for *P. caribaea*. These results suggest that tree survival rates were mainly reduced during the first year following planting.

Table 1 *Eucalyptus camaldulensis* and *Pinus caribaea* growth data from each study site (17-year-old trees)

Study site	dbh (cm)†	Height (m)†	Basal area (m^2 ha^{-1})	Top height (m)‡	Survival rate (%)	Volume (m^3 ha^{-1})
E. camaldulensis						
E1	10.1 ± 3.6	11.9 ± 3.0	2.2	14.9	32.0	12.80
E2	18.4 ± 5.3	19.9 ± 3.6	15.1	24.4	78.7	131.28
E3	19.2 ± 4.0	20.1 ± 3.3	12.5	21.7	70.3	105.40
E4	13.3 ± 5.2	15.3 ± 3.8	2.0	17.7	23.3	14.65
E5	17.6 ± 6.2	15.3 ± 3.6	8.3	18.0	55.3	56.21
E6	15.6 ± 4.3	16.5 ± 2.7	10.1	18.7	49.2	72.90
E7	15.9 ± 2.9	17.6 ± 2.2	10.1	19.5	49.2	77.35
E8	16.7 ± 4.0	18.5 ± 3.4	9.6	21.0	68.2	77.47
E9	14.4 ± 3.8	16.6 ± 3.2	9.2	20.4	86.6	70.34
E10	13.9 ± 4.4	17.1 ± 3.7	11.6	21.6	72.7	93.45
E11	15.9 ± 4.0	19.2 ± 2.9	21.4	22.4	97.3	182.50
E12	14.8 ± 4.4	18.3 ± 3.7	19.2	21.6	97.3	159.63
E13	12.9 ± 4.4	17.1 ± 5.2	7.7	18.7	49.5	63.69
E14	16.4 ± 2.1	19.4 ± 3.4	12.1	21.9	52.5	101.07
E15	14.8 ± 2.9	19.8 ± 2.4	14.3	20.8	74.9	124.31
P. caribaea						
P1	12.9 ± 3.1	10.0 ± 1.8	7.9	11.4	50.3	36.16
P2	10.8 ± 3.1	8.2 ± 1.1	4.9	10.0	54.7	19.28
P3	9.5 ± 2.9	7.0 ± 1.2	1.5	7.9	16.9	5.18
P4	18.0 ± 3.3	14.7 ± 1.7	23.1	16.5	86.8	141.49
P5	11.2 ± 2.3	7.9 ± 1.6	4.8	8.9	45.8	17.98
P6	11.9 ± 2.2	9.3 ± 1.1	2.9	10.3	25.3	12.30
P7	15.8 ± 3.0	11.3 ± 1.5	8.5	12.4	41.0	41.81
P8	11.6 ± 2.3	7.8 ± 1.5	1.7	8.5	15.8	6.39
P9	15.7 ± 3.1	11.9 ± 1.6	14.5	13.0	71.0	75.02
P10§	11.8 ± 2.1	8.9 ± 1.0	2.7	9.1	24.3	10.80
P11	11.1 ± 2.5	8.5 ± 1.7	3.9	10.5	38.9	15.73

†Mean of site trees ± standard deviation. ‡Mean height of the five greatest trees in dbh §P10 was 20 m × 25 m, and the other sites were 25 m × 25 m.

There are several reports on *E. camaldulensis* and *P. caribaea* growth in Nigeria and other countries (Table 2). The mean height and top height of *E. camaldulensis* observed in our study, and in other Nigerian studies (Otegbeye and Samarawira 1991), were lower than those in India (Tewari *et al.* 2002), but comparable to those in Morocco (Jacobs 1979a). Although there is less annual rainfall in India than Nigeria, which is considered to be a semi-arid region (like that of Nigeria), *E. camaldulensis* growth was higher in the Indian study relative to our study. In its native range, *E. camaldulensis* experiences annual rainfall from 250 to 625 mm (Jacobs 1979b). Therefore, annual rainfall in India might be suitable for *E. camaldulensis* growth. Consequently, we concluded that *E. camaldulensis* growth was not limited by rainfall during the study period. The mean and top height of *P. caribaea* were less than those observed in other studies (Bhodthipuks 1979; Calvo-Alvarado *et al.* 2007; Liegel 1991; Wang *et al.* 1999), including reports from other Nigerian localities (Adegbehin and Onyibe 2001; Adegbehin *et al.* 1988; Kadeba 1991). In *P. caribaea*, the native range conditions of this species show annual rainfall of 1,500–3,900 mm (Liegel 1991). The annual rainfall measured in the present study was approximately 1,200 mm, less that that of the natural habitat of *P. caribaea*. However, the climatic conditions of other Nigerian study sites were similar to the present study; and *P. caribaea* growth was comparable to that of other countries. These results suggest that climatic conditions were not the main limiting factor in *P. caribaea* growth over the 17-year growth period.

Soil physico-chemical properties

The chemical properties of the top and bottom soil profile layers are shown in Table 3. There have been several reports on the chemical properties of the surface soil of *E. camaldulensis* and *P. caribaea* plantations in Nigeria and other countries (Table 4). The mean pH, total C and exchangeable Ca and Mg contents in the top soil layers were comparable to those of other Nigerian

Table 2 Tree growth and climatic conditions derived from other *Eucalyptus camaldulensis* and *Pinus caribaea* studies

Study site	Age (years)	Mean height (m)	Volume (m^3 ha^{-1})	Air temperature (°C) (Maximum)	Air temperature (°C) (Minimum)	Annual rainfall (mm)	Reference
Eucalyptus camaldulensis							
Present study site	17	18.1 (22.0)[†]	89.5				
India	17–18	18.6–30.2[‡]	87.0–271.1	39.5–42.5[††]	14–16[††]	120–300	(Tewari *et al.* 2002)
Morocco	16	11.6–19.9	39.7–177.0				(Jacobs 1979a)
Nigeria	18	13.2–24.60		35–36[††]	14–15[††]	1,056–1,290	(Otegbeye and Samarawira 1991)
Pinus caribaea							
Present study site	17	10.5 (11.5)[†]	34.7				
China	16	15.6				1,527–2,253	(Wang *et al.* 1999)
Costa Rica	7	8.6–10.4		21.3–27[‡‡]		2,688–4,314	(Calvo-Alvarado *et al.* 2007)
Costa Rica	15	18–26[§]				1,500–6,000	(Liegel 1991)
Jamaica	15	16–24[§]				1,000–5,000	(Liegel 1991)
Puerto Rico	15	18–26[§]				800–5,000	(Liegel 1991)
Trinidad	15	14–22[§]		29 (Day)[§§]	23 (Night)[§§]	1,700–3,300	(Liegel 1991)
Venezuela	15	13–21[§]		30–33 (Day)[§§]	20–22 (Night)[§§]	1,000	(Liegel 1991)
Nigeria	16	20.1[¶]	275.3	13–36[††]		1,290–1,750	(Adegbehin *et al.* 1988)
Nigeria	16	14.0–23.2[¶]	135.7–426.9				(Adegbehin and Onyibe 2001)
Nigeria	15	17.4 ± 0.5		14–35[††]		1,250	(Kadeba 1991)
Thailand	10	11.9–12.3		24.8–27.2[‡‡]			(Bhodthipuks 1979)

[†]Top height. [‡]Dominant height. [§]Average height of the tallest trees. [¶]Mean height of the largest trees 100 ha^{-1}. [††]Mean monthly temperatures. [‡‡]Mean annual temperatures. [§§]Mean daily temperatures. ±, standard error of the mean.

sites and other countries. Exchangeable K content in the top soil layers for *E. camaldulensis* was lower than that in Zimbabwe (Sanginga *et al.* 1991), and as low as that reported in India (Hunter 2001) and Benin (Drechsel and Schmall 1990). For *P. caribaea*, the total N content in the top soil layers was lower than that in Belize (Stewart and Kellman 1982) and Liberia (Zech and Drechsel 1992) and comparable to that in Nigeria (Kadeba and Aduayi 1985a). The available P value generated by the Bray-1 method was higher than that recorded using the Olsen and Truog methods (Lopez-Pineiro and Garcia-Navarro 2001). The available P content in the top soil layers in *E. camaldulensis* plantations was lower than that of other countries. These results demonstrate that the *E. camaldulensis* and *P. caribaea* soils in the present study were more nutrient poor than the soils from other plantation sites.

The physical properties of the top and bottom soil profile layers are shown in Table 5. The volume of the core sample liquid phase was used to ascertain the volumetric water content, and the weight of the core sample solid phase was used to determine the bulk density. Field surveys indicated that soil hardness and compactness negatively impacted tree root growth. Similar relationships have been observed in other countries. Tree root growth generally declines when soil hardness exceeds 1.0 MPa, and is severely restricted when the hardness exceeds 2.0 MPa (Greacen and Sands 1980; Morris and Campbell 1991). In *Pinus tabulaeformis* Carr. plantations, Zhou and Shangguan (2007) reported that root mass decreased exponentially with an increase in bulk density from 1.03 to 1.33 Mg m^{-3}.

A comparison of different soil depths from a 150-cm deep soil profile was used to compare the relationship between soil hardness and plinthite layer distribution. The mean soil hardness for absent, soft, soft–hard mixed and hard plinthite layers was 1.92, 1.21, 3.07 and 2.07 MPa, respectively, at depths less than 50.8 cm; and 1.31, 1.18, 2.49 and 3.13 MPa, respectively, for depths greater than 50.8 cm. Results of a multiple comparisons test indicated the mean soil hardness from the absent plinthite layer was significantly higher than that in the soft plinthite layer at depths less than 50.8 cm ($P < 0.05$). At depths greater than 50.8 cm, the mean soil hardness in the hard plinthite layer was significantly higher than that in the absent and soft plinthite layers ($P < 0.05$). The mean soil hardness in the soft–hard mixed and hard plinthite layers was above 2.0 MPa, values reported to influence plant root elongation (Greacen and Sands 1980; Morris and Campbell 1991). These results suggested that hard plinthite layers increased soil hardness and prohibited root growth.

Table 3 Top and bottom layer soil profile chemical properties at a depth of 150 cm

Study site	Layer	pH_w	Total C	Total N	Exchangeable cations Ca	Mg	K	Na	Available P
			(g kg^{-1})		(cmol$_c$ kg^{-1})				(mg kg^{-1})
Eucalyptus camaldulensis	Top	6.01 ± 0.22	11.65 ± 3.80	0.78 ± 0.22	2.87 ± 1.15	1.14 ± 0.29	0.22 ± 0.10	0.03 ± 0.01	2.75 ± 1.05
	Bottom	5.60 ± 0.26	1.27 ± 0.34	0.20 ± 0.03	1.19 ± 0.89	0.57 ± 0.34	0.15 ± 0.08	0.05 ± 0.02	0.41 ± 0.18
Pinus caribaea	Top	5.85 ± 0.15	7.56 ± 1.23	0.58 ± 0.09	1.82 ± 0.58	0.62 ± 0.32	0.15 ± 0.06	0.04 ± 0.01	2.53 ± 1.32
	Bottom	5.58 ± 0.69	1.18 ± 0.36	0.18 ± 0.04	1.22 ± 1.11	0.63 ± 0.69	0.14 ± 0.11	0.07 ± 0.05	0.40 ± 0.25

Mean of study sites ± standard deviation. The depth of the top and bottom layers was approximately 0–11 ± 4 cm and 112–150 ± 18 cm, respectively.

Table 4 Surface soil chemical properties derived from other *Eucalyptus camaldulensis* and *Pinus caribaea* studies

Study site (g kg^{-1})	Depth (cm)	pH_w	Total C (g kg^{-1})	Total N (g kg^{-1})	Exchangeable cations Ca (cmol$_c$ kg^{-1})	Mg (cmol$_c$ kg^{-1})	K (cmol$_c$ kg^{-1})	Available P (mg kg^{-1})	Reference
Eucalyptus camaldulensis									
India	0–25	5.9		0.80†		1.11§	0.11§	7.1††	(Hunter 2001)
Zimbabwe	0–15	5.2–5.5			1.5–1.7	0.3	0.7–0.8	4.9–6.7‡‡	(Sanginga *et al.* 1991)
Benin	0–10	5.0	11.7	0.60†	0.67	0.39	0.06		(Drechsel and Schmall 1990)
Pinus caribaea									
Belize	0–5	4.5–4.6		1.00–1.60‡	0.17–0.78	0.15–0.63	0.12–0.21	1.5–20§§	(Stewart and Kellman 1982)
Nigeria	0–10	5.9–6.1		0.51–0.70†	1.54–2.02	1.08–1.34	0.15–0.20	4.6–5.8¶¶	(Kadeba and Aduayi 1985a)
Liberia	0–4			1.71†	7.53¶	1.10¶	0.20¶		(Zech and Drechsel 1992)

†Kjeldahl. ‡Block digest. §NH_4NO_3. ¶0.1 mol L^{-1} $MgCl_2$. ††Olsen. ‡‡Bray 2. §§Truog. ¶¶0.1 mol L^{-1} H_2SO_4. Other cations were extracted ammonium acetate.

Table 5 Top and bottom layer soil profile physical properties at a depth of 150 cm at each study site

Study site	Layer	Volumetric water content (m^3 m^{-3})[†]	Bulk density (Mg m^{-3})[‡]	Hardness (MPa)[§]
Eucalyptus camaldulensis	Top	0.22 ± 0.09	1.53 ± 0.10	2.51 ± 1.91
	Bottom	0.34 ± 0.07	1.64 ± 0.17	2.71 ± 1.73
Pinus caribaea	Top	0.21 ± 0.08	1.60 ± 0.07	2.04 ± 1.38
	Bottom	0.41 ± 0.06	1.48 ± 0.12	1.21 ± 0.68

[†]The volume of the liquid phase in core samples. [‡]The weight of the solid phase in core samples. [§]Measurement values using a Yamanaka-type soil hardness meter. Mean of study sites ± standard deviation. The top and bottom layers in the soil profiles of 150 cm depth. The depth of the top and bottom layers was approximately 0–11 ± 4 cm and 112–150 ± 18 cm, respectively.

Table 6 Correlations between the surface soil properties at soil depths of 0–20 cm and *Eucalyptus camaldulensis* and *Pinus caribaea* growth

	Eucalyptus camaldulensis (n = 15)				*Pinus caribaea* (n = 11)			
0–20 cm	Mean height (m)	Top height (m)	Survival rate (%)	Volume (m^3 ha^{-1})	Mean height (m)	Top height (m)	Survival rate (%)	Volume (m^3 ha^{-1})
Total C	0.182	0.041	0.041	0.298	0.343	0.350	0.502	0.309
Total N	0.146	0.011	0.012	0.305	−0.119	−0.069	0.249	−0.074
Exch. Ca	0.104	0.091	0.008	0.268	−0.225	−0.171	0.102	−0.163
Exch. Mg	0.231	0.146	0.007	0.251	−0.292	−0.249	−0.081	−0.284
Exch. K	0.406	0.550*	0.435	0.459	−0.334	−0.272	−0.026	−0.285
Exch. Na	−0.389	−0.341	−0.329	−0.432	−0.114	−0.185	−0.258	−0.218
Available P	0.268	0.104	0.171	0.451	0.833**	0.800**	0.673*	0.739**
VWC	0.066	0.202	0.271	0.364	0.008	0.008	−0.156	−0.020

VMC, volumetric water content. *P <0.05: **P <0.01.

Relationship between soil properties and tree growth

The correlation between the soil physico-chemical properties at a depth of 0–20 cm and the tree growth parameters is shown in Table 6. *Eucalyptus camaldulensis* exhibited a positive correlation between exchangeable K content in the soil and tree top height. Available P for *P. caribaea* was positively correlated with all growth parameters, that is, mean height, top height, survival rate and standing tree volume. In addition, some soil physico-chemical properties at a depth of 20–150 cm were correlated with tree growth. *Eucalyptus camaldulensis* showed a negative correlation between total N and exchangeable Na content in the soil and mean height (r = −0.570* for total N; r = −0.532* for exchangeable Na). *Pinus caribaea* demonstrated a positive correlation between soil volumetric water content and top height (r = 0.660*).

The influence of K and P on *E. camaldulensis* and *P. caribaea* growth have also been reported in other countries. Drechsel and Schmall (1990) recorded reduced growth in *E. camaldulensis* as a result of K and P deficiencies in the coastal zone of Benin. In the present study, soil exchangeable K content might also be a limiting factor for *E. camaldulensis* growth. Platteborze and Sen (1972) reported that *P. caribaea* growth in Malaysia was correlated with available P. Srivastava and Zainorin (1979) reported that P was the most important nutrient for increased height in *P. caribaea* seedlings. Liegel (1991) found that P levels in shallow and stony limestone localities limited *P. caribaea* growth in Jamaica. The results of these studies were congruent with the results of the present study. We speculated that available P was a key factor in *P. caribaea* growth in Northern Nigeria. In terms of the influence of the soil volumetric water content on *P. caribaea* growth, Liegel (1991) reported that soil conditions resulting in poor growth for *P. caribaea* included excessively dry conditions during the long dry season or an increase in water beyond optimal conditions during the rainy season in Venezuela. Drainage is impeded above a soil depth of 40 cm when soils become oversaturated (Liegel 1991). In the present study, no sites were observed where drainage was impeded above a soil depth of 40 cm. Therefore, water availability, expressed as soil volumetric water content, was a possible limiting factor in *P. caribaea* growth. In addition, our results suggested a negative relationship between total N, exchangeable Na content and *E. camaldulensis* growth. In general, N is found to be an essential element in plant growth. The exchangeable Na content had a negligible influence on *E. camaldulensis*

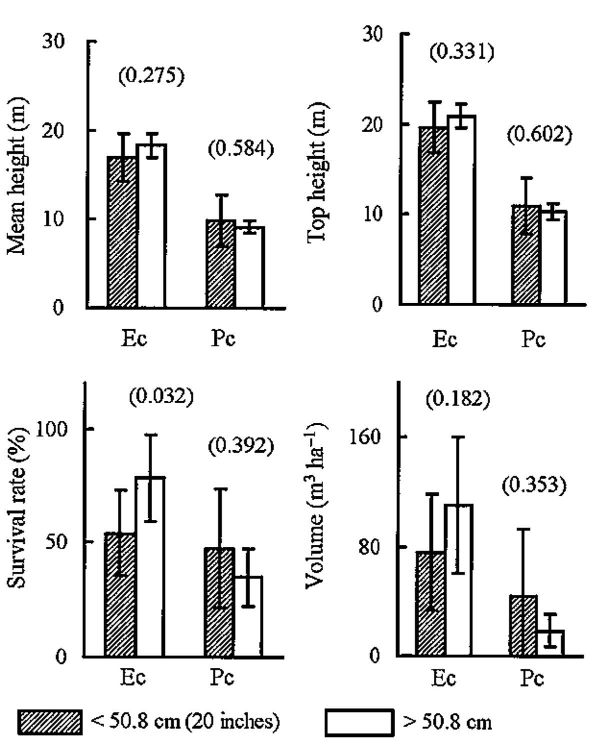

Figure 2 Comparisons of mean height, top height, survival rate and volume of *Eucalyptus camaldulensis* (Ec) and *Pinus caribaea* (Pc) between shallow plinthite and deep plinthite sites. Soil depth over plinthite is less than 50.8 cm at the shallow plinthite site and greater than 50.8 cm at the deep site. Numbers in parentheses indicate the level of significance determined by a *t*-test. Error bars represent the standard deviation.

growth. However, a negative correlation between total N, exchangeable Na and *E. camaldulensis* growth was observed, but we were unable to determine a biological cause for this result.

Plinthite depth and tree growth

Relationships between tree growth and soil thickness above the plinthite layer were observed in the soil profiles of *E. camaldulensis* and *P. caribaea* (Fig. 2). The growth of *P. caribaea* was not statistically different among study sites exhibiting different soil thicknesses above the plinthite layer (*t*-test; $P > 0.05$). However, the survival rate of *E. camaldulensis* was significantly higher ($P < 0.05$) at sites with a soil thickness exceeding 50.8 cm above the plinthite layer. Sun and Dickinson (1995) indicated that *E. camaldulensis* has a deep root system, and hardpan blasting improved *E. camaldulensis* growth (Shiono *et al.* 2007). Thus, a physical property of the soil, that is, soil thickness above the plinthite layer, could be a factor influencing root growth in *E. camaldulensis*.

In general, the soil physico-chemical properties of the study area can be characterized as very hard and nutrient poor. The data obtained in the present study did not lead to conclusive results. However, our results indicated that *E. camaldulensis* was better suited than *P. caribaea* for timber production in the study area. The plinthite layer, which was commonly distributed in shallow soil depths in the study region, negatively influenced *E. camaldulensis* growth, but not *P. caribaea* growth. Therefore, we suggest afforestation methods consider *E. camaldulensis* plantations over *P. caribaea*. However, it should be noted that *P. caribaea* might be a viable option at sites with a well-developed plinthite layer, that is, conditions where *E. camaldulensis* growth is limited.

ACKNOWLEDGMENTS

This study was supported by the Japan Society for the Promotion of Science (Grants-in-Aid Scientific Research No. 15101002 and No. 19002001). We gratefully acknowledge the Japan International Cooperation Agency and the Forestry Research Institute of Nigeria for kindly allowed us to conduct our study at the plantation sites.

REFERENCES

Adegbehin JO, Okojie JA, Nokoe S 1988: Growth of *Eucalyptus tereticornis* and *Pinus caribaea* at different sites in Northern Nigeria. *For. Ecol. Manage.*, 23, 261–272.

Adegbehin JO, Onyibe JE 2001: Growth and yields of *Pinus caribaea* in northern Nigeria. *Pakistan J. Forest.*, 51, 1–19.

Ali MM, Saheed SM, Kubota D, Masunaga T, Wakatsuki T 1997: Soil degradation during the period 1967–1995 in Bangladesh. I. Carbon and nitrogen. *Soil Sci. Plant Nutr.*, 43, 863–878.

Ball JB 1995: Development of *Eucalyptus* plantations–an overview. Proceedings Regional Expert Consultation on Eucalyptus, Vol. 1. Eds K White, J Ball and M Kashio. FAO Regional Office for Asia and the Pacific, Bangkok. [cited April 2008.] Available from URL: http://www.fao.org/docrep/005/ac777e/ac777e00.HTM

Barrera AV, Amujo SJ 1971: The Soil Survey of Afaka Forest Reserve. Research paper No. 9. Savanna Forestry Research Station, Zaria.

Bhodthipuks P 1979: Height increment of *Pinus caribaea* var. *hondurensis* in Thailand. *Tro. Agr. Res.*, 12, 7–10.

Bray RH, Kurtz LT 1945: Determination of total organic and available forms of phosphorus in soils. *Soils Sci.*, 59, 39–45.

Buckley GP 1988: Soil factors influencing yields of *Eucalyptus camaldulensis* on former tin-mining land in the Jos Plateau Region, Nigeria. *For. Ecol. Manage.*, 23, 1–17.

Calvo-Alvarado JC, Arias D, Richter DD 2007: Early growth performance of native and introduced fast growing tree species in wet to sub-humid climates of the Southern region of Costa Rica. *For. Ecol. Manage.*, 242, 227–235. doi: 10.1016/j.foreco.2007.01.034

Coile TS 1952: Soil and the growth of foresters. *In* Advances in Agronomy 4. Ed. AG Norman, pp. 329–398. Academic Press, New York.

Drechsel P, Schmall S 1990: Mineral deficiencies and fertilization of coastal reforestations in Benin, West Africa. *Fertilizer Research*, 23, 125–133.

Egunjobi JK, Onweluzo BS 1979: Litter fall, mineral turnover and litter accumulation in *Pinus caribaea* L. stands at Ibadan, Nigeria. *Biotropica*, 11, 251–255.

Friday KS 1987: Site index curves for teak (*Tectona grandis* L.) in the limestone hill region of Puerto Rico. *Commonw. For. Rev.*, 66, 239–253.

Greacen EL, Sands R 1980: Compaction of forest soils. A review. *Aust. J. Soil Res.*, 18, 163–189.

Hunter I 2001: Above ground biomass and nutrient uptake of three tree species (*Eucalyptus camaldulensis*, *Eucalyptus grandis* and *Dalbergia sissoo*) as affected by irrigation and fertilizer, at 3 years of age, in southern India. *For. Ecol. Manage.*, 144, 189–199.

The International Institute of Tropical Agriculture (IITA) 1979: Determination of exchangeable Ca, Mg, K, Na, Mn, and effective CEC in soil. *In* Selected Methods for Soil and Plant Analysis, Manual Series No.1. pp. 10. IITA, Ibadan.

Jacobs MR 1979a: Example for yield tables. *In* Eucalyptus for Plantating. FAO Forestry series no.11, pp. 533–555. Food and Agriculture Organization, Rome.

Jacobs MR 1979b: Choice of species for planting. *In* Eucalyptus for Plantating. FAO Forestry series no.11, pp. 337–354. Food and Agriculture Organization, Rome.

Jaiyeoba IA 1998: Changes in soil properties related to conversion of savannah woodland into pine and eucalyptus plantations, northern Nigeria. *Land Degrad. Develop.*, 9, 207–215.

Jaiyeoba IA 2001: Soil rehabilitation through afforestation: evaluation of the performance of eucalyptus and pine plantations in a Nigerian savanna environment. *Land Degrad. Develop.*, 12, 183–194. doi: 10.1002/idr.447

Japanese Society of Pedology 1997: 4.4 Mottling and Concretion. *In* Soil Survey Handbook, revised. pp. 63–69. Hakuyusha, Tokyo (in Japanese).

Japan International Cooperation Agency and Forest Research Institute of Nigeria 1991: The Trial Afforestation Project in Semi-Arid Area, Federal Republic of Nigeria, vol. 2. Japan International Cooperation Agency, Tokyo.

Kadeba O 1991: Above-ground biomass production and nutrient accumulation in an age sequence of *Pinus caribaea* stands. *For. Ecol. Manage.*, 41, 237–248.

Kadeba O 1994: Growth and nutrient accumulation by *Pinus caribaea* on three savanna sites in northern Nigeria. *Agr. Ecosyst. Environ.*, 49, 139–147.

Kadeba O, Aduayi EA 1985a: Impact on soils of plantations of *Pinus caribaea* stands in natural tropical savannas. *For. Ecol. Manage.*, 13, 27–39.

Kadeba O, Aduayi EA 1985b: Litter production, nutrient recycling and litter accumulation in *Pinus caribaea* Morelet var. *hondurensis* stands in the northern Guinea savanna of Nigeria. *Plant Soil*, 86, 197–206.

Keay RWJ 1959: An Outline of Nigerian Vegetation, 3rd edn. Government Printer, Lagos.

Kemp RH 1970: Trials of Exotic Tree Species in the Savanna Region of Nigeria. Res. Pap. No. 6 (Savanna series). Federal Department of Forest Research, Ibadan.

Klinka K, Wang Q, Kayahara GJ 1994: Quantitative characterization of nutrient regimes in some boreal forest soils. *Can. J. Soil Sci.*, 74, 29–38.

Liegel LH 1991: Growth and site relationships of *Pinus caribaea* across the Caribbean Basin. Gen. Tech. Rep. SO-83. US Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans.

Lopez-Pineiro A, Garcia-Navarro A 2001: Phosphate fractions and availability in vertisols of south-western Spain. *Soil Sci.*, 166, 548–556.

Lowry GL 1975: Black spruce site quality as related to soil and other site conditions. *Soil Sci. Soc. Am. Proc.*, 39, 125–131.

Mader DL 1976: Soil-site productivity for natural stands of white pine in Massachusetts. *Soil Sci. Soc. Am. J.*, 40, 112–115.

Morris LA, Campbell RG 1991: Soil and site potential. *In* Forest Regeneration Manual. Eds ML Duryea and PM Dougherty, pp. 183–206. Kluwer Academic Publishers, Dordrecht.

Olufemi AO, Ameh CE 1999: Status of vegetation and forests in Nigeria. *In* Forest Resource Situation Assessment of Nigeria. Food and Agriculture Organization, Rome. [cited March 2008.] Available from URL: http://www.fao.org/docrep/004/ab578e/AB57800.HTM

Otegbeye GO 1985: Provenance productivity in *Eucalyptus camaldulensis* Dehnh. and its implications to genetic improvement in the savanna region of Nigeria. *Silvae Genetica*, 34, 121–126.

Otegbeye GO, Samarawira I 1991: Growth and form of *Eucalyptus camaldulensis* Dehnh. provenances in northern Nigeria. *For. Ecol. Manage.*, 42, 219–228.

Otegbeye GO, Samarawira I 1992: Correlations of growth and form characteristics of *Eucalyptus camaldulensis* Dehnh. provenances in northern Nigeria. *For. Ecol. Manage.*, 50, 275–285.

Platteborze A, Sen EC 1972: Initial Site Survey of Potential Forest Plantation Sites in West Malaysia. FO:SF/MAL 12, Working paper no. 3. Food and Agriculture Organization, Rome.

Sanginga N, Gwaze D, Swift MJ 1991: Nutrient requirement of exotic tree species in Zimbabwe. *Plant Soil*, 132, 197–205.

Schonau APG 1991: Role of eucalyptus plantations in timber supply and forest conservation in Sub-Saharan Africa. *South African Forestry Journal*, 156, 56–60.

Shiono K, Abe Y, Tanouchi H *et al.* 2007: Growth and survival of arid land forestation species (*Acacia aneura*, *Eucalyptus camaldulensis* and *E. salubris*) with hardpan blasting. *J. Arid Land Stud.*, 17, 11–22.

Srivastava PBL, Zainorin ANBA 1979: The response of *Pinus caribaea* Mor. var. *hondurensis* seedlings to nitrogen, phosphorous and potassium fertilizers. *Plant Soil*, 51, 215–232.

Stewart H, Kellman M 1982: Nutrient accumulation by *Pinus caribaea* in its native savanna habitat. *Plant Soil*, 69, 105–118.

Sun D, Dickinson GR 1995: Salinity effects on tree growth, root distribution and transpiration of *Casuarina cunninghamiana* and *Eucalyptus camaldulensis* planted on a saline site in tropical north Australia. *For. Ecol. Manage.*, 77, 127–138.

Tewari VP, Verma A, Kumar VSK 2002: Growth and yield functions for irrigated plantations of *Eucalyptus camaldulensis* in the hot desert of India. *Bioresource Technology*, 85, 137–146.

US Department of Agriculture 2003: Keys to Soil Taxonomy. University Press of the Pacific, Honolulu.

Wang H, Malcolm DC, Fletcher AM 1999: *Pinus caribaea* in China: introduction, genetic resources and future prospects. *For. Ecol. Manage.*, 177, 1–15.

Zech W, Drechsel P 1992: Multiple mineral deficiencies in forest plantations in Liberia. *For. Ecol. Manage.*, 48, 121–143.

Zhou Z, Shangguan Z 2007: Vertical distribution of fine roots in relation to soil factors in *Pinus tabulaeformis* Carr. forest of the Loess Plateau of China. *Plant Soil*, 291, 119–129. doi: 10.1007/s11104-006-9179-z